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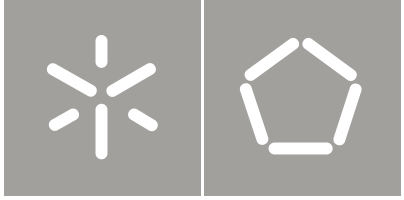
Alaize Dall’Orsoletta

Exploring the Systemic Impacts of a Low-emission Transport Sector: Pathways to a Just Energy Transition

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Alaize Dall’Orsoletta
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Exploring the Systemic Impacts of a Low-emission Transport Sector: Pathways to a Just Energy Transition

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Thesis Supervisors
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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho. This research has been approved by "Comissão de Ética para a Investigação em Ciências Sociais e Humanas" (CEICSH) as per document number CEICSH 070/2023.

Exploring the Systemic Impacts of a Low-emission Transport Sector: Pathways to a Just Energy Transition

ABSTRACT

Energy transitions involve more than technological change; they unfold within complex socio-technical systems and depend on technical, financial, material, and governance capacities that are unevenly distributed across regions and countries. As local transitions advance, the unequal distribution of burdens and benefits has raised growing concerns about equity and justice in both research and practice. Within this context, energy justice has emerged as a normative framework to identify and address justice-related issues in energy transitions.

This PhD explores energy justice concerns associated with one of the most widely promoted low-carbon technologies: electric vehicles (EVs). It examines the social, economic, and environmental implications of large-scale EV adoption through a whole-systems energy justice perspective. It also investigates how justice considerations can be translated into quantitative indicators and incorporated into computational modeling, while recognizing the inherent limitations.

The thesis consists of a collection of articles using mixed and multi-method approaches. Literature reviews were conducted to map current knowledge on EV-related justice issues, the operationalization of justice in EV research, and the inclusion of social dimensions in system dynamics models. Documentary analysis informed a case study on EV adoption in Portugal, highlighting issues such as lithium mining conflicts and disparities in EV access and charging infrastructure between urban and rural areas. These concerns were further examined using quantitative system dynamics models developed from primary and secondary data.

Key contributions include: (i) linking energy justice concepts to the EV lifecycle using six normative tenets and a systems perspective; (ii) operationalizing justice-related issues in EV adoption; and (iii) integrating social and justice dimensions into systems-based energy transition models to support more reflective and informed decision-making and modeling towards a low-carbon and just energy transition.

Keywords: Electric vehicles, Energy justice, Just energy transition, Systems approach, System dynamics.

Explorando os Impactos Sistémicos de um Setor de Transportes de Baixa Emissão: Caminhos para uma Transição Energética Justa

RESUMO

As transições energéticas envolvem mais do que mudanças tecnológicas, ocorrendo em sistemas sociotécnicos complexos que exigem capacidades técnicas, políticas, financeiras e de governação, desigualmente distribuídas entre regiões e países. Com o avanço destas transições, emergem questões de justiça e equidade na investigação e na prática. Neste contexto, o conceito de justiça energética surge como uma abordagem normativa para identificar e analisar desigualdades associadas às transições energéticas.

Esta tese centra-se nas problemáticas de justiça energética associadas a uma das tecnologias de baixo carbono mais promovidas: os veículos elétricos (VEs). O objetivo é explorar os impactos sociais, económicos e ambientais da adoção em larga escala dos VEs a partir de uma perspetiva sistémica. Além disso, investiga-se como integrar preocupações de justiça em indicadores quantitativos e modelos computacionais, reconhecendo as limitações inerentes.

A investigação estrutura-se numa coleção de artigos científicos que aplicam diferentes metodologias. Foram realizadas revisões de literatura para mapear: as problemáticas ao longo do ciclo de vida dos VEs; a operacionalização da justiça em estudos relacionados com VEs; e a inclusão de aspetos sociais em modelos de dinâmica de sistemas. A análise documental permitiu identificar desafios específicos no contexto português, como conflitos ligados à mineração de lítio e desigualdades no acesso a VEs e infraestruturas de carregamento entre populações rurais e urbanas. Estas questões foram também analisadas através de modelos quantitativos de dinâmica de sistemas desenvolvidos com base em dados primários e secundários.

As principais contribuições incluem: (i) a articulação entre justiça energética e o ciclo de vida dos VEs, com base em seis pilares normativos e numa abordagem sistémica; (ii) a operacionalização de problemáticas associadas à adoção de VEs; e (iii) a incorporação de dimensões sociais e de justiça em modelos computacionais, promovendo maior compreensão e reflexividade na transição energética e na modelação quantitativa para uma transição mais justa e de baixo-carbono.

Palavras-chave: Abordagem sistémica, Dinâmica de sistemas, Justiça energética, Transição energética justa, Veículos elétricos.

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Abbreviations and Acronyms List

ABMs – Agent-Based Models

AC – Air Conditioning

ACAP – Associação Automóvel de Portugal

AFVs – Alternative Fuel Vehicles

AMU – Medium Urban Area

APA – Portuguese Environmental Agency (Agência Portuguesa do Ambiente)

APR – Predominantly Rural Area

APU – Predominantly Urban Area

B – Balancing

BEVs – Battery Electric Vehicles

BIPOC – Black, Indigenous, People of Color

CAE – National Classification of Economic Activities

CCI – Car Cost Index

CEICSH – Comissão de Ética para a Investigação em Ciências Sociais e Humanas

CEPII – Centre d'Etudes Prospectives et d'Informations Internationales

CLD – Causal Loop Diagram

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

COP26 – Climate Change Conference

CSR – Corporate Social Responsibility

DAC – Disadvantaged Communities

DER – Distributed Energy Resource

DGEG – Energy and Geology General Directorate (Direção Geral de Energia e Geologia)

DRC – Democratic Republic of Congo

Dmnl – Dimensionless

EAFO – European Alternative Fuels Observatory

EIA – Environmental Impact Assessment

EPA – Environment Protection Agency

EV – Electric Vehicle

EVCS – Electric Vehicle Charging Station

EVCI – Electric Vehicle Charging Infrastructure

ESG – Environmental, Social, and Governance

ESM – Energy System Model

ESMAP – Energy Sector Management Assistance Program

EU – European Union

FAO – Food and Agriculture Organization

GDP – Gross Domestic Product

GDPR – General Data Protection Regulation

GHG – Greenhouse Gas

GIS – Geographic Information System

GVA – Gross Value Added

GTL – Grupo Trabalho Lítio

HEMS – Home Energy Management Systems

HEVs – Hybrid Electric Vehicles (non-hybrid)

HHI – Herfindahl-Hirschman Index

IAMs – Integrated Assessment Models

IAPMEI – Agência para a Competitividade e Inovação

IEA – International Energy Agency

ICCT – International Council on Clean Transportation

ICEV – Internal Combustion Engine Vehicle

ILO – International Labor Organization

IMT – Instituto da Mobilidade e dos Transportes

INE – Instituto Nacional de Estatística

IPCC – Intergovernmental Panel on Climate Change

ISV – Imposto Sobre Veículos

JET – Just Energy Transition

LCE – Lithium Carbonate Equivalent

Li-ion Batteries – Lithium-Ion Batteries

Li_2CO_3 – Lithium Carbonate

LiS – Lithium Spodumene

LPG – Liquefied Petroleum Gas

MAE – Mean Absolute Error

MAPE – Mean Absolute Percentage Error

MLP – Multi-Level Perspective

MNLM – Multinomial Logit Model

MSE – Mean Squared Error

MTF – Multi-Tier Framework

MUSTs – Micro-Urban Social Typologies

NGO – Non-Governmental Organization

NO_x – Nitrogen Oxides

OECD - Organization for Economic Co-operation and Development

PHEVs – Plug-in Hybrid Electric Vehicles

PM2.5 – Particulate Matter

PPP Lítio – Programa de Prospeção e Pesquisa do Lítio

PV – Photovoltaics

R – Reinforcing

RE – Renewable Energy

RES – Renewable Energy Sources

RET – Renewable Energy Technology

RMSE – Root Mean Squared Error

SDGs – Sustainable Development Goals

SFD – Stock-and-Flow Diagram

SLO – Social License to Operate

SMP – Sustainable Mobility Project

SNM – Strategic Niche Management

SO_2 – Sulfur Dioxide

STET – Socio-Technical Energy Transitions

TIPAU – Tipologia de Áreas Urbanas

TIS – Technological Innovation Systems

TM – Transition Management

UK – United Kingdom

UN – United Nations

UNDP - United Nations Development Program

US – United States

VAT – Value Added Taxes

V2G – Vehicle-to-Grid

WBCSD – World Business Council for Sustainable Development

WEF – Water-Energy-Food

W2W – Well-to-Wheel

3E – Energy-Economy-Environment

1 Introduction

This Chapter introduces the PhD thesis by first outlining the broader context and motivation underpinning the research (**Section 1.1**), including the complexities of transitioning to low-carbon technologies, the associated asymmetries, and the research gaps addressed herein. **Section 1.2** presents the research questions and objectives, while **Section 1.3** outlines the research methodology. **Section 1.4** describes the overall structure of the thesis, explaining how each chapter contributes to the research objectives and detailing the corresponding scientific outputs, as the thesis is presented as a collection of articles.

1.1 Context and motivation

Changes in how energy is produced, distributed, and consumed are the core of energy transitions. Consequently, much of the current research on the ongoing energy transition has focused on technological advancements (Araújo, 2014), exploring renewable energy (RE) generation, energy storage, energy efficiency, and alternative fuel technologies. This strong technological emphasis arises from several interconnected factors: the persistent influence of technocratic approaches[1], the inherent production-consumption dynamics of capitalist systems[2], and the pressing urgency of climate change[3]. This urgency may drive a prioritization of relatively rapid technological solutions over more fundamental, long-term societal transformations needed to align human activity with Earth's finite biophysical resources.

However, energy transitions comprehend more than technological processes. They unfold within complex socio-technical systems, involving a variety of social, economic, environmental, political, and cultural dynamics. This implies that the energy transition does not consist of simple technological replacements, from fossil fuels to renewables generation; rather it requires changes across policy, supply chains, energy-

[1] Technocratic approaches refer to methods of decision-making and policy development that rely heavily on technical expertise, technology, and "hard measures" to address issues, often with minimal public participation or consideration of social, economic, and ethical factors. In the context of climate change adaptation, technocratic approaches focus predominantly on physical risks and infrastructure solutions, such as implementing advanced technologies, while neglecting the social vulnerabilities and systemic inequalities that exacerbate climate risks. These approaches are typically top-down, rigid, and prioritize tangible outcomes over collaborative and inclusive processes (Kehler & Birchall, 2021).

[2] In essence, the inherent dynamics of capitalism – its drive for growth, profit, production, and relatively short-term market signals – tend to favor technological solutions to climate change because these solutions offer pathways for continued economic activity and wealth generation within the existing framework (e.g., green capitalism). While technological innovation is undoubtedly crucial for addressing climate change, this prioritization can sometimes overshadow the need for broader systemic changes and a re-evaluation of production and consumption patterns. See Fox (2023) for a critical analysis on the green capitalism concept.

[3] See for instance the Planetary Health Check (Caesar et al., 2024) produced by the Potsdam Institute for Climate Impact Research based on the Planetary Boundaries (Rockström et al., 2009), which indicate a series of environmental thresholds within which humanity can operate safely. Crossing these thresholds imply triggering non-linear, abrupt environmental change at continental and planetary scales. In 2024, six of the nine planetary boundaries had been crossed.

related infrastructure, financing mechanisms, international trade, as well as social and behavioral aspects. All this coupled with the fact that different countries and regions have varying technical, financial, resource-based, and governance capacities to implement required changes, underscoring the inherently uneven nature of transitions.

Accordingly, as local energy transitions progress, the inequitable distribution of burdens and benefits of transitions has raised questions of equity and justice across research and practice. These questions refer to, for example, socio-environmental burdens surrounding raw material extraction for the energy transition (Ciftci & Lemaire, 2023), effects of the energy transition on labor (García-García et al., 2020), and low-carbon technology elitism (Sovacool, Kester et al., 2019). Such problematics relate to the concept of a just transition[4] and how countries can succeed in reducing emissions without necessarily exacerbating inequalities.

Accordingly, a growing body of research has also recognized the social and ethical dimensions of energy transitions. One way to structure this inquiry is through the lens of energy justice[5] (McCauley et al., 2013), which highlights how energy and low-carbon technology decisions affect different societal groups and geographies in unequal ways. Here, the focus is directed to electric vehicles (EVs), which represent a particularly relevant case study for several reasons. First, they are widely regarded as a key technology for reducing greenhouse gas (GHG) emissions in the transport sector, more specifically in road transportation (Raugei & Winfield, 2019). Second, their adoption has been heavily incentivized through subsidies and policy support (IEA, 2024b). Third, EVs lie at the intersection of two of the most influential global industries: automotive manufacturing and fossil fuels[6]. Fourth, several concerns have been raised regarding the life-cycle impacts of EV production and use, including resource extraction for batteries, supply chain inequities, and disparities in access to EV technology and infrastructure (Sovacool, Hook et al., 2019). These concerns extend across different spatial and temporal scales, reinforcing the need for

[4] As discussed in Wang and Lo's (2021) comprehensive review, the just transition concept, although lacking a universal definition, revolves around five main themes: (i) as a labor-oriented concept rooted on the origins of the labor movements in the US in the 1970s; (ii) as an integrated framework for justice connecting environmental justice, energy justice, etc.; (iii) as a theory of socio-technical transition examining structural systemic changes that can integrate justice principles into socio-technical transition studies; (iv) as a governance strategy aimed at addressing the challenges associated with systemic transformations; and (v) as public perception surrounding low-carbon energy transitions. Although the present study also aims at integrating justice principles (iii) into quantitative modeling studies, it is not based on the broader socio-technical transition literature addressed by, e.g., the Multi-Level Perspective (MLP) (Geels, 2002, 2010), as suggested by Wang and Lo (2021). Therefore, when the concept of a just transition is used hereafter, it represents an integrated conceptual framework for justice (ii) and the integration of justice considerations into transition studies.

[5] This thesis does not seek to engage in the long-standing debate over how justice should be defined (Miller, 2025). Instead, it employs the normative framework of energy justice as a guiding conceptual tool to identify asymmetries in the distribution of social, economic, and environmental impacts of low-carbon technology adoption.

[6] According to IBISWorld, the Global Car & Automobile Sales had a revenue of $4,357,5B while the Global Oil & Gas Exploration & Production had a revenue of $4,233,8B in 2024. Available at: https://www.ibisworld.com/global/industry-trends/biggest-industries-by-revenue/ Accessed on 20th September, 2024.

a whole-systems perspective[7] assessing the sustainability and justice implications of energy transition decisions (Jenkins et al., 2014).

Although energy justice has gained traction as a normative lens to assess these energy transition asymmetries (Van Uffelen et al., 2024), there remains a significant gap in how to integrate it into quantitative modeling approaches for low-carbon technology adoption (Sovacool & Dworkin, 2015). Existing energy and transport models often prioritize technical feasibility, cost optimization, and emissions reductions (see for instance (Fattahi et al., 2020)) but lack an integrated perspective on justice-related concerns (Sundaram et al., 2024).

At the same time, the inherent complexity of energy transitions, characterized by interdependence, feedback loops[8], delays, nonlinear dynamics and unintended consequences, requires modeling approaches that go beyond linear projections and static assessments (Bale et al., 2015). Complex systems approaches are particularly valuable in this context because they provide tools to analyze system interactions, which are essential for understanding the long-term consequences of energy policies and technological shifts. However, few studies have attempted to bridge the gap between energy justice and complex systems thinking (see for instance the unpublished work of Jenkins et al. (2014) in the assessment of asymmetries in low-carbon technologies adoption, specifically, EVs. To date, one of the few attempts to integrate energy justice concepts into a complex-system-based model is the work of Gladkykh et al. (2021), which employed energy justice to create narratives guiding system dynamics modeling in the assessment of energy sufficiency and access in Sub-Saharan Africa.

Additionally, Sundaram et al. (2024) recently presented a conceptual framework for operationalizing energy justice in models used for planning regional energy transitions. The authors concluded with examples of how normative interpretations of justice could be translated into requirements throughout the model development process and the model itself. Nonetheless, Sundaram et al. (2024) did not focus

[7] A whole-systems perspective implies a comprehensive assessment of energy and low-carbon technology decisions, pertaining production, consumption, and end-of-life stages (temporal scales) and different geographical scales (Sovacool, Hook, et al., 2019). Nonetheless, it is assumed here that a whole-systems perspective extends beyond a lifecycle analysis of technologies toward a nonlinear, systemic view of energy and technological decisions able to capture their intended and unintended consequences. This relates to systems theory and an interactionist understanding of reality, in which sub-systems interact within a larger system and can be coordinated in the direction of predefined goals (Bevir, 2009; Jenkins et al., 2014).

[8] Feedback loops refer to closed causal chains of events, which are characteristic of our daily lives but also a basic component of systems thinking and system dynamics modeling tools. For a detailed explanation please refer to Section 2.4 or the seminal Sterman's book "Business Dynamics: Systems Thinking and Modeling for a Complex World" (Sterman, 2000).

on any modeling tool nor provided justice-related quantitative proxies to be integrated into quantitative models (i.e., operationalization[9]), a gap which this thesis aims to address.

This thesis addresses this gap by integrating the normative framework of energy justice with system dynamics modeling to explore asymmetries developed in association with EV adoption and whether policy interventions can mitigate these asymmetries. Specifically, this research examines (i) the lifecycle socio-environmental impacts of EV technology, (ii) the ways in which energy justice has been conceptualized and operationalized in EV research, (iii) the suitability of system dynamics modeling to capture social dynamics in energy transitions, (iv) and the applicability of system dynamics to model asymmetries related to EV adoption, taking the case of Portugal.

By applying system dynamics modeling to the specific case of EV-related asymmetries in Portugal, this thesis offers empirical insights into how a national-level energy transition could unfold in a manner that aligns with justice principles. The focus on Portugal, a country-member of the European Union (EU), financed by the Just Transition Fund (European Commission, 2022b), and characterized by one of the oldest vehicle fleets and a high volume of imports in Europe (IMT & INE, 2022), allows for context-specific policy recommendations that are relevant to other countries facing similar challenges in balancing sustainability goals with justice concerns.

Consequently, this thesis makes several key contributions to the interdisciplinary fields of socio-technical energy transitions[10], energy justice, and complex systems through system dynamics modeling, with a particular focus on EV technology and its systemic impacts. Among contributions, it can be highlighted: (i) the integration of the conceptual framework of energy justice with EV lifecycle activities through six normative tenets and a whole-systems approach; (ii) the operationalization of justice-related issues of EV adoption; and (iii) the integration of social and justice considerations into systems-based energy modeling approaches, which can be re-applied in different contexts and for other low-carbon technologies.

[9] By operationalization, it is meant the process by which quantitative proxies are linked to justice-related dimensions to support the assessment of asymmetries in policies and low-carbon technologies' adoption. However, it is important to note that the operationalization of such issues should not replace rich qualitative, narrative-based analysis, but rather complement them.

[10] Conceptualizing the energy transition as a socio-technical system means adopting "the 'wider system' view to encompass not only the natural and built components, such as energy resources or infrastructures, but the societal and institutional elements as well" (Li et al., 2015).

1.2 Research questions and objectives

The overarching research questions of this thesis are as follows:

> **RQ1.** "What social, economic, and environmental are associated with EV adoption from a whole-systems energy justice perspective?"
>
> **RQ2.** "How can energy justice considerations be operationalized through indicators and embedded in system dynamics models to support policy recommendations for the EV transition?"

Therefore, the general objective of this thesis is to explore systemic socio-environmental asymmetries associated with EV adoption through an energy justice and whole-systems lens, integrating energy justice considerations into system dynamics modeling as a means to identify pathways for a just energy transition (JET).

This general objective is broken down into the following specific objectives:

01. To identify social, economic, and environmental asymmetries associated with EV technology and their asymmetric distribution from a whole-systems energy justice perspective.

02. To develop quantitative indicators that can operationalize energy justice in EV research.

03. To explore the use and assess the capacity of system dynamics modeling to incorporate social dynamics related to energy transitions.

04. To quantitatively explore the asymmetries in the whole-systems impacts of EVs in Portugal and provide policy-related insights on how to address them.

1.3 Research design

This research is guided by a pragmatic philosophy, which views research as a tool for solving problems, focusing on the use of methods that best address the research questions, regardless of they being qualitative, quantitative, or a combination of both (Robson, 2002). By adopting a pragmatic approach, this research does not adhere to any single methodological dogma but instead selects methods based on their capacity to yield valuable insights into the complex issue of justice in energy transitions. Pragmatism supports the integration of both deductive and inductive reasoning, depending on the needs of the research. In identifying and operationalizing key justice issues related to EV transitions, this research is

largely deductive (Robson, 2002), drawing on the extensive body of literature surrounding the normative framework of energy justice. The energy justice tenets outlined in the literature are used to structure the analysis in two system dynamics models and their related case studies. Although this operationalization (i.e., deductive approach) is aligned with the positivist philosophy (Saunders et al., 2009), it is pertinent to mention that social impacts may not be discussed without considering social constructions of welfare, for instance, which require an interpretivist perspective.

Throughout the several articles that compose this thesis, the research strategy follows a multi- and mixed-methods approach (Creswell, 2014), combining literature reviews, simulation-based system dynamics, and case study methods. The choice of different methods ensures that both the objective outcomes of quantitative modeling and the subjective justice implications are thoroughly explored.

Additionally, this thesis is both exploratory and explanatory in nature. The former aspect stems from the literature reviews included in the research design, which aim at providing an overview of and insights on the current state of art (Saunders et al., 2009). The latter refers to the process of identifying and explaining the causal relations between variables (Saunders et al., 2009), which is characteristic of system dynamics modeling as a "*white-box*" approach (Barlas, 1996). An explanatory approach also aligns with the realization of interviews with specialists to qualitatively identify causal links to be incorporated into models' structure, as discussed in **Chapter 6**.

A longitudinal time horizon is adopted, particularly in the system dynamics modeling, which simulates the long-term effects of policy decisions. As a quantitative method, system dynamics modeling allows for the simulation of complex systems, while qualitative methods such as interviews, literature reviews, and document analysis provide deeper insights into the normative questions of fairness and justice. More information on system dynamics modeling, including causal loop diagrams (CLDs), stock-and-flow diagrams (SFDs), and computational simulation techniques are presented in the Appendix (**Appendix I**).

Figure 1-1 illustrates the research design based on Saunders' research onion (Saunders et al., 2009). Specific data collection and data analysis methods are presented in each respective chapter.

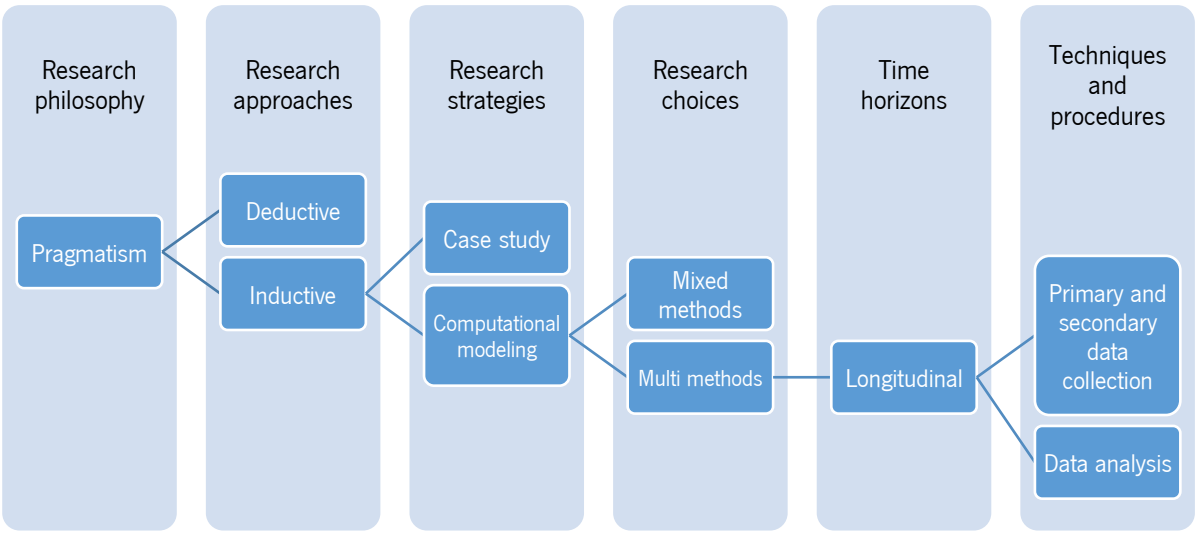


Figure 1-1. Overall research design.

The ethical integrity of this thesis has been carefully evaluated and approved by the "*Comissão de Ética para a Investigação em Ciências Sociais e Humanas*" (CEICSH) of the University of Minho. CEICSH reviewed all submitted documents and determined that the research meets the required ethical standards. As per document number CEICSH 070/2023, the committee has granted its favorable opinion for the project to proceed as outlined in the submitted "Project Identification and Characterization Form" **(Appendix II)**. It has been ensured that this research complies with both national and international standards for conducting research in the social sciences and humanities, including General Data Protection Regulation (GDPR) guidelines. This includes adherence to best practices for the ethical treatment of human participants, particularly regarding informed consent, confidentiality, and data protection.

1.4 Thesis structure

This PhD thesis is structured as a collection of research papers. Except for **Chapter 5**, which contains an overview of the case study of the EV transition in Portugal, and **Chapter 8**, which concludes with main findings, limitations, and a future research agenda, this thesis comprises five core chapters, **Chapters 2, 3, 4, 6 and 7,** reproducing scientific publications made throughout the course of this PhD. **Chapters 2, 3, and 4** build the conceptual and methodological basis for the system dynamics models developed in **Chapters 6 and 7**.

As mentioned in **Section 1.3**, this thesis employed multi- and mixed-method approaches. Accordingly, **Table 1-1** outlines the theme, main research methods, and contribution to the research objectives of each Chapter.

Table 1-1. Chapters' theme, methods, and research objectives.

Chapter	Title	Methods	Research objectives
2	Energy justice and the EV lifecycle: A conceptual framework	Exploratory literature review	O1
3	Operationalizing energy justice: A systematic literature review	Systematic literature review	O2
4	Integrating social aspects into system dynamics models	Systematic literature review	O3
5	Case study context: Energy justice issues in Portugal's EV transition	Case study, documentary analysis	O4
6	Modeling lithium mining project dynamics in Portugal	Case study, System dynamics modeling	O3, O4
7	Modeling disparities in EV adoption in Portugal	Case study, System dynamics modeling	O3, O4

The paragraphs that follow provide a summary of each chapter and their respective scientific contributions.

Chapter 2 introduces the theoretical framework of this study in the form of an exploratory review, which is the first in the peer-reviewed literature to link energy justice tenets to the lifecycle activities of EVs. This chapter conceptually links the six tenets of energy justice (i.e., distributive, procedural, recognition-based, cosmopolitan, restorative, and flexibility justice) to EV lifecycle activities. By doing so, it lays the foundation for a justice-oriented analysis of the EV lifecycle, mapping out key asymmetries across different spatial-temporal scales, from material extraction to end-of-life disposal. This work provides an original contribution, which was presented in the following conference and journal papers:

1. Dall-Orsoletta, A. and Ferreira, P. (2021), "**Energy justice conceptual framework for technology assessment**", 16th Conference on Sustainable Development of Energy, Water, and Environment Systems (SDEWES). Dubrovnik, Croatia.

2. Dall-Orsoletta, A., Ferreira, P. and Dranka, G.G. (2022), "**Low-carbon technologies and just energy transition: Prospects for electric vehicles**", Energy Conversion and Management: X, Vol. 16 No. December 2021, p. 100271, doi: 10.1016/j.ecmx.2022.100271.

Chapter 3 builds on this foundation by conducting a systematic literature review to identify indicators used to operationalize energy justice in EV research, another novel contribution to the field. The review critically assesses existing conceptual framings and indicators employed in quantitative justice-related assessments. The chapter also identifies gaps in current approaches, proposing a set of potential indicators that can be used as proxies for justice outcomes within the context of EV research. This work is the first attempt to define justice indicators for operationalizing energy justice tenets in EV adoption. Accordingly, it has been submitted to an international journal of high impact factor.

3. Dall-Orsoletta, A., Dranka, G.G., and Ferreira, P. (Submitted), "**Charging up justice? A critical review for operationalizing energy justice in electric vehicle research**"

Chapter 4 shifts the focus to an evaluation of system dynamics modeling as a methodological tool to integrate the social dimensions of energy transitions. This chapter provides a comprehensive review of the literature to assess the extent to which system dynamics has been employed to capture social aspects of energy transitions, including justice-related dynamics. By addressing this gap, the chapter sets the stage for the subsequent empirical work, exploring the potential of system dynamics to incorporate justice concerns into the modeling of energy transitions. This assessment also highlights the strengths and limitations of system dynamics modeling in dealing with complex socio-technical systems like the EV transition. The findings of this Chapter were presented at one international conference and published as a journal paper:

4. Dall-Orsoletta, A., Ferreira, P. and Dranka, G.G. (2022), "**A systematic review of social dynamics in complex energy system models**", 5th International Conference on Energy and Environment (ICEE). Porto, Portugal.
5. Dall-Orsoletta, A., Uriona-Maldonado, M., Dranka, G. and Ferreira, P. (2022), "**A review of social aspects integration in system dynamics energy systems models**", International

Journal of Sustainable Energy Planning and Management, Vol. 36, pp. 33–52, doi: 10.54337/ijsepm.7478.

Chapter 5 bridges previous theoretical and methodological chapters (**Chapters 2, 3, and 4**) to the modeling chapters (**Chapters 6 and 7**). It presents the context of Portugal and its transition to a low-carbon transport sector, reflects on the whole-systems energy justice issues that arise from the EV transition, and discusses the application of system dynamics modeling in justice-related assessments. This chapter contains excerpts from two conference papers, the first on the automotive industry in Portugal and the second on the use of system dynamics for justice-related assessments of the energy transition.

6. Dall-Orsoletta, A., Oosthuizen, R., Pillay, N., Dranka, G. and Ferreira, P. (2024), "**Evaluating the impact of electric vehicles on employment: The Portuguese case**", 6th International Conference on Production Economics and Project Evaluation (ICOPEV). Guimarães, Portugal.
7. Dall-Orsoletta, A., Manfroni, M., Dranka, G, and Ferreira, P. (2025) "**A justice perspective over low-carbon transitions: A system dynamics-based framework**", 20th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES). Dubrovnik, Croatia.

Chapter 6 applies system dynamics modeling to one of the most controversial lifecycle activities linked to EVs in Portugal: lithium mining. Lithium mining was identified in **Chapter 2** as a critical EV lifecycle activity with profound justice implications, especially concerning distributive, procedural, recognition-based, and restorative justice. This energy justice relationship was further validated for the case study through empirical work conducted by Canelas and Carvalho (2023), which highlighted several distributive, procedural, and recognition-based injustices in the Barroso project, one of the largest lithium mining projects in Europe (Savannah Resources, 2023). Accordingly, this Chapter models the dynamics of the Barroso lithium project in Northern Portugal, highlighting the effect of local communities' resistance on project development. Empirical validation of the causal relationships included in the model is provided through semi-structured interviews and secondary data. **Chapter 6** has been presented at a conference and published as a journal article, as follows.

8. Dall-Orsoletta, A., Uriona-Maldonado, M., Dranka, G. and Ferreira, P. (2023), "**Community engagement practices: Social dynamics in lithium mining in Portugal**", 41st International System Dynamics Conference (ISDC). Chicago, USA.
9. Dall-Orsoletta, A., Verrier, B., Uriona-Maldonado, M., Dranka, G. and Ferreira, P. (2025) "**How does social acceptance affect transition minerals production in Europe? A system dynamics approach and case study in Portugal**", Extractive Industries and Society, Vol. 22, 101625, doi: 10.1016/j.exis.2025.101625

Chapter 7 applies system dynamics modeling to distributive justice issues related to EV adoption in Portugal, particularly the disparities between urban and rural populations in terms of EV ownership and access to charging infrastructure. The Chapter establishes proxies to examine how these inequalities evolve over time, emphasizing the role of system dynamics modeling in testing policy interventions. By integrating justice indicators into a systems dynamics model, it offers a novel methodological contribution. The work of this Chapter comprises two conference papers and one published journal paper.

10. Dall-Orsoletta, A., Oosthuizen, R., Dranka, G. and Ferreira, P. (2024), "**A systems approach to energy justice: The case of electric vehicle adoption**", 6th International Conference on Energy and Environment (ICEE). Guimarães, Portugal.
11. Dall-Orsoletta, A., Oosthuizen, R., Dranka, G. and Ferreira, P. (2024), "**Toward Fairer Transportation: Modeling Energy Justice in Electric Vehicle Operation**", 42nd International System Dynamics Conference (ISDC). Bergen, Norway.
12. Dall-Orsoletta, A., Oosthuizen, R., Dranka, G. and Ferreira, P. (2025), "**A quantitative modelling approach to energy justice in electric vehicle adoption**", Energy, Vol 322, 135676, doi: 10.1016/j.energy.2025.135676

Chapter 8 concludes the thesis by synthesizing the key findings, discussing methodological and conceptual limitations, and outlining directions for future research. Similar to **Chapter 5**, parts of **Chapter 8**, particularly the discussion of limitations, draw upon insights from Publication No. 6. This integration was intended to improve the coherence of the thesis and strengthen the connections between its empirical and theoretical components, thereby enhancing overall readability and thematic continuity.

Table 1-2 presents a summary of publications per chapter.

Table 1-2. Summary of publications per chapter.

Chapter	Publications
2	1. Dall-Orsoletta, A. and Ferreira, P. (2021), "**Energy justice conceptual framework for technology assessment**", 16th Conference on Sustainable Development of Energy, Water, and Environment Systems (SDEWES). Dubrovnik, Croatia. 2. Dall-Orsoletta, A., Ferreira, P. and Dranka, G.G. (2022), "**Low-carbon technologies and just energy transition: Prospects for electric vehicles**", Energy Conversion and Management: X, Vol. 16 No. December 2021, p. 100271, doi: 10.1016/j.ecmx.2022.100271.
3	3. Dall-Orsoletta, A., Dranka, G.G., and Ferreira, P. (Submitted), "**Charging up justice? A critical review for operationalizing energy justice in electric vehicle research**"
4	4. Dall-Orsoletta, A., Ferreira, P. and Dranka, G.G. (2022), "**A systematic review of social dynamics in complex energy system models**", 5th International Conference on Energy and Environment (ICEE). Porto, Portugal. 5. Dall-Orsoletta, A., Uriona-Maldonado, M., Dranka, G. and Ferreira, P. (2022), "**A review of social aspects integration in system dynamics energy systems models**", International Journal of Sustainable Energy Planning and Management, Vol. 36, pp. 33–52, doi: 10.54337/ijsepm.7478.
5	6. Dall-Orsoletta, A., Oosthuizen, R., Pillay, N., Dranka, G. and Ferreira, P. (2024), "**Evaluating the impact of electric vehicles on employment: The Portuguese case**", 6th International Conference on Production Economics and Project Evaluation (ICOPEV). Guimarães, Portugal. 7. Dall-Orsoletta, A., Manfroni, M., Dranka, G, and Ferreira, P. (2025) "**A justice perspective over low-carbon transitions: A system dynamics-based framework**", 20th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES). Dubrovnik, Croatia.
6	8. Dall-Orsoletta, A., Uriona-Maldonado, M., Dranka, G. and Ferreira, P. (2023), "**Community engagement practices: Social dynamics in lithium mining in Portugal**", 41st International System Dynamics Conference (ISDC). Chicago, USA. 9. Dall-Orsoletta, A., Verrier, B., Uriona-Maldonado, M., Dranka, G. and Ferreira, P. (2025) "**How does social acceptance affect transition minerals production in Europe? A system**

	dynamics approach and case study in Portugal", Extractive Industries and Society, Vol. 22, 101625, doi: 10.1016/j.exis.2025.101625
7	10. Dall-Orsoletta, A., Oosthuizen, R., Dranka, G. and Ferreira, P. (2024), "**A systems approach to energy justice: The case of electric vehicle adoption**", 6th International Conference on Energy and Environment (ICEE). Guimarães, Portugal. 11. Dall-Orsoletta, A., Oosthuizen, R., Dranka, G. and Ferreira, P. (2024), "**Toward Fairer Transportation: Modeling Energy Justice in Electric Vehicle Operation**", 42nd International System Dynamics Conference (ISDC). Bergen, Norway. 12. Dall-Orsoletta, A., Oosthuizen, R., Dranka, G. and Ferreira, P. (2025), "**A quantitative modelling approach to energy justice in electric vehicle adoption**", Energy, Vol 322, 135676, doi: 10.1016/j.energy.2025.135676

2 Energy justice and the EV lifecycle: A conceptual framework

This chapter is based on the article titled "*Low-Carbon Technologies and Just Energy Transition: Prospects for Electric Vehicles*" which has been published in the international journal "*Energy Conversion and Management: X*". The content presented here reflects the key findings and discussions of the original article, with some adaptations to fit the overall structure of this thesis.

Low-Carbon Technologies and Just Energy Transition: Prospects for Electric Vehicles

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Energy Conversion and Management: X, Vol. 16:100271 (2022)
https://doi.org/10.1016/j.ecmx.2022.100271

Abstract: The impacts of low-carbon technologies are spread across countries and lifecycle stages in ways that can compromise the achievement of an inclusive and equitable energy transition. Based on an exploratory review, this paper identifies the main activities of the EVs life cycle, where they occur, and potentially associated injustices. Through a whole-systems approach, energy justice tenets are extended to EV technology, highlighting how it might fail to fully support a low-carbon and just energy transition. Results provide insights into how EVs can contribute to flexibility justice through smart grids and vehicle-to-grid developments, cosmopolitan justice as a consequence of GHG emissions and global resource depletion, and restorative justice through laws and standards that demand environmental restoration and social compensation over affected communities. However, reviewed documents indicate that efforts must be directed toward reducing distributional, procedural, and recognition injustices across the North-South divide, especially those related to mining activities in the resource extraction and processing stage. EVs upfront costs and charging infrastructure issues may also exclude poor and rural communities during its operational stage. Recommendations for future research include technical aspects, such as battery composition and recycling, and social aspects of EV-technology, such as the quantification of social impacts of low-carbon technologies.

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2.1 Introduction

Energy transitions are socio-technical processes that encompass more than technological innovations. While energy transitions profoundly impact society, the economy, and the environment, their pace and reach also depend on social dynamics, such as social acceptance of technologies. Nevertheless, techno-centric perspectives have dominated transitions' discourses (Labanca et al., 2020), and social aspects have been commonly overlooked or instrumentalized with socioeconomic gaps widening globally. From this background, efforts to include justice and equity as the focus of energy research have emerged. By assessing social impacts on individuals and communities, policymakers can implement measures that contribute to a JET. At first, the concept of a "just transition" originated in the 1970s within trade union movements in the US (Stevis & Felli, 2015), but since then it has been used in debates around "*green new deals*", "*circular economy*" (Healy & Barry, 2017), and countries' Nationally Determined Contributions (NDCs), e.g., Chile (Gobierno de Chile, 2020). Focused on energy systems and their social implications, the concept has evolved to the term JET, which has been applied to energy transitions research. The broad goal of the JET is to find ways of reconciling environmental sustainability with social and economic development globally, with a particular focus on countries that have a history of exploitation, low socioeconomic indicators, and struggle over energy access, security, and affordability (García-García et al., 2020).

Likewise, a just energy system would be "*a global energy system that fairly disseminates both the benefits and costs of energy services and one that has representative and impartial energy decision-making*" (Sovacool & Dworkin, 2014, p. 13). However, the benefits and burdens of an energy system go beyond its operational stage, i.e., energy supply and demand, and spillovers to other life cycle stages. Particularly, the United Nations (UN) Climate Change Conference (COP26) held in Glasgow in 2021 highlighted the criticality of resource extraction and usage for sustainable development, as "*minerals demand for renewable energy technologies is projected to skyrocket, particularly for battery metals being used in electric vehicles - and the associated environmental and human impacts are likely to rise steeply as well*" ("Declaration on Mining and the Energy Transition for COP26," 2021). Special mention was made to EVs in this statement because of their expected contribution to decarbonizing the transport sector (Fragkos et al., 2021) and resource requirements for EVs battery manufacturing (Dolganova et al., 2020). According to the International Energy Agency (IEA), the number of EVs should increase from 11 million in 2020 to 350 million in 2030, reaching almost 2 billion vehicles in 2050, in addition to a four-fold increase in the number of electric two- and three-wheelers and 50 million electric buses (IEA, 2021). Nevertheless, it is

not only the largeness of the electrified fleet that dictates the demand for raw materials but also batteries' size and capacity. Light-duty EV batteries can have a specific energy or energy density from around 30 to 275 Wh/kg with capacities varying from approximately 10 to 200 kWh (Sanguesa et al., 2021). Comparatively, the battery capacity requirements for a cellphone (e.g., Apple iPhone 6, 6.9 Wh) can be ten thousand times smaller than for an EV (e.g., Tesla Model S 85D vehicle, 85 kWh) (Hao, Liu et al., 2017). Accordingly, the average mass of batteries used in popular EV models in the US is around 350 kg (Gottesfeld, 2019).

Conversely to internal combustion engine vehicles (ICEVs), EVs are powered by battery-stored electricity. They are among the most promising technologies to decarbonize road transportation, along with sustainable fuels (e.g., advanced biofuels and electro fuels produced from electricity and CO_2 (Hannula & Reiner, 2019)) and advanced powertrain vehicles (e.g., hybrid and fuel cells (Del Pero et al., 2020)). As batteries are fundamentally composed of two electrodes in an electrolyte (Miao et al., 2019), several different materials qualify as candidates for battery manufacturing. Among the battery technologies available for electric mobility, we can mention lead-acid, nickel-cadmium, and lithium-ion batteries (Li-ion batteries), each with a variety of electrode chemistry options (Miao et al., 2019). Nevertheless, Li-ion batteries remain one of the most efficient and reliable battery systems for EVs (Miao et al., 2019). Still, increasing the autonomy of EVs through enhancing battery capacities or reducing cars' energy consumption (e.g., lightweight design (Del Pero et al., 2020) and energy requirements of auxiliary systems (Berzi et al., 2020)) will continue to be an important research stream if the fore sought EVs uptake is to be fulfilled.

However, this upsurge in transport electrification may disrupt the EVs supply chain and worsen social and environmental issues where related activities take place. To compound the problem, EVs supply chain relates to mining activities in a politically unstable country, the Democratic Republic of Congo (DRC) (Sovacool, 2019), where cobalt is extracted for Li-ion batteries production, and environmentally sensitive areas such as the Salar de Atacama in Chile (Tabelin et al., 2021). Drawing from extensive fieldwork, Sovacool, Hook et al. (2020) focused on cobalt mining in the DRC and electronic waste in Ghana and perceived that "*decarbonization enhances existing vulnerabilities in the Global South, contributing to environmental degradation, ethnic and gender discrimination, and child labor*" (Findlay, 2020). It also highlighted that much of previously published research has focused on future innovations, such as EVs, "*but overlooks or obscures downstream and upstream processes, such as mining or waste flows*" (Sovacool, Hook et al., 2020). Therefore, considering the entire lifecycle of technologies is essential "*from*

the front end where metals and minerals are extracted, to the back end where waste streams reside" (Sovacool, Hook et al., 2020).

This systemic analysis is aligned with the so-called whole systems approach, in which downstream and upstream processes are considered when evaluating a particular project or technology chain (Sovacool, Hess, & Cantoni, 2021). In order to provide a theoretical basis for discussions on justice, a multi-scalar or whole-systems energy justice approach was employed herein to evaluate EVs contribution to a JET. Energy justice has been addressed from a conceptual perspective (see for example, the principled approach (Sovacool, Heffron, et al., 2016), whole-systems approach (Jenkins et al., 2014), and tenet-based approach (Jenkins et al., 2016)) with some attempts to better understand how technologies can contribute to energy justice (e.g., hydropower in Laos (Llamosas & Sovacool, 2021), solar and wind projects in Chile, India, Kenya, and Mexico (Calzadilla & Mauger, 2018), utility-scale wind power in Mexico (Mejía-Montero et al., 2021), the afterlife of off-grid solar products in Sub-Saharan Africa (Cross & Murray, 2018), energy service contracts, EVs, solar panels, and low-carbon heating (Sovacool, Lipson, & Chard, 2019)). For the association of energy justice and technologies, Lacey-Barnacle et al. (2020) provided a systematic review of theoretical frameworks and energy *foci* of academic works on energy justice in the developing world, concluding that the largest bulk of papers addresses renewables and only 4% of secondary papers included in the review focus on EVs. Sovacool, Matiskainen et al. (2019) evaluated the energy injustices (distributional, procedural, recognition-based, and cosmopolitan) of four low-carbon transitions – nuclear power in France, EVs in Norway, solar energy in Germany, and smart meters in Great Brain – without employing a whole systems perspective. Along the same lines, Sovacool, Hook et al. (2019) evaluated the same four cases using a whole systems perspective to give a spatial scale (micro, meso, and macro) for the injustices' extent. However, to the best of the authors' knowledge, the linkage between EV technology and JET considering a whole systems approach in association with the distributional, procedural, recognition-based, cosmopolitan, restorative, and flexibility energy justice tenets are yet not explored. By employing a whole systems thinking, our study attempts to highlight the distribution of injustices across the globe that follow the EVs life cycle, from the extraction of resources for Li-ion batteries manufacturing to the end of life of EVs. We focus on battery-powered light-duty road vehicles thanks to the significance of this low-carbon technology to decarbonize the transport sector and the larger sales volume of battery EVs in comparison to plug-in hybrid EVs (IEA, 2021).

Specifically, this work has the following objectives: (i) identify what are the main activities of EVs' life cycle, where they take place, and what are potential injustices associated with these activities; (ii) conceptually

link potential injustices to energy justice tenets; (iii) identify how EV uptake challenges the achievement of a JET, and (iv) highlight research gaps to be further addressed. The remainder of this paper is structured as follows. **Section 2.2** provides a theoretical background on energy justice, while **Section 2.3** identifies this work's scope concerning the lifecycle activities of EVs. **Section 2.4** describes the research methods and highlights potential EV-related injustices found in the exploratory review. The linkages between EVs lifecycle stages and energy justice tenets, and the technology contribution or opposition to a JET are discussed in **Section 2.5**. Lastly, **Section 2.6** summarizes the main findings, limitations, and recommendations for future research.

2.2 Theoretical background: Energy justice

Even though the concept of energy justice was firstly used in academia as a defined concept only in 2013 (Heffron & McCauley, 2017), it shares the same philosophical foundation as environmental and climate justice movements that began decades earlier (Jenkins et al., 2014). Energy justice "*aims to provide all individuals across all areas with safe, affordable and sustainable energy*", (McCauley et al., 2013). There are three main approaches in the literature regarding energy justice: (1) the principled approach (Sovacool et al., 2016), (2) the whole systems approach (Jenkins et al., 2014), and (3) the tenet-based approach (Jenkins et al., 2016). In the principled approach, Sovacool et al. (2016) reframed energy decisions as justice and ethical concerns and developed a framework for decision-making based on eight core principles: availability, affordability, due process, transparency and accountability, sustainability, intra-generational equity, inter-generational equity, and responsibility. Nevertheless, the principled-approach is less used than the tenet-based (Jenkins et al., 2021) and most of its principles can be seen as aspects of the tenet-based approach (Hearn et al., 2021), which are described in the **Section 2.2.1**.

2.2.1 Energy justice tenets

The tenet-based approach has three central tenets: distributional, procedural, and recognition justices (Jenkins et al., 2016). A recent review proposed by Jenkins et al. (2021) comprehensively reviewed the energy justice literature topic and identified that these three tenets are the most commonly used within energy justice frameworks. **Distributional justice** calls for an even distribution of environmental ills and benefits and associated responsibilities regardless of income, wealth, gender, and color (McCauley et al., 2013). It also relates to the physical distribution of burdens and advantages, which has been used as an

argument in local activities against the development of wind (Mejía-Montero et al., 2021) and hydropower (Crootof et al., 2021) projects, for example. **Procedural justice** refers to including all stakeholders, particularly misrecognized parties, in the decision-making process in a non-discriminatory way (Walker, 2009). Markedly, Jenkins et al. (2016) explicitly took into account three mechanisms for achieving procedural justice: local knowledge mobilization, greater information disclosure, and better institutional representation. **Recognition justice** is about people being rightfully represented and having equal political rights (Jenkins et al., 2016). It is concerned with political and institutional oppression, disrespect of local culture, and misrecognition of communities' interests and visions for the future (Heffron et al., 2015).

In addition to these three main components, two other tenets must also be highlighted cosmopolitan and restorative justices (Heffron & McCauley, 2017). **Cosmopolitan justice** suggests that "*the ultimate unit of concerns are human beings and persons, not communities or nation-states*" (Sovacool, Kester, et al., 2019). Therefore, it argues that moral and justice concerns apply to everyone equally as people are all members of a global community (Sovacool, Kester, et al., 2019). In contrast, **Restorative justice** calls for the energy sector to take responsibility (moral and financial) for negative impacts on the environment and surrounding communities and work towards restoring the landscape (Heffron & McCauley, 2017). Finally, in a recent work evaluating justice in solar development, Heffron et al. (2021) pointed to a new tenet: **Flexibility justice**, which is concerned with ensuring a market open to existing and new players and a flexible energy system. Flexibility justice is based on the idea of a flexible energy transition, in which all sectors have potential contributions if appropriately coupled, e.g., vehicle-to-grid (V2G) technologies and smart mobility in the transport sector (Heffron et al., 2020).

2.2.2 Whole systems

The whole systems approach supports a cradle-to-grave perspective for identifying the real impacts of energy projects through interactions among system components (Jenkins et al., 2014). Without this systemic view, the impacts of extracting rare metals for manufacturing energy technologies, or biofuel production on biodiversity and land use, for example, cannot be wholly understood and, therefore, mitigated (Jenkins et al., 2017). In energy systems modelling, a whole-systems appraisal would also consider the fuel supply chain (Barton et al., 2018). Among the works that have employed a whole systems approach to energy justice, the work of Sovacool, Hook et al. (2019) was already mentioned, which evaluated four European low-carbon transitions and identified several injustices classified according

to their spatial scales. Also, Sovacool, Hess & Cantoni (2021) developed a cradle-to-grave framework to evaluate energy transitions, and Mejía-Montero et al. (2021) evaluated a utility-scale wind power in Mexico, providing "*clear evidence against the notion that RETs (renewable energy technologies) [...] are inherently good or sustainable*" (Mejía-Montero et al., 2021). **Figure 2-1** presents the combination of the tenet-based and the whole systems approaches to energy justice that will be explored in this study for the case of EVs.

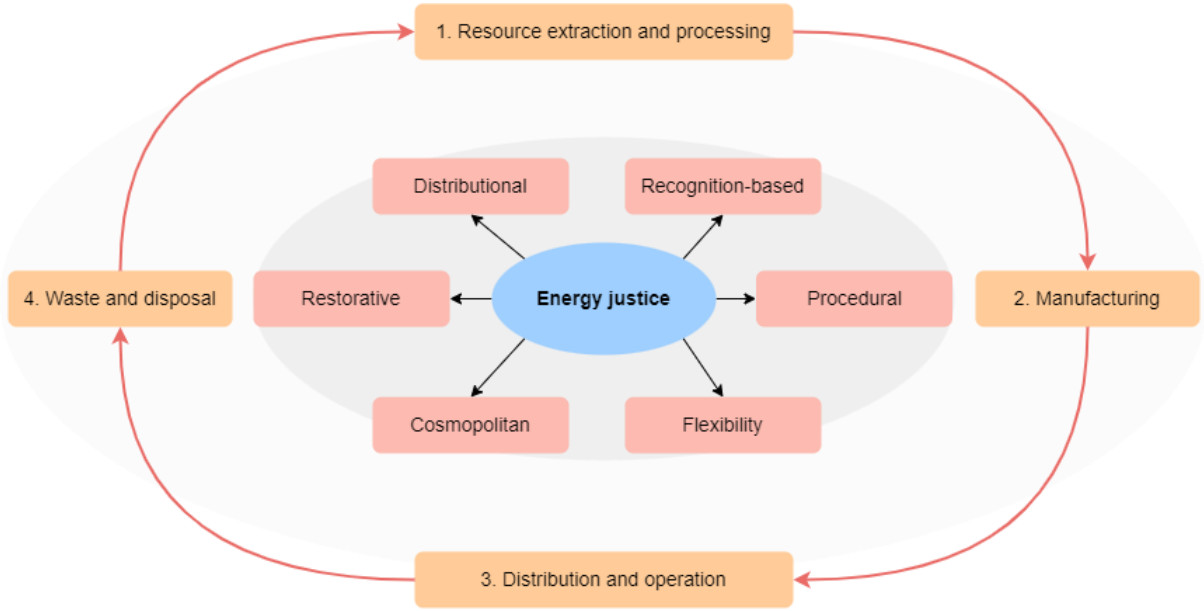


Figure 2-1. The tenet-based and the whole systems approaches to energy justice.

2.3 Scope definition: The lifecycle stages of EVs

In this section, we review battery-powered EVs' life cycle according to four lifecycle stages: (1) resource extraction and processing, (2) manufacturing, (3) distribution and operation, and (4) waste and disposal. Even though transportation of car components takes place between lifecycle stages, we are not able to consider it fully herein thanks to the complexities of evaluating freighting of all EV components. Alternatively, we consider the distribution of finished vehicles in the distribution and operation phase, battery shipping in the manufacturing phase, and reverse logistics in the end-of-life stage.

2.3.1 Stage 1: Resource extraction and processing

The first lifecycle stage includes mining and refining activities. For EVs, first-stage impacts are mostly linked to the extraction and processing of raw materials for energy storage as batteries are a key component and high contributor to EVs' cost and environmental impacts (Kotak et al., 2021). As the Global EV Outlook asserts, "*depending on its size and assuming a typical range of emissions from battery manufacturing and the global average carbon intensity of electricity in the use phase, [EV battery] accounts for 10-30% of the total life-cycle emissions"* of battery-powered EVs (IEA, 2020b). Even though there are different types of batteries that employ different negative and positive electrode materials (see (Miao et al., 2019)), we consider Li-ion batteries for their reliability and technical efficiency and the fact that lithium-cobalt-manganese oxide cathode formulations have prevailed in the battery industry (Kallitsis et al., 2020). Raw materials commonly needed for manufacturing Li-ion batteries are manganese, cobalt, lithium, copper, nickel, aluminum, titanium, and carbon (Lebedeva et al., 2017), whereas iron, rare-earth metals, and silicon are essential for electric motors (Wen et al., 2021). Cobalt and lithium, in particular, were labeled as critical raw materials by the European Commission (European Commission, 2020a) and the United States (US) Geological Survey (US Geological Survey, 2021) because of their economic importance and supply risk. Therefore, the extraction and processing of lithium and cobalt were considered the two main activities of the first stage of EVs' lifecycle because of these materials' critical supply (European Commission, 2020a) and potential environmental impacts of Li-ion batteries (e.g., global warming potential, resource depletion, ecological toxicity, and human health (EPA, 2013)).

Lithium can be mined from salt-lake brines, hard-rock pegmatitic lithium ores, or lithium-rich clays, but, even though its occurrence in nature is common, few countries have significant economic exploitation as is the case of Argentina, Australia, US, Chile, Bolivia, and China (Tabelin et al., 2021). In Europe, Portugal has received attention thanks to its lithium reserves with the development of extraction and processing activities for EVs manufacturing being considered in the country (DGEG & Grupo de Trabalho, 2017). According to the US Geological Survey , "*five mineral operations in Australia, two brine operations each in Argentina and Chile, and two brine and one mineral operation in China accounted for the majority of world lithium production*" (US Geological Survey, 2021). Each of these countries produced over 5 million tons of lithium in 2020 (US Geological Survey, 2021). After being mined, lithium must be further processed in chemical plants to remove impurities and produce lithium carbonate, which is then used for battery manufacturing. On the amount of raw material required, "*it takes 250 tons of the mineral ore spodumene when mined, or 750 tons of mineral-rich brine to produce one ton of lithium*" (Zhao et al.,

2021). According to the Australian Trade and Investment Commission (ATIC), "*China dominates lithium processing, accounting for an estimated 89 percent of the world's lithium hydroxide. Chinese refineries produce lithium carbonate, lithium hydroxide and lithium chloride — the precursors to lithium-ion battery cathode materials*" (ATIC, 2018). Accordingly, China has the largest lithium consumption globally (Hao, Liu, et al., 2017). For cobalt, commonly produced as a byproduct of copper or nickel mining, the DRC was responsible for almost 70% of the global cobalt mine production (US Geological Survey, 2021). Apart from the DRC, which mined 95 million tons of cobalt in 2020, only Australia and Russia mined over 5 million tons of cobalt in the same year. The refinement of cobalt is also concentrated in China, the largest consumer of cobalt, which is used in the rechargeable battery industry (US Geological Survey, 2021).

2.3.2 Stage 2: Manufacturing

Resource extraction and processing are followed by manufacturing components and assembly into the final product. For EVs' batteries, refined raw materials have to be combined into cathodes, anodes, electrolytes, and separators (IEA, 2020b). The vast majority of battery components manufacturers are located in China, Japan, and South Korea (Harrison & Ludwig, 2021). After components are manufactured, they have to be combined into battery cells, an activity that takes place mainly in China, the US, Europe, South Korea, and Japan (Harrison & Ludwig, 2021). Nevertheless, battery cell manufacturing has been taken near EVs manufacturing and assembly plants in Europe and the US mainly because of geopolitical tensions, risks and costs associated with shipping, and the security of supply (Harrison & Ludwig, 2021). Lithium can become highly inflammable when not packed and shipped appropriately, requiring temperature control, product enclosing, and stability during battery transportation. Therefore, if current trends continue, China will have 140 battery factories, Europe around 30, and the US, ten factories by 2030 (Sovacool, Hook, et al., 2019). Additionally, most EV assembly plants are found in China, the USA, Japan, Germany, France, and the United Kingdom (UK) (Harrison & Ludwig, 2021). As the demand for EVs grows, so does manufacturing capacity, and some of the largest automotive companies have built or planned gigafactories to meet future demand (see (CIC energiGUNE, 2021) for an interactive map of battery factory initiatives around the world).

2.3.3 Stage 3: Distribution and operation

For distribution and operation, we consider the activities related to sales and distribution and also re-charging and operation. Among the 40 countries with the largest total imports (US$) of battery EVs, plug-

in hybrid EVs, and full hybrid models, including Hong Kong as separate from mainland China, 31 are located in the Global North (Automotive from Ultima Media, 2021). The five largest importers are Belgium, Norway, China, Netherlands, and Germany (Automotive from Ultima Media, 2021). Similarly, considering total battery, plug-in hybrid, and full hybrid EV exports (US$), among the top 40 countries, 34 are in the Global North (Automotive from Ultima Media, 2021). The five largest exporters are Germany, the US, South Korea, Belgium, and Slovakia (Automotive from Ultima Media, 2021). Nevertheless, as our focus consists of battery-powered EVs, the next section evaluates injustices and trade values related to vehicles with electric propulsion only and Li-ion batteries. Once bought by end-users, EVs enter their operational lifetime (around ten years (IEA, 2020b)). The largest concentration of EVs is in China, Europe, and North America. In 2020, China had 3.5 million battery electric cars and 1.0 million plug-in hybrid EVs, Europe 1.8 and 1.4 million, the US 1.1 and 0.6 million, and the rest of the world around 0.4 and 0.3 million (IEA, 2020a).

2.3.4 Stage 4: Waste and disposal

The final stage comprises the waste and disposal of technologies, i.e., recycling, re-use, and waste. Recycling and reusing are part of a circular economy proposal, in which resource consumption and waste are reduced through the optimized utilization of by-products and the establishment of closed loops (Bonsu, 2020). EVs recycling concerns, first, the dismantling of different components. The vehicle (without battery) and its traction battery follow different recycling paths. While some materials are wasted in landfills, vehicles undergo a shredding and post-shredding process for metal scrap (Qiao et al., 2019). For batteries, some commercial recycling processes are available such as pyro-metallurgy, hydro-metallurgy, hybrid and bio-processes, each with its advantages and disadvantages (see (Meng et al., 2021)), aiming to recover metals and cathode materials. In this lifecycle stage, once again, Li-ion batteries have been considered the primary concern as batteries re-use and recycling can reduce waste flows and raw materials extraction (Harper et al., 2019). In other words, "*widespread battery recycling can create a more stable domestic source of materials for battery production, reduce the demand for raw materials, and minimize the risks of geopolitical disruptions of the supply chain*" (Ambrose & O'Dea, 2021). However, there are some challenges such as the low volumes of spent batteries (Meng et al., 2021), the hazards of shipping and dismantling batteries (Meng et al., 2021), the incomplete recovery of valuable metals in commercial processes and the low economic value of some recovered materials (Zhao et al., 2021). As it is estimated that less than 5% of Li-ion batteries get recycled at their end of life (International Institute for Sustainable Development, 2019), most of them still end up in common landfills around the

world. Currently, Asia seems to dominate the battery recycling market with Sony Corporation in Japan (Meng et al., 2021) and companies such as Green Eco Manufacturing Resource (GEM), Hunan Brunp Recycling Technology, and Wuzhou Huayou Cobalt New Material in China (Harrison & Ludwig, 2021).

At the end of EVs operation, batteries are assumed to retain 80% of their initial capacity (IEA, 2020b), making them eligible for use in several applications such as urban e-mobility and RE storage, both at residential and utility scales (Kotak et al., 2021). Giving batteries a second-life is the focus of some pilot projects of car manufacturing companies such as General Motors (GM), Renault, Nissan, and BMW, and it has taken place mainly in Europe and the US (Reinhardt et al., 2019). **Figure 2-2** depicts the main regions where EV's life cycle activities occur. Also, it illustrates what would be a simplified flow for the typical trades across continents, including raw materials, batteries, and EVs.

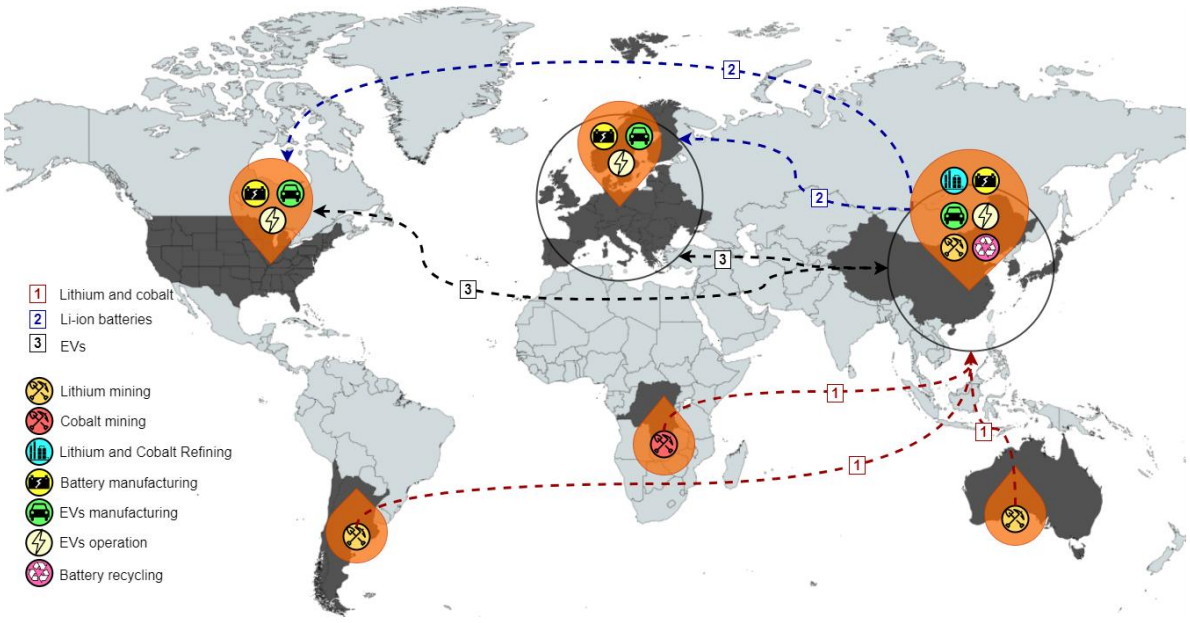


Figure 2-2. Simplified map of EV's life cycle activities. The arrows represent flow of (1) lithium and cobalt for processing, (2) Li-ion batteries, and (3) EVs.

2.4 Identifying injustices across EVs lifecycle stages

2.4.1 Research methods

This work explored works indexed in Science Direct, Scopus, and Web of Knowledge databases to identify potential injustices associated with EVs lifecycle activities. Sources in English were considered and

research from 2012 onward was included in this study. A combination of EV- and justice-related terms were used, resulting in works linked to energy justice frameworks, as well as environmental and social life cycle analysis of EVs and associated materials/components. Given the wide scope and geographical resolution of this work, a systematic literature review of works covering all EVs lifecycle stages would not be practicable.

When linking potential injustices to energy justice tenets, six energy justice tenets of the tenet-based approach, i.e., distributional, procedural, recognition, restorative, cosmopolitan, and flexibility justices, were considered. Even though relevant to energy justice literature, this work did not consider the principled approach as most of the latter's principles can be seen as aspects of the tenet-based approach (Hearn et al., 2021). Intra and intergenerational equity, for instance, which are pillars of sustainable development, can be framed within distributive and cosmopolitan justice (Sovacool, Kester, et al., 2019). The six energy justice tenets were combined with the whole-systems approach to be as comprehensive as possible when evaluating the relationship between EVs and a JET across lifecycle stages. The proposed approach can also be extended to analyze other technologies' lifecycles. In the following subsections, injustices gathered from the exploratory review are synthesized according to related lifecycle stages and performed activities.

2.4.2 EVs and resource requirements: The burdens of cobalt and lithium mining

Mining activities have been linked to environmental justice issues due to air, soil, and water pollution (Kaunda, 2020), effects on human health and local biodiversity (Farjana et al., 2019), water consumption (Egbue, 2012), energy intensity (Farjana et al., 2019), and conflicts with local and indigenous people (Egbue, 2012). Increasing demand has advanced mining activities toward more remote and unmined regions, which happen to overlap or be in the proximities of global protected areas in some cases (Durán et al., 2013). Mining activities at the Lithium Triangle, i.e., Chile, Argentina, and Bolivia, are an example of overlapping with nature conservation areas (Agusdinata et al., 2018). In particular, lithium mining and low-efficient evaporitic technologies (Flexer et al., 2018) in Chile have been linked to the forced delocalization of natives (Agusdinata et al., 2018) and the depletion of water resources (Kaunda, 2020). In Bolivia, as an opportunity for developing the national mining industry, it has generated local biodiversity concerns (Hancock et al., 2018), whereas in the US, attempts to increase local production have produced conflicts with local communities (Penn & Lipton, 2021).

Conflicts between mining companies and indigenous people are not new in the lithium supply chain and have already been documented in the lithium triangle (Egbue, 2012). Locals also seem to be blind-sighted due to poor knowledge sharing and are traditionally excluded in the decision-making process, even though their lives can be drastically affected by new mining activities (Agusdinata et al., 2018), as they raise local pollution and health issues, for example (Kaunda, 2020). In Portugal, even though lithium mining for battery manufacturing is only in the prospection and research stage, the initiative has already faced opposition from local communities thanks to poor communication and lack of transparency from companies and the government's side (Ribeiro et al., 2021) and the negative impacts associated with the activity, e.g., effects on ecotourism, local agriculture, water consumption and pollution, and environmental degradation (Chaves et al., 2021).

Concerning cobalt extraction, the struggles faced by Congolese people due to cobalt mining have been well documented by Sovacool (2019), which highlighted pollution and health issues, terrible work conditions for artisanal miners, conflicts between small and large-scale miners, corruption and malfeasance, exploitation and unfair market practices, forced delocalization of native people, and child labor (Sovacool, Hook et al., 2020). Once batteries with cobalt and nickel cathodes have the highest potential for environmental impacts, reducing their use and/or exposure to these materials has been recommended (EPA, 2013). Some progress has been made in replacing cobalt, but lithium is expected to continue as a critical element in batteries for energy storage and e-mobility (Armand et al., 2020). In 2018, China dominated the production of refined cobalt with a 63% share being responsible for producing of 78,152 tons per year (Piçarra et al., 2021). According to Piçarra et al. (2021), the Herfindahl-Hirschman Index (HHI) for cobalt refining indicates a problematic "*monopolistic hold of the market from China*", which increases the vulnerability of other countries due to refined cobalt dependencies. The Chinese hold on the cobalt supply chain after cobalt extraction from DRC is also highlighted in Gulley et al. (2019). Lithium extracted from brines can be used in end-markets, whereas lithium extracted from hard rocks has to be further processed before being used in Li-ion batteries (ATIC, 2018). Australia, as the largest producer of lithium from spodumene, has most of its lithium shipped to China for further processing in lithium carbonate, lithium hydroxide, or lithium chloride (ATIC, 2018). China is also the world's largest consumer of lithium thanks to its developed energy storage industry (Hao, Liu, et al., 2017). However, when comparing the manufacturing of battery components in China and the US, Hao, Lio et al. (2017) found that the Chinese manufacturing industry can emit more than twice as much GHG emissions compared to the American due to the electrical grid composition and the energy intensity of

industrial activities. Nevertheless, in average, the factory construction cost and the skilled labor rate is lower in China than other countries. For instance, the factory construction cost is around US$ 333/m^2 in China, US$420/$m^2$ in Poland, and US$656/$m^2$ in the US, whereas the skilled labor rate for these same countries is US$5/h, US$6/h, and US$85/h, respectively (ATIC, 2018). However, in addition to environmental aspects, there have been no social impacts and injustices related to lithium and cobalt processing alone documented in the reviewed literature.

2.4.3 Jobs, health, and emissions: impacts of an electrified automotive industry

As China dominates the Li-ion batteries supply and is expected to continue at the top of raw material processing and manufacturing of battery cell components and cell manufacturing for the next years (Zhao et al., 2021), it is reasonable to assess the Chinese manufacturing company's work conditions potential injustices. According to Sovacool (2021), low-wage factory workers in countries such as China and Malaysia are the ones "*inhaling toxic fumes and exposed to hazardous materials*" and seeing "*their lives shortened and environments degraded so that climate mitigation options can be used or exported elsewhere*" (Sovacool, 2021). Furthermore, attention must be paid to the effects of low-carbon technologies on labor and employment rates. There is a concern about job losses and employee retention in the automotive manufacturing industry because of the substitution of ICEVs for EVs (Di Felice et al., 2021). As gigafactories are being planned and constructed in Europe and the USA (Harrison & Ludwig, 2021), they can create work opportunities and foster regional and national economic development. On the other hand, their construction activities may negatively impact the environment as a large area is required for their establishment, and their operation requires high water and energy availability, which has created conflicts with local communities (Dartford & AFP, 2021).

Moreover, it is not only the number of jobs that must be considered but also the different skillsets needed in an electrified powertrain industry and the locations where these skills will be needed. Among the findings of Günther et al. (2015) when evaluating the effects of fleet electrification mainly in China and Germany, there is a positive trend in job results from a whole location perspective (Günther et al., 2015). However, the majority of jobs would be created in Eastern Europe (+3.9 million) against a +0.1 million in China, which can be considered unsatisfactory figures due to the country's population size and demand for labor (Günther et al., 2015). Nevertheless, according to the IEA, the development of more sustainable battery supply chains alone could create +10 million jobs worldwide (IEA, 2020b). However, Onat et al. (2015) underscored that, even though EVs can create more green jobs, ICEVs and hybrid vehicles have

the largest long-term employment potential, as they demand labor force in the petroleum and fossil fuel distribution industries. This is also highlighted by Di Felice et al. (2021), who, after comparing different employment projections, stated that less labor and more energy seem to be required in the electric powertrain industry.

Nevertheless, a growing demand for EVs does not impact jobs alone. In the same way that the fossil-fuel industry brings health risks to society (e.g., it is estimated that fossil-fuel-related emissions are responsible for about 65% of the excess mortality rate related to air pollution (Lelieveld et al., 2019)), EVs and Li-ion batteries manufacturing can also affect populations' health and must receive governments' attention (Gottesfeld, 2019). As a still-evolving technology, only recently is that the health hazards of Li-ion batteries started to be assessed, e.g., Sironval et al (2018) on the respiratory hazard of Li-ion batteries particles. In China, Shen et al. (2021) analyzed the presence of heavy metals, including cobalt, on individuals from local communities in the Chinese battery industrial capital and identified dust as the main vector, being young children the most affected ones. Concerning environmental impacts, EVs manufacturing has been linked to higher GHG emissions than the fossil-fuel counterpart, but again, this is subject to the country's electricity mix and the efficiency of industrial processes (Hao, Mu, et al., 2017). In this vein, Xiong et al. (2019) evaluated the lifecycle of EVs based on China's energy mix, and concluded that vehicle body and battery manufacturing account for the largest amount of energy consumption and GHG emissions.

2.4.4 Potential consequences of EVs ownership

As the EVs and electric batteries exports-imports trade values show in **Figure 2-3**, EVs and battery trades are highly concentrated in Europe, Asia, and North America, highlighting a distributional injustice. Moreover, apart from China and South Korea, only a handful of countries in the Global South are among the largest importers and exporters of EVs and electric batteries. For EVs importation and exportation, Europe dominates the market, whereas for batteries, Asia figures as the largest exporter with China holding an expressive 30% share of total trade values (CEPII, 2021). The five largest importers of battery-powered EVs are Germany (13.5%), UK (13.1%), Norway (9.4%), France (7.5%), and Netherlands (7.5%) (CEPII, 2021). On the other hand, main exporters are Germany (24.4%), US (15.8%), South Korea (11.6%), Belgium (11.2%), and France (5.8%) (CEPII, 2021). For battery imports, these are the trade value shares amongst continents: Europe (43.7%), Asia (32.0%), North America (18.7%), Africa (2.8%), South America (1.6%), and Oceania (1.4%) (CEPII, 2021). Even though it can be perceived a more distributed demand for batteries across countries, imports in Asian countries are most likely linked to an internal

market. Conversely, the five largest exporters of electric batteries are China (30.4%), South Korea (11.3%), Germany (8.3%), Poland (7.7%), and Japan (6.6%) (CEPII, 2021).

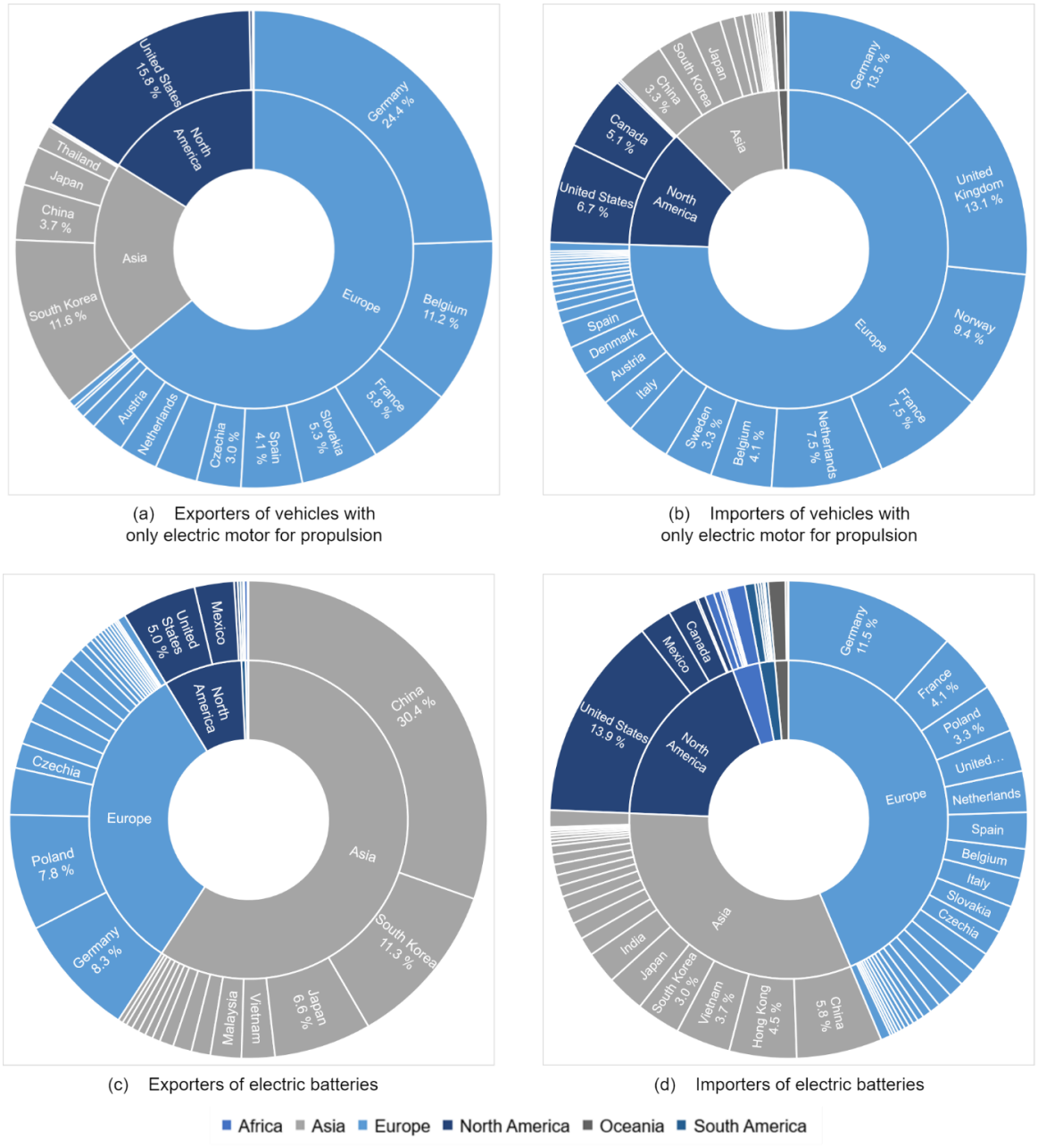


Figure 2-3. Trade values by country as a percentage of total. Adapted from (CEPII, 2021).

Summed to these evident geographical disparities, EVs also highlight socioeconomic imbalances as their purchase is limited to consumers of higher social classes due to high upfront costs (Reinhardt et al., 2019), which has been referred to as the 'elitism of EVs' (Sovacool, Kester, et al., 2019). The current

high purchase price is due mainly to battery costs (Liu et al., 2021). However, Liu et al. (2021) highlighted that, compared to some ICEV models, the initial cost of EVs can be recovered in five years after purchase. Nevertheless, authors advised that the economic advantages of powertrains vary according to geographic specificities due to electricity prices and matrix (Liu et al., 2021). Moreover, the operation and distribution of EVs directly affect jobs related to vehicles' maintenance and fueling. Furthermore, despite EVs job creation potential, created jobs are "*often in different locations, skill sets, and sectors than the jobs that will be lost as fossil fuel decline*" (IEA, 2021). Around the 5 million jobs that could be lost by 2030, many are well paid and in the proximities of fossil fuel resources, "*meaning structural changes can cause shocks for communities with impacts that persist over time*", (IEA, 2021).

Besides distributional inequalities and job losses due to EVs distribution and operation, the substitution of ICEVs may pour millions of environmentally non-regulated second-hand vehicles into developing and less developed countries (UN Environment Programme, 2020). According to the UN Environment Program, the three largest exporters of used vehicles are the EU, Japan, and the US, with 54%, 27%, and 18% of the 14 million used light-duty vehicles exported between 2015 and 2018, respectively (UN Environment Programme, 2020). About 70% of exported vehicles go to developing countries, which in the majority have limited or no regulations on safety and emissions standards of imported vehicles (UN Environment Programme, 2020). In Africa, for example, used vehicles comprise 85% of the fleet, and most African countries do not have used vehicle standards or age restrictions in place (Ayetor et al., 2021). For instance, Doumbia et al. (2018) evaluated the fleet composition in Abidjan, Côte d'Ivoire during a field study and identified that more than 60% of personal cars are older than 10 years, with 6% surpassing 30 years on the road. In opposition to newer vehicles holders of higher Euro standards, older cars in the fleet have been linked to worse air quality (André et al., 2018). Morales-Betancourt et al. (2019), when evaluating the exposure to air pollution from urban buses in Bogotá, Colombia, identified that "*average exposure levels inside Euro II and Euro III (older buses) was twice as large as those measure inside vehicles with stricter emission standards, Euro IV or superior*". In their study, the authors considered concentrations of fine aerosol particles, equivalent black carbon, and carbon monoxide (CO), concluding that a fleet renewal would significantly reduce population exposure to them (Morales-Betancourt et al., 2019).

Furthermore, EVs have been linked to the rural-urban divide during their operation due to range constraints and lack of infrastructure to recharge vehicles, which may exclude distant communities, contributing to the urban-rural divide (Sovacool, Hook, et al., 2019). There is also a concern about the

marginalization of other forms of mobility such as cycling and public transport, due to the predominance of battery-powered private cars (Sovacool, Kester, et al., 2019). Additionally, in countries with fossil fuel-based electricity mixes (e.g., China and India), the utilization of EVs causes emissions to be offset from tailpipe to power plants (Di Felice et al., 2021). Dillman et al. (2020) evaluated the GHG intensities of electric grids across the European Economic Area and concluded that for some countries, "*EVs could lead to greater life-cycle GHG emissions than a comparable diesel counterpart*" (Dillman et al., 2020). On the other hand, according to Moro and Lonza (2018), the use of EVs instead of gasoline-fueled in EU member states can avoid, on average, 60% of GHG emissions. However, this reduction may not be evenly distributed across countries since, if a Well-to-Wheel (W2W) methodology that considers the carbon intensity of the electricity sector as well as electricity imports-exports is employed, GHG emissions might increase (Moro & Lonza, 2018). This emphasizes the need for holistic and cross-sectoral approaches that connect energy supply to transport, industrial, and residential sectors, increase the share of RE in electricity matrices (Liu et al., 2021), and develop smart grids (Shaukat et al., 2018). Such holistic approaches can also avoid negative effects on electricity prices due to increased peak-load (Dranka & Ferreira, 2020) since electrifying end sectors increases the electricity demand and grid flexibility requirements.

In this regard, V2G technologies arise as options that allow a bidirectional flow of electricity from EVs to smart grids (Shaukat et al., 2018). V2G can provide unused energy back to the grid during high peak demand periods (Shaukat et al., 2018), for instance. In a study in Portugal, Nunes and Brito (2017) showed that even a small share of EVs for load balancing can positively affect grid flexibility as a means to reduce natural gas usage and energy excess. Accordingly, Zhou and Cao (2019) focused on building energy management systems and numerically modeled the contribution of EVs and batteries to balance peak and off-peak periods, identifying a positive contribution.

2.4.5 Used batteries: troublemaker or proponent of a regulated circular economy?

Spent Li-ion batteries are considered hazardous due to their content of heavy metals and have four main disposal routes: recycling, landfilling, illegal disposal, and informal processing (Mrozik et al., 2021). If not disposed properly, batteries can contaminate water, soil, and air through a series of pollution routes such as leaching and dissolution (Mrozik et al., 2021). Generated pollution can bring harm to the environment and human health, accumulate in soils, plants and crops, being battery toxicity harmful to various trophic levels (Mrozik et al., 2021). Accordingly, Sovacool, Hook et al. (2020) pointed out that informal processing

and inappropriate disposal of Li-ion batteries are likely to expose workers and local communities to hazardous materials. Given the hazardous nature of Li-ion batteries, fire accidents at recycling stations, transport vehicles, and landfills have been reported in connection to used Li-ion batteries, for instance (Connor & Wise, 2021). These fire accidents have impacted the waste facilities and surrounding communities through injuries, service disruptions, and monetary losses (Connor & Wise, 2021).

Nevertheless, recycling and reusing activities can go beyond environmental and health aspects and can create millions of jobs thanks to the "*job-intensive nature of the logistics and industrial facilities needed to realize domestic recycling*" (IEA, 2020b). Nevertheless, for this industry to grow, recycling processes have to be further developed to avoid inefficient recycling processes and waste generation (Tabelin et al., 2021). According to Qiao et al. (2019), in a study evaluating the economic and environmental benefits of EV recycling in China, the total potential reduction of energy consumption and GHG emissions per technology cost is 241.3 MJ/US$ and 36.3 kg CO2eq/US$, respectively. Nonetheless, the reduction from recycling vehicles without batteries is larger than the reduction achieved with battery recycling, as the latter process is not completely developed and subject to large efficiency improvements (Qiao et al., 2019). To reduce the loss of circularity and take advantage of the opportunities that accompany battery recycling, laws and standards that enforce responsible and safe disposal of low-carbon technologies and promote sustainable supply chains must be in place, which is not the case for most developing and less developed countries (IEA, 2020b). The European Commission has recently taken action towards establishing rules for battery design, production, and disposal as means to enforce environmental and social sustainability (European Commission, 2020b). However, there is no universal standard battery recycling (Mrozik et al., 2021), even though lithium and cobalt, in particular, can significantly contribute to the UN SDGs and a circular economy agenda (International Institute for Sustainable Development, 2019).

According to what has been presented in this section (**Section 2.4**), **Table 2-1** summarizes EVs lifecycle stages, associated activities, most representative countries where these activities take place, and potential injustices.

Table 2-1. Most representative countries and potential injustices of EVs lifecycle activities.

Lifecycle stage	Activity	Most representative countries	Potential injustices
Resource extraction and processing	Lithium mining and processing	Chile, Australia, China, and Argentina [1]	Knowledge asymmetry among stakeholders (Agusdinata et al., 2018); forced delocalization of natives (Agusdinata et al., 2018; Egbue, 2012); conflicts between mining companies and indigenous people (Egbue, 2012); depletion of water resources (Agusdinata et al., 2018; Kaunda, 2020); local pollution and health issues (Kaunda, 2020); local biodiversity concerns (Hancock et al., 2018);
	Cobalt mining and processing	Democratic Republic of Congo (DRC) [2]	Local pollution and health issues (Sovacool, 2019); terrible work conditions (Sovacool, 2019); child labor (Sovacool, Hook et al., 2020); conflicts between small and large-scale miners (Sovacool, 2019); corruption and malfeasance (Sovacool, 2019); exploitation and unfair market practices (Sovacool, 2019); forced delocalization of natives (Sovacool, 2019); monopolistic hold of cobalt processing (Piçarra et al., 2021);
Manufacturing	Battery components manufacturing	China, Japan, and South Korea[3]	Low-wage factory workers (e.g., China) (Sovacool, 2021); construction of gigafactories (Harrison & Ludwig, 2021) and conflicts with local communities (Dartford & AFP, 2021); job losses in the automotive manufacturing industry (Di Felice et al., 2021); health hazards (Shen et al., 2021);
	Battery cell manufacturing	China, US, Europe[4], South Korea, and Japan (D. Harrison & Ludwig, 2021)	
	EVs manufacturing and assembly	China, US, Japan, Germany, France, and the UK (D. Harrison & Ludwig, 2021)	
Distribution and Operation	Sales and Distribution	Main importers vs. Main exporters[5]	Job losses in the fossil fuel industry (Sovacool, Kester, et al., 2019); EVs purchased by consumers with high socioeconomic conditions (Sovacool, Kester, et al., 2019); distributional inequality across countries due to uneven uptake (CEPII,

Lifecycle stage	Activity	Most representative countries	Potential injustices
			2021; IEA, 2021a) ; price of EVs (Reinhardt et al., 2019); second-hand ICE markets (UN Environment Programme, 2020);
	Re-charging and Operation	China, Europe, and the US [6]	Urban-rural divide (Sovacool, Hook, et al., 2019); marginalization of other forms of mobility (Sovacool, Kester, et al., 2019); job losses in the fossil fuel industry (IEA, 2021); offset of emissions from tailpipe to power plants (Di Felice et al., 2021); North-South divide (Sovacool, Hook et al., 2020); adverse effects on electricity price due to increased peak-load (Dranka & Ferreira, 2020);
End of life	Waste and Re-use of batteries (Second life)	Worldwide[7]	Spent Li-ion batteries have been linked to pollution and health hazards (Mrozik et al., 2021), accidents and injuries (Connor & Wise, 2021), informal recycling and inappropriate disposal to environmental and health issues (Sovacool, Hook et al., 2020); inefficient recycling processes and waste generation to resource depletion and loss of circularity (Tabelin et al., 2021);
	Recycling of batteries	China (>60%) and South Korea (Harrison & Ludwig, 2021)	

[1] Countries with a lithium mine production of over 5 million tons in 2020 (US Geological Survey, 2021). [2] DRC is responsible for 70% of global cobalt production in 2020 (US Geological Survey, 2021). [3] China, Japan, and South Korea are home to a significant share of Li-ion batteries components manufacturing capacity: cathodes (85% of global capacity), anodes (97%), separators (84%), and electrolytes (64%) (Chung et al., 2016). [4] Battery-cell manufacturing in Europe is concentrated mainly in the United Kingdom, France, and Germany (Harrison & Ludwig, 2021). [5] Main importers: Germany, UK, Norway, France, Netherlands, and Main exporters: Germany, US, South Korea, Belgium, France (CEPII, 2021). [6] EV stock in 2019: China 3.3 million, Europe 1.8 million, and the US 1.5 million (IEA, 2020a). [7] Battery second life projects: Germany, US, France, UK, Netherlands, Japan (Reinhardt et al., 2019).

2.5 The linkage between EVs lifecycle and EJ tenets

As one of the aims of this paper is the framing of injustices according to the energy justice tenets, this section brings, for the first time in literature, the linkages between EVs lifecycle activities and distributional, flexibility, procedural, recognition-based, cosmopolitan, and restorative justices. By combining the energy justice topic with EV technology, we intend to shed light on the most critical downsides of the road transport electrification, which are spread across EVs lifecycles, and provide policymakers and researchers with targets for action to counteract the identified downsides and strive for mitigating injustices.

2.5.1 Distributional and flexibility justice

The concept of distributional justice is especially relevant when investigating globalized supply chains to ensure that benefits and illnesses are evenly distributed. As can be linked to both physical (environmental) and social burdens, distributional injustices are present in all EVs lifecycle stages. For lithium and cobalt extraction, burdens are borne by a small number of countries. The extraction of lithium from brines in the Lithium Triangle, i.e., Chile, Bolivia, and Argentina, has been linked to the regional depletion of water resources and local biodiversity concerns (Flexer et al., 2018). In contrast, cobalt extraction from the DRC has been linked to local pollution and health issues (Sovacool, 2019). Cobalt and lithium processing are concentrated in China (ATIC, 2018), and trade values indicate that economic gains through value-adding manufacturing activities in the EV lifecycle are contained in large economies in Asia, Europe, and North America (CEPII, 2021). The Chinese hold on lithium and cobalt processing activities gives it an almost monopolistic power over Li-ion batteries supply chain (Piçarra et al., 2021). However, battery manufacturing has been linked to negative effects on local populations health in China (Shen et al., 2021). Moreover, the construction of gigafactories in Europe, in an attempt to localize manufacturing activities in the continent, raised concerns over local water, land, and energy use (Dartford & AFP, 2021). Given the location of lifecycle activities with the most injustices, we can say that EVs contribute to the North-South divide. On the discussion over job creation and losses, even though some works point to an overall positive net employment, there will be a possible mismatch between created jobs and the skills and the location of available workforce (Di Felice et al., 2021), which highlights a both positive and negative effect of EVs on employment.

Likewise, benefits due to emissions and air pollution reduction, which are expected in EVs' operational phase, are likely to materialize in urban environments in a selected number of countries in the Global North, depending on countries' electricity matrices (Moro & Lonza, 2018). China, for instance, even though concentrating the largest number of EVs, has seen an increase in emissions from the transport sector as 65% of its electricity was generated from coal in 2019 (EPA, 2013). This offset of emissions from tailpipes to power plants stresses the importance of integrating RE into energy mixes and having flexible demand strategies. Nevertheless, there is a clear advantage when offsetting tailpipe emissions from power stations since it is simpler to manage and reduce emissions from a few sources than from countless ICEVs on the road (Hawkins et al., 2013). Besides, an asymmetrical EV uptake across continents has consequences for the market of used ICEVs, commonly directed to developing countries in Africa and South America and linked to air pollution and safety, energy efficiency, and operational costs

issues (UN Environment Programme, 2020). On the other hand, a second-hand EV market can help less developed countries accelerate their fleet electrification if electric cars reach domestic markets with accessible purchasing prices (UN Environment Programme, 2020) since another aspect that contributes to the distributional injustice of EV technology is its high upfront costs, which limits its acquisition to wealthier socioeconomic groups. Nevertheless, costs are expected to considerably fall with technological development (IEA, 2021a).

Lastly, good management of used EVs at the end-of-life stage can help establish sustainable supply chains through reuse and recycling loops of batteries. This is a determinant aspect of Li-ion batteries impact so they do not end up in common landfills or are dismantled by workers under unsafe and unhealthy conditions, affecting local health and biodiversity, as already reported in the literature (Sovacool, Hook et al., 2020). Batteries' recycling is currently dominated by Asia and is subject to efficiency improvements before it becomes financially and environmentally attractive (Qiao et al., 2019). Flexible production and waste management processes are also linked to a flexible energy transition (Heffron et al., 2020) in conjunction with reusing batteries for energy storage systems. The flexibility justice tenet relates to EVs thanks to sector coupling and its effect on energy demand and storage.

Concerning costs for re-charging at the operational phase, appropriate market pricing mechanisms and strategic charging can help avoid large-scale EVs charging at times of peak demand, which would impact grid stability and energy price. Higher electricity prices have been linked to energy poverty issues as raising prices inflict an extra burden on a household that do not have large disposable incomes (Lowans et al., 2021). V2G technologies can also help reduce costs of infrastructure changes (Ghosh, 2020) and contribute to a flexible energy transition by balancing variable energy supply from RES and demand (Heffron et al., 2020). V2G services depend on several technical aspects, but it could "*unlock up to 600 GW of flexible capacity distributed across the main electric vehicle markets in 2030 and moderate intermittency of variable renewables during peak demand*" (IEA, 2020b). **Figure 2-4** represents the main aspects to be considered concerning distributional justice and flexibility justice according to the lifecycle stages together with a positive (+), negative (-), or combined sign (-+) indicating the potential effect of EVs. As can be seen, distributional injustices, which indicate a potential negative effect of EVs and offer opposition to a JET, are fairly distributed across lifecycle stages. On the other hand, EVs seem to have the potential to positively affect flexibility justice mostly during the distribution and operation phase. Accordingly, Li-ion batteries recycling and reuse rate will dictate whether the technology contributes to or

opposes a JET concerning natural resources usage at resource extraction and waste and disposal lifecycle stages.

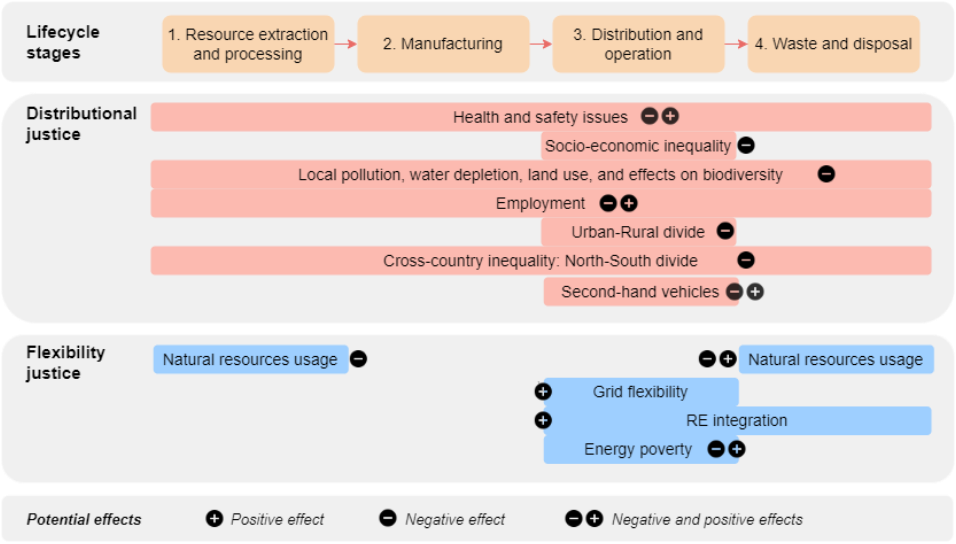


Figure 2-4. Distributional and flexibility justice: Potential effects of EVs.

2.5.2 Procedural and recognition justice

Knowledge asymmetry and stakeholder conflicts are particularly relevant for justice issues at the resource extraction and processing stage. Increasing demand has advanced mining activities toward more remote and unmined regions, which happen to overlap or be in the proximities of global protected areas in some cases (Durán et al., 2013), as in the Lithium Triangle (Agusdinata et al., 2018). Even though Chile ratified the International Labor Organization (ILO) Indigenous and Tribal Peoples Conventions in 2008, internal factors and governmental policies have limited the participation of indigenous people in decision-making processes about land requirements and water use, once their participation can harm the mining industry interests and intensify conflicts between indigenous people and the mining industry (Egbue, 2012). This is associated with the injustices presented in the previous section related to the forced delocalization of native people and the abandonment of ancestral settlements due to water scarcity as the mining industry requires large amounts of water to operate in one of the driest regions in the world (Agusdinata et al., 2018; Kaunda, 2020). As ensuring lithium supply becomes one of the priorities of carmakers, countries want to become independent in both sourcing and manufacturing EV technology. However, this rush to extract more lithium can lead to more conflicts, environmental degradation, and disregard for local communities' interests.

Even at the European level, conflicts about the potential expansion of lithium exploitation activities are emerging, as mentioned in the previous section for the case of Portugal, where mining locations pose challenges to local communities' wellbeing and functioning (Chaves et al., 2021). Concerning cobalt mining, besides critical environmental and human health issues (Farjana et al., 2019), mining activities have been associated with the displacement of indigenous communities, corruption, malfeasance, political oppression, and conflicts in the DRC (Sovacool, 2019). Moreover, the construction of gigafactories for battery manufacturing may also generate conflicts with local communities and produce procedural injustices (Dartford & AFP, 2021). And not only gigafactories, but industrial practices that negatively affect the health and safety of surrounding populations often lack the participatory processes and decision-making that should be in place concerning people's interests. **Figure 2-5** summarizes the linkages between EVs lifecycle stages and procedural and recognition justices. As can be seen, activities at resource extraction and processing and manufacturing stages have been offering opposition to establishing a JET.

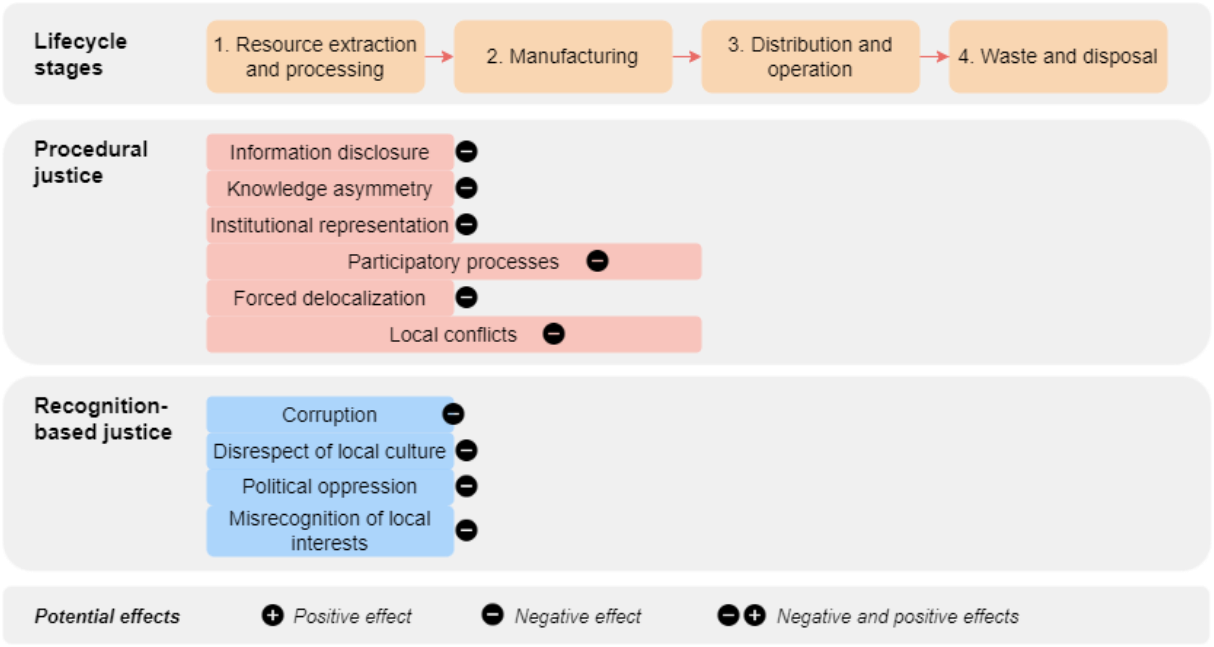


Figure 2-5. Procedural and recognition-based justice: Potential effects of EVs.

2.5.3 Cosmopolitan and restorative justice

Concerning cosmopolitan justice, EVs have been related to the consumption of finite mineral resources (Dolganova et al., 2020), toxicity increase (Kallitsis et al., 2020), water scarcity (Chaves et al., 2021), and a shift from tailpipe to power plant emissions in cases where electricity supply is heavily dependent on fossil fuels (Onat et al., 2015). These issues inflict a burden on the environment as a whole and have intra and intergenerational consequences through GHG emissions, natural resource depletion, and climate change. In case EVs fail to reduce overall GHG emissions, this technological choice will not help the world stay below the 1.5 °C global average temperature threshold, which will bring serious and damaging effects to the current and future generations. These aspects must compel us to act as global citizens towards building and inclusive and resource efficient future (McCauley et al., 2019), in the same way they prompt interlinked and holistic sustainability assessments for intergenerational 'strong sustainability' (Dillman et al., 2021). In circumstances in which social and environmental damage is unavoidable, such as mining activities, restorative justice must compel companies to take responsibility for optimizing processes as much as possible, maintaining sustainable practices, and compensating the most impacted people by improving local working conditions, respecting local cultures and interests, as well as access to essential services in order to avoid 'green colonialism' practices (Normann, 2021). This is clearly not the case in many mining sites around the world, where the environment is not appropriately restored and surrounding communities are not given the means to thrive after the end of mining activities (e.g., (Annandale et al., 2021) on the impacts of mining on Indigenous livelihood and the importance of pre- and post-mining management).

Restorative justice may also imply establishing specific laws and standards according to the activities developed in each region, such as mandatory recollection of used batteries by manufacturers through reverse logistics to avoid dumping in inappropriate fields (IEA, 2020b). These laws and standards are expected to establish socially and environmentally sustainable supply chains, as referred to in EU regulations over batteries sourcing and recycling (European Commission, 2020b). Therefore, restorative justice obliges companies to take moral and financial responsibility for their operations when they negatively impact society, as well as bidding to laws and standards, restoring the environment in cases of degradation, pollution, and accidents, and social compensation through the improvement of essential local services and job opportunities, for instance.

Figure 2-6 encapsulates the aforementioned relationships. Within restorative justice, negative effects on social compensation and environmental restoration are contained to the resource extraction and processing stage, while we attribute to laws and standards a potentially positive effect on the sustainability of the entire EVs supply chain. Nevertheless, like V2G technologies, this potential positive effect is yet to materialize. As expected, aspects linked to cosmopolitan justice are evenly spread across lifecycle stages. Particularly, pollution and effects on biodiversity receive a potential positive effect in addition to the negative as, in the long term, the substitution of ICEVs by EVs can reduce the CO_2 concentration in the atmosphere and, therefore, climate change effects.

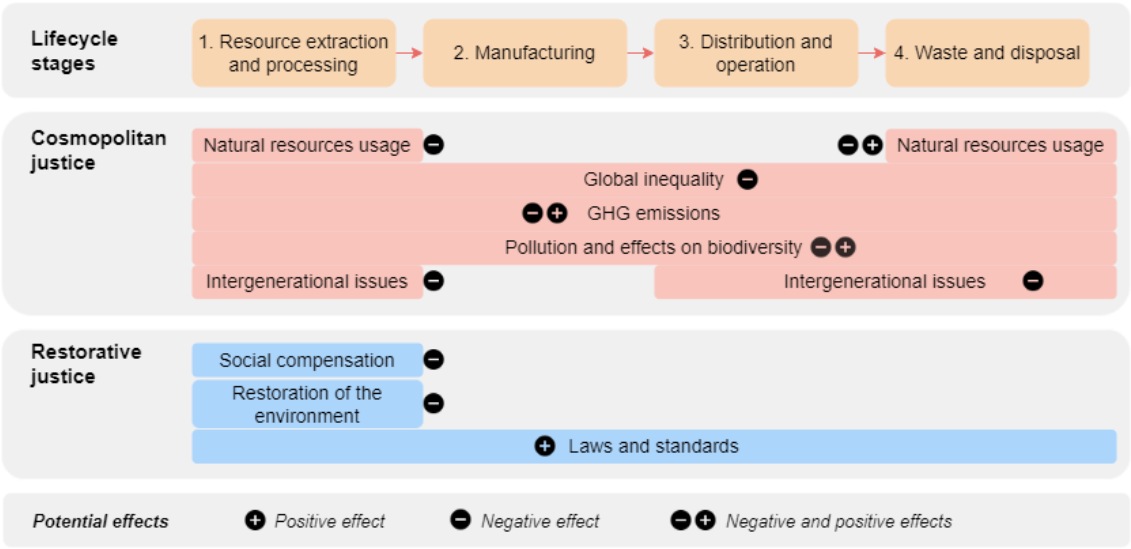


Figure 2-6. Cosmopolitan and restorative justice: Potential effects of EVs.

2.6 Conclusion

A whole-systems perspective over low-carbon technologies can contribute to a JET since, by analyzing what activities are performed in each lifecycle stage, where they take place, and which communities are affected, injustices can be identified and further addressed. However, there can be no one-size-fits-all solution, given each country's different challenges. Decarbonizing the transport sector is essential for reducing GHG emissions, and EVs are undoubtedly playing a key role in this process. However, our exploratory review shows that efforts must be directed toward reducing injustices that are spread across lifecycle stages and countries. Among the most critical aspects of this work, we highlight the distributional injustices caused by: (i) the disregard of social and environmental aspects in lithium and cobalt mining

activities, (ii) work, emissions, and health-related issues during manufacturing stages, (iii) the concentration of value-adding activities in China and developed countries which can potentially widen cross-country and continent inequality, (iv) EVs infrastructure and charging requirements that can exclude rural communities, (v) EVs price which sustain the technology's elitism (Sovacool, Kester, et al., 2019) (vi) the market of used ICEVs which can transfer emissions and health issues associated with ageing and less efficient fleet mostly to developing and less developed countries in South America and Africa, and (vii) the lack of recycling and reusing activities at waste and disposal waste of Li-ion batteries and its associated health and environmental hazards. Also, the extension of flexibility justice to EVs shows the relevance V2G technologies can have in ensuring a more reliable and flexible energy system. The effects of EVs on this energy justice tenet are mostly contained to the distribution and operational stage due to energy-transport coupling. Also, considering that a flexible energy system would also imply compliant resource management practices, EVs can positively or negatively contribute to a reduction in resource usage depending on recycling and reuse rates. Conversely, EVs can burden electric grids due to high peak demand and poor households in case demand and supply are ill-coordinated. This may cause electricity prices to go up, restricting the fight against energy poverty and the achievement of SDG7.

The framing of injustices according to procedural and recognition-based tenets showed that the most critical stage for attaining a JET from this side is the resource extraction and processing lifecycle stage. Our review showed that lithium and cobalt extraction impacts on surrounding communities are commonly neglected, causing local conflicts, and the forced relocation of native people. Moreover, activities in the DRC have been linked to corruption and unethical work aspects (Sovacool, Hook et al., 2020). In the manufacturing phase, injustices may also appear within industries and their vicinities as participatory decision-making is also missing. For sustainable and ethical supply chains, adequate international laws and standards are critical. These standards are directly connected to companies' legal obligation to restore the environment and the communities affected by their activities. These are key aspects of restorative justice, which are currently and mostly required at the resource extraction stage. Lastly, the use of finite resources, global emissions, and climate change put a lot of pressure on EV-technology development and uptake as the ultimate goal of EVs is to reduce transport emissions and fossil fuel dependency. However, even though EV-related GHG emissions can be contradictory in literature, especially when a lifecycle perspective is employed, low-emission electricity matrices, technological development, and flexible energy systems can provide the technology with the means to fulfil its purpose. Concerning resource usage, EVs' positive or negative effects continue to depend on the enhancement of

recycling processes, their regulation and distribution across countries, as well as the development of energy storage technologies.

Therefore, in relation to whether EVs contribute to or oppose a JET, our exploratory review shows that it depends. From one side, EVs have great potential to reduce GHG emissions, create jobs in the electric powertrain and recycling industries, enhance energy systems flexibility, improve health in urban environments, and reduce energy and resource consumption. On the other hand, they can increase socioeconomic inequalities across countries, perpetuate stories of green colonialism, stretch gaps between socioeconomic classes, add a load to natural resources extraction, negatively affect health and biodiversity through air, water, and soil pollution, and even increase GHG emissions across the whole lifecycle if RE integration does not happen in tandem with EVs uptake. Nevertheless, even though we do not discuss the injustices associated with fossil fuel chains and ICEVs, we acknowledge they are many and widespread. As EVs are an essential part of transport decarbonization plans, they should have their most critical environmental and social aspects identified and addressed. Since low-carbon technologies are not essentially just or inclusive, as our analysis of EVs shows, action must be taken to reduce inequalities and unintended negative impacts.

Among the limitations of this work, we could cite the exploratory nature of the review and the lack of quantitative analysis to support justice claims for the case of EVs. The extent to which these findings have wider relevance should be further evaluated. Moreover, our assessment of EVs lifecycle and associated injustices at resource extraction and waste and disposal was limited to Li-ion batteries, which makes us recognize the scope limitations of this work. Accordingly, this work was also limited to energy storage technologies employing lithium and cobalt. However, as a rapidly evolving technology, battery chemistry can reach a point where neither of these raw materials is required (Sanguesa et al., 2021).

Given the interdisciplinary nature of this work, we have future research recommendations that include technical and social aspects. In technical terms, as already highlighted by many works (e.g., (Kotak et al., 2021; Skeete et al., 2020)), it is necessary to keep working on (i) the development of batteries that use less critical raw materials, e.g., cobalt and lithium, without impairing EVs performance; (ii) the improvement, regulation, and dissemination of battery recycling processes; (iii) research on battery re-use and development of pilot projects and (iv) grid stability and flexibility and the effects of large-scale EV charging on electric grid and price. Additionally, the appropriateness of EVs and other modes of transport in specific contexts and regions, following advances made in other transport-related technologies (e.g., biofuels (Malode et al., 2021)) must be analyzed. Ergo, research on the impact of policies on emissions,

socioeconomic aspects, and alternative fuel vehicles' (AFVs) uptake is critical (Hassani & Maleki, 2021). On the social side, we recognize the relevance of (v) research on social innovations and new business models for overcoming socioeconomic barriers imposed by EVs upfront and infrastructural costs and associated distributional inequalities. Likewise, (vi) research and funding towards ensuring access to clean and affordable energy for all, as proposed by SDG7, can reduce wealth inequalities and, in the long run, contribute to EVs uptake. (vii) As car manufacturers rush toward ensuring supply, the impacts of localized supply chains on environmental, social, and market dynamics both international and national, must be further explored. (viii) Lastly, research on justice aspects of low-carbon technologies that employ methods to quantify aspects related to technologies' justice can substantially contribute to a JET by providing ways of measuring progress.

3 Operationalizing energy justice: A systematic literature review

This chapter is based on the article titled "*Charging up justice? A critical review for operationalizing energy justice in electric vehicle research* ", which has been submitted to an international journal of high impact. The content presented here reflects the key findings and discussions of the original manuscript, with some adaptations to fit the overall structure of this thesis.

Charging up justice? A critical review for operationalizing energy justice in electric vehicle research

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Submitted

Abstract: Energy justice offers a normative framework for qualitative analyses of low-carbon transitions, including EV adoption. However, the framework has faced criticism regarding limitations in its empirical applicability and normative ambiguities. Addressing these critiques, this research proposes connecting measurable proxies with specific justice concerns for low-carbon technologies. This is applied to EVs, focusing on justice dimensions related to their ownership and infrastructure distribution, given the ongoing controversies surrounding their rollout. This research systematically reviews the literature on equity and justice in relation to EVs, with a focus on quantitative indicators and methods used to operationalize related aspects. A total of 60 peer-reviewed studies, mainly quantitative, were analyzed based on their conceptual framing and methodological approaches. Main findings underscore the prevalence of distributional equity assessments, the normative uncertainty of studies, and the infrequency of mixed-method research. Quantitative proxies and their limitations are proposed in relation to distributive, procedural, recognition, restorative, cosmopolitan, and flexibility justice in EV research. This study is pioneer in synthesizing metrics and indicators aligned with energy justice tenets, particularly in relation to EV technology. The identified research gaps point to the need for clearer theoretical frameworks and

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diverse methodologies to better integrate energy justice into EV-related policies and assessments, ensuring a fair and sustainable transition to EVs.

3.1 Introduction

As local and global energy transitions progress, the inequitable distribution of burdens and benefits has raised questions of equity and justice across research and practice. These questions refer to, for example, socio-environmental conflicts surrounding raw material extraction for the energy transition (Ciftci & Lemaire, 2023), effects of the energy transition on labor (García-García et al., 2020), and low-carbon technology elitism (Sovacool, Kester, et al., 2019). Hence, the concept of a just transition has been increasingly recognized as crucial for a low-carbon future (see (Wang & Lo, 2021) for a comprehensive conceptual review of the literature on "just transition").

In this context, it has been claimed that energy justice offers a valuable framework for addressing justice-related concerns (Sovacool & Dworkin, 2015). Aiming at a global energy system that fairly distributes its burdens and benefits (Sovacool & Dworkin, 2014), energy justice provides guiding principles to reflect upon the distribution of impacts, and whose voices are recognized and included in decision-making. It is mainly concerned with "*what are the unjust impacts associated with energy systems,*" "*where they are located,*" "*who is most affected,*" and "*how these injustices become embedded in procedures and mechanisms*" (Jenkins et al., 2016). In the tenet-based approach (Jenkins et al., 2016), energy justice is evaluated through three central tenets: distributional, procedural, and recognition justices (Jenkins et al., 2016). Distributional justice focuses on the fair distribution of the costs and benefits of energy supply and consumption, considering spatial, temporal and social dimensions (Sovacool, Martiskainen, et al., 2019). Procedural justice emphasizes the importance of inclusive decision-making in energy-related matters, advocating for the participation of all affected parties (Heffron & McCauley, 2017; Sovacool et al., 2016). Recognition justice seeks to extend cultural and political respect and recognition to vulnerable and marginalized social groups in relation to energy transition issues, ensuring they are not bypassed or ignored (Sovacool, Martiskainen, et al., 2019).

In conceptual contributions to the field, other tenets have also been proposed, such as restorative justice arguing for rectification of injustices caused by the energy sector (Heffron & McCauley, 2017), flexibility justice related to the ability to be flexible in energy use (i.e., flexibility capital (Powells & Fell, 2019)), and cosmopolitan justice (Sovacool, Kester, et al., 2019). Cosmopolitan justice stems from the perspective

that we are all citizens of the same world, calling for a cross-border view over transition effects (Sokołowski & Heffron, 2022). Nonetheless, cosmopolitan justice has been recently reframed as a normative principle rather than a tenet (Van Uffelen et al., 2024). Apart from flexibility justice, all aforementioned tenets were also pointed out as key for bringing energy justice into practice (Baker et al., 2019; Sokołowski & Heffron, 2022).

In fact, one of the primary criticisms of energy justice refers to its limited empirical applicability (Sokołowski & Heffron, 2022). Another recent critique concerns the normative uncertainty found within the energy justice literature (Van Uffelen et al., 2024) or, in other words, the insufficient depth in explaining what is meant by justice, even when the established tenets are used as analytical guides. By specifying what justice means in a given situation, it is anticipated that superficial applications of the concept can be avoided, and a deeper understanding of the moral diversity surrounding energy decisions and expectations can emerge (Van Uffelen et al., 2024). This approach may also help shift the energy justice framework away from Western perceptions of justice, such as those articulated by the moral philosopher John Rawls (Galvin, 2019). Conversely, a more extensive focus on justice theories and philosophies could potentially distance the framework from its empirical application (Wood et al., 2024), particularly in guiding policy and decision-making in the energy transition.

Building on these critiques, this study aims to advance both theoretical and practical dimensions of energy justice by linking its core tenets to specific metrics and indicators. The goal of this operationalization, understood here as the establishment of measurable proxies for specific justice-related concerns, is to enable the tracking of progress on key justice issues within the energy transition (Jodoin, 2021). Additionally, this study argues that indicators are inherently tied to their methodological assumptions and require explicit clarification of their meaning and scope, potentially helping address normative uncertainties.

To meet its objectives, this study adopts a technology-centered perspective, premised on the idea that despite the context-dependent and diverse nature of justice issues, they can be linked to technology-specific quantitative proxies. These proxies can then be adapted to reflect different contexts, as well as the varying expectations and interpretations of justice among different groups. The selected technology for this study is EVs, including both battery electric (BEV) and plug-in electric (PHEV) passenger vehicles, and its related infrastructure (i.e., electric vehicle charging stations – EVCS). The choice of EVs is justified by their increasing prominence in contemporary policy agendas. In the EU, for instance, the Clean Vehicles Directive (Directive (EU) 2019/1161) aims to accelerate the uptake of zero- and low-emission

vehicles, including EVs. It sets minimum targets for procuring clean vehicles by 2025 and 2030 at Member State levels, varying from 17.6% to 38.5% by 2030 (European Commission, 2019). Likewise, many countries have implemented policies and subsidies to accelerate EV adoption (IEA, 2023), while companies in the automotive industry have committed to transitioning from fossil fuel-based vehicles to zero-emission alternatives (IEA, 2021c). However, this technological shift is not without socio-environmental and political problems, as it is shaped by existing power structures (Haas, 2022) and locked-in systems (Haarstad et al., 2022) that favor private mobility. Its success is also dependent on how affected communities are included in the EV transition, as discussed by Silva et al. (2023).

In essence, this study has three main objectives. First, it aims to systematically review justice-related metrics used in research on EV transitions, analyzing their conceptual framings and methodological approaches. Second, it seeks to link these metrics to the energy justice framework based on distributive, procedural, recognition, restorative, cosmopolitan, and flexibility justice. Finally, by linking tenets to measurable proxies, this study aims to enhance the empirical applicability of the energy justice framework while emphasizing the importance of clarifying underlying ethical positions and deepening the understanding of justice issues.

3.2 Background and research gaps

This section provides an overview of key research contributions on justice-related metrics in EV transitions (**Section 3.2.1**) and energy justice operationalization efforts (**Section 3.2.2**). **Section 3.2.3** presents the concept of flexibility justice, a recently explored aspect of justice in energy systems. By identifying existing literature gaps, this section clarifies how this study advances energy justice operationalization in EV research.

3.2.1 Electric vehicles, equity, and metrics

Several literature reviews have been conducted on the topic of EVs, equity, and quantitative assessments. Carlton and Sultana (2023) conducted a scoping review on transportation equity in EV charging research, identifying several research gaps. They found that much of the existing literature lacks explicit normative evaluations of equity, meaning that equity concerns were often discussed without clear definitions or frameworks. Additionally, their review highlights the dominance of North American and European perspectives and the prevalence of utilitarian social welfare approaches in charging equity research. While

their study underscores the need for more specific and deliberate considerations of transportation equity and justice, it does not propose a concrete framework for assessing or addressing inequities in EV charging, thereby limiting its applicability for empirical evaluation.

Similarly, Israel et al. (2023) examined how electric mobility adoption mechanisms sustain inequalities and prevent a socially inclusive transition, focusing on factors such as purchase costs, charging accessibility, socio-demographic characteristics, and policies (Israel et al., 2023). They advocate for incorporating justice dimensions into the early stages of EV transitions to mitigate inequities. However, while their review engages with broad justice dimensions, including distributive, procedural, and recognition, it does not explicitly employ energy justice nor systematically associate specific metrics with justice-related concerns.

c a multi-dimensional equity metric system to assess the equity-related impacts of EV and public chargers deployment across socio-demographic groups. Their framework considers horizontal equity, involving a fair distribution of resources and external costs, and vertical equity, encompassing inclusivity and affordability. However, despite its strengths, the study does not explicitly engage with energy justice tenets. By focusing primarily on equity (and distributive justice both spatially and socioeconomically), it overlooks other justice dimensions that are critical for a more comprehensive assessment of justice in EV transitions.

In a recent state-of-the-art review, Gao et al. (2025) analyzed equity issues and opportunities in four emerging transportation technologies, including EVs. Their study aims to develop equity-based performance measures to ensure that these technologies are accessible and beneficial to all users. Specifically, for EVs, they propose various spatial and socioeconomic equity metrics, such as Moran's I statistics for spatial autocorrelation, accessibility levels per household based on proportional EV charging opportunities, and a deprivation index linking socioeconomic aspects to EVCS locations. Moran's I statistics are spatial analysis tools used to determine if the geographic pattern of data under evaluation shows statistically significant clustering, dispersion, or randomness (Mitchell & Griffin, 2005). While their study contributes valuable methodological insights, it does not incorporate the energy justice framework, leaving a gap in understanding how these metrics align with broader justice considerations.

Finally, Mandolakani and Singleton (2024) explored equity and justice theories in transportation and their relevance to the measurement of accessibility in EV charging infrastructure (EVCI). They examined how different justice theories, including those from economic and political philosophy, can be operationalized to assess accessibility disparities, offering a theoretical foundation for evaluating EVCI equity. However,

their work is focused on charging infrastructure and does not explicitly link indicators to the energy justice tenets.

3.2.2 Energy justice operationalization

Sovacool and Dworkin (2015) called for the development of metrics and indicators that could better measure energy justice and integrate these metrics into energy modeling and quantitative research efforts. In this regard, efforts to operationalize energy justice have been made in various studies. For example, Szulecki (2018) linked energy democracy to specific indicators by defining it along three dimensions: popular sovereignty, participatory governance, and civic ownership, as a means to facilitate comparisons and inform policy changes. However, while Szulecki's work provides valuable insights into the operationalization of energy democracy, it does not directly address the operationalization of energy justice tenets.

Another study by Bartiaux et al. (2018) examined the relationship between energy justice, energy poverty, and the capabilities approach in Belgium. Using quantitative analysis, the authors highlighted inequalities in access to affordable warmth and the broader social implications of these disparities. While their work focuses on energy poverty and capabilities, it does not extend to the operationalization of energy justice tenets themselves.

Building on both the capabilities approach and energy justice, Jodoin (2021) explored how developing countries like Guinea could move toward energy justice. This study proposed indicators linked to the Energy Sector Management Assistance Program (ESMAP) Multi-Tier Framework (MTF) to assess electricity access through seven attributes: capacity, service hours, reliability, quality, affordability, legality, and safety. While Jodoin's work provides useful indicators for assessing energy access from a capability and energy justice principles perspective (Sovacool et al., 2016), further research is necessary to operationalize energy justice for other technologies and cases.

Another contribution to energy justice operationalization is by Gladkykh et al. (2021), who aimed to construct socially sustainable energy system narratives focused on energy sufficiency and energy justice principles in the context of household electricity provision in Sub-Saharan Africa. In their study, energy justice was operationalized by translating its three core tenets (distributive, recognition, and procedural justice) into specific principles for evaluating energy provision technologies. These principles were used in a system dynamics model to assess different technologies for household electricity. However, while

this approach operationalizes energy justice, it does not propose concrete metrics or quantitative proxies for its tenets.

Also in relation to computation modeling, Sundaram et al. (2024) explored how justice considerations can be integrated into energy transition planning models. Their study emphasizes the complexity of a JET, involving diverse stakeholders with varying interests. They propose a conceptual framework that integrates the three tenets of energy justice into energy transition models, using guiding questions for modelers.

Despite the substantial contributions of these studies, there remains a significant gap in operationalizing energy justice tenets through quantitative proxies, particularly in relation to EVs, which this article seeks to address.

3.2.3 Flexibility justice

Flexibility justice focuses on the fairness of access to flexibility capital, which refers to the ability of energy users to adapt their behavior in response to the needs of the energy system (Powells & Fell, 2019). This capacity to adapt their behavior is shaped by socio-technical factors such as work schedules, household structure, technological access, and financial resources (Powells & Fell, 2019). Consequently, flexibility capital is unevenly distributed among socioeconomic groups. Powell and Fell (2019) emphasize that flexibility justice aims to ensure that the benefits of flexibility are equitably distributed and that less affluent users are not unfairly burdened by the need to adjust their energy consumption behaviors.

Heffron et al. (2021) highlighted that flexibility justice in solar energy ensures that all stakeholders, including households and energy storage facilities, can contribute to grid stability. This also relates to the creation of a marketplace where these actors can participate equitably through legal frameworks and economic incentives (Heffron et al., 2021). While discussions on flexibility justice in relation to energy technologies like EVs have started to be explored in previous studies ((Chen, Chen, & Tomasik, 2024; Chen, Chen, Tomasik, Pournaras, & Liu, 2024), which will be further discussed in **Section 3.4.3.3**), its connection with the energy justice tenets deserves further exploration. This study aims to contribute to this research gap by expanding its link with other tenets and exploring its operationalization in the context of EV technology.

3.3 Methods

3.3.1 Selection of relevant literature

A systematic process was employed to identify, select, and critically analyze existing literature on the operationalization of energy justice in EV research (Sovacool, Axsen, & Sorrell, 2018). A systematic search was conducted on Scopus, Science Direct, and Web of Science databases in January 2024, with an update in March 2025. Research, conference, or review papers were considered (i.e., books and book chapters excluded) without any criteria concerning the year of publication. An initial search targeted studies explicitly referencing "energy justice" and EVs. To broaden the coverage and mitigate potential normative bias, a second search incorporated the additional terms "justice," "equity," and "fairness", in titles, abstracts, and keywords. This query selection is supported by several factors, including (i) energy justice shares the same pillars (i.e., tenets) as earlier environmental and climate justice movements, (ii) fairness is often used interchangeably with justice, and (iii) equity concerns are mainly linked to distributive and recognition justice.

After removing duplicates, 575 abstracts were screened for agreement with the following criteria: (i) assessed battery electric vehicles (BEVs) or plug-in hybrid electric vehicles (PHEVs); (ii) focused on passenger cars or related charging infrastructure, excluding those solely addressing freight transport, e-scooters, or other modes; (iii) engaged with justice-related issues, discussing, e.g., fairness, affordability, accessibility, and equity in EV transitions.

These criteria yielded 169 studies for full-text review, of which 14 full texts were unavailable. During the full-text screening of the remainder 155 studies, those (i) treating fairness purely through mathematical or algorithmic optimization (e.g., Humfrey et al. (2019) focused on dynamic charging of EVs integrating RE, defining system fairness as the disparity in user experience based on the amount of charge received and the available battery capacity), (ii) lacking methodological clarity, and (iii) that did not contribute to the identification of metrics or indicators with the potential to represent energy justice tenets (e.g., Wood and Jain (2021) discussed social equity and affordability issues related to policies for PHEVs adoption but did not provide specific measurable indicators or aspects) were not included. The final selection comprised 60 studies, mainly quantitative studies, but also literature reviews and mixed-methods studies.

3.3.2 Analysis of selected studies

After collecting relevant studies, we systematically assessed their explicit conceptual framings, such as environmental justice, energy justice, social equity, spatial equity, energy equity, and transportation equity. These framings were identified inductively during the screening and reviewing processes, by coding the entire articles. Framings were non-exclusionary, meaning that one article could be framed by more than one concept. We then analyzed the metrics and indicators used or proposed in each study to evaluate quantitative dimensions within these framings.

Subsequently, the six tenets of energy justice (as outlined in **Table 3-1**) were applied as a conceptual lens to assess how each study quantitatively engaged with these dimensions in the context of EVs. This analysis considered sentences as the coding unit. Both explicit and inferred reference to energy justice tenets were considered based on the descriptions presented in **Table 3-1**, which presents the considered broad understanding of each energy justice tenet and its relevance to the case of EVs.

The coding process was performed by one researcher (first author). Borderline cases were discussed with co-authors. To ensure consistency, the coder periodically revisited previously coded data throughout the analysis period to ensure uniform application of the codes longitudinally.

Table 3-1. Conceptual lens: Energy justice tenets.

Tenet	Description	Application to the case of EVs
Distributive	Concerns the fair allocation of the costs and benefits of energy production and use across spatial, temporal and social dimensions (Sovacool, Martiskainen, et al., 2019).	Equity in EV access and adoption; distribution of environmental and economic burdens and benefits over the EV lifecycle.
Procedural	Emphasizes inclusive and transparent decision-making in energy governance, ensuring meaningful participation of all stakeholders (Heffron & McCauley, 2017; Sovacool et al., 2016).	Fairness in EV-related planning, policymaking, and the design of incentives and regulations.
Recognition	Advocates for the acknowledgment and respect of marginalized and vulnerable groups within energy transitions, ensuring their needs	Consideration of minority, indigenous, and low-income populations in EV adoption, accessibility, and policy design.

	and perspectives are not overlooked (Sovacool, Martiskainen, et al., 2019).	
Restorative	Calls for the remediation of historical and ongoing injustices caused by energy systems (Heffron & McCauley, 2017).	Compensation or mitigation measures for negative social and/or environmental impacts linked to EV deployment.
Cosmopolitan	Promotes a global and intergenerational perspective on energy justice, recognizing transboundary and long-term effects of energy decisions (Sokołowski & Heffron, 2022).	Globally produced or distributed externalities resulting from EV adoption, including embodied emissions and biophysical constraints.
Flexibility	Focuses on equitable access to flexibility in energy use (Powells & Fell, 2019), ensuring that less affluent users are not disproportionately burdened by energy system demands.	Distribution of flexibility capital in EV usage, including impacts of V2G, battery reuse, and grid responsiveness.

3.3.3 Limitations

The methodological approach employed in this study presents several limitations. First, the search strategy employed may have inadvertently excluded relevant literature. The choice of keywords, databases, and search parameters can limit the scope of the review. While efforts were made to use a comprehensive search strategy, it is possible that some pertinent studies were not identified. Second, while the strict inclusion and exclusion criteria implemented during the screening process aimed to mitigate potential biases, the possibility of reviewer bias cannot be entirely eliminated. Third, the process of linking energy justice tenets to quantitative proxies presents inherent challenges. It required not only the explicit verification of information within the included studies but also a degree of interpretation of their conceptual framings, methodological approaches, and stated implications. Specifically, the reviewers' understanding and interpretation of the included studies may have influenced the information extracted for the operationalization of energy justice tenets. This interpretive step introduces a degree of subjectivity and may affect the reproducibility of findings.

3.4 Results and discussion

3.4.1 Conceptual framing

The reviewed literature employed a range of conceptual framings to address equity and justice in EV adoption, exhibiting both distinct and overlapping characteristics. The main identified explicit framings are briefly summarized in **Table 3-2**. Particularly, the presented definitions are those mentioned by the reviewed papers.

Table 3-2. Conceptual framings and their definition.

Conceptual framing		**Definition**
Justice	*Environmental justice*	Environmental justice refers to the fair distribution of environmental burdens (Ji et al., 2015). While there are numerous definitions of environmental justice theory (Slattery et al., 2023), the most common understanding of environmental justice encompasses distributive, recognition, and procedural justice.
	Energy justice	Energy justice "*aims to provide all individuals across all areas with safe, affordable and sustainable energy*" (McCauley et al., 2013). Energy justice is mainly concerned with "*what are the unjust impacts associated with energy systems,*" "*where they are located,*" "*who is most affected,*" and "*how these injustices become embedded in procedures and mechanisms*" (Jenkins et al., 2016). It shares the same philosophical foundation of environmental and climate justice movements that began decades earlier c
	Transportation justice	Transportation justice refers to fair and equitable access to transportation systems, services, and infrastructures, as well as fair distribution of transportation-related burdens (Martens, 2016).
Equity	*Spatial equity*	Spatial equity revolves around the idea that all residents should be treated equally, regardless of location (Li et al., 2022). Derived from the broader principle of social equity (Li et al., 2022), it means ensuring that people have equitable access to essential services and facilities, such as EVCS.
	Energy equity	"*Energy equity is defined as the fair distribution of benefits and burdens of energy production, distribution, and consumption. This concept can be*

		applied as a lens to understand how distribution system benefits and burdens are distributed across different customer groups, allowing for targeted infrastructure investment decision-making that results in the equitable allocation of new technology solutions." (Bharati et al., 2023)
	Transportation equity	Transportation equity discusses how resources (e.g., access to transportation services and infrastructure) should be allocated among different populations (Carlton & Sultana, 2023).
	Horizontal and vertical equity	Horizontal equity ensures equal opportunities and resources among groups with similar needs and abilities (Delbosc & Currie, 2011). Vertical equity advocates for differential resource allocation based on varying societal needs and abilities (Halimi et al., 2025).

A quantitative assessment of the literature revealed that the most frequently utilized framings, in descending order, were equity (n=22), environmental justice (n=9), transportation equity (n=9), and energy justice (n=8), as shown in **Figure 3-1**. The following paragraphs will discuss the application of these framings in the reviewed EV literature.

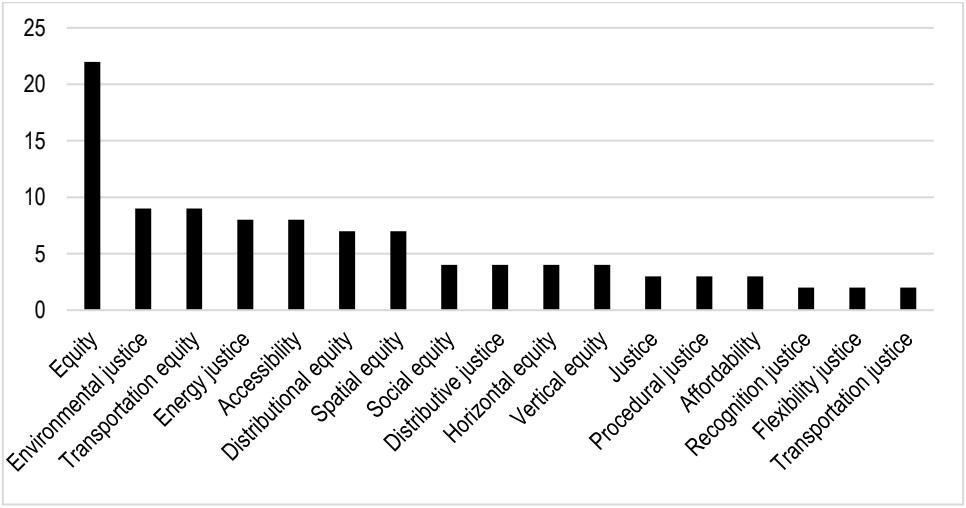


Figure 3-1. Distribution of conceptual framings across reviewed studies.

3.4.1.1 Environmental, transportation, and energy justice

Notably, while environmental justice is often considered a broad, "umbrella" paradigm, its operationalization within EV research was predominantly confined to the analysis of air pollutant

emissions (e.g., CO_2, NOx, PM2.5, and SO_2) (Bai et al., 2021; Chang et al., 2023; Ji et al., 2015; Ku et al., 2021; Mejía-Duwan et al., 2023; Peshin et al., 2024; Singh et al., 2024; Visa et al., 2023) and the assessment of population exposure to environmental risks (Ji et al., 2015). Studies within this framing examined the spatial redistribution of air pollution resulting from transport electrification, specifically the shift from vehicle tailpipe emissions (traffic-related emissions (Bai et al., 2021)) to power plant emissions (Bai et al., 2021), thereby potentially altering health risk distributions (Singh et al., 2024) across urban and rural areas (Ji et al., 2015) and sociodemographic groups (Mejía-Duwan et al., 2023). This can be explained by the direct link of pollution distribution to historical environmental justice struggles (Schlosberg & Collins, 2014). Furthermore, environmental justice studies frequently incorporated the concept of disadvantaged communities (DACs), employing definitions derived from tools such as CalEnviroScreen[1] (Canepa et al., 2019; Ku et al., 2021; Mejía-Duwan et al., 2023) and the EPA EJSCREEN[2] (Romero-Lankao et al., 2022), to evaluate the impacts on communities experiencing cumulative environmental and socioeconomic burdens. This is also linked to the movement's origins and its concerns among minority populations (Schlosberg & Collins, 2014).

Nevertheless, the implications of EV technology for transport and energy systems necessitate the application of more specific analytical lenses, such as transportation and energy justice. Transportation injustice is defined "*as a lack of transportation options or a lack of access to transportation that ultimately leads to a lack of opportunities and social exclusion*" (Canepa et al., 2019), which was comparatively less prevalent in the reviewed studies (Canepa et al., 2019; Jiao et al., 2024; Ku et al., 2021). This could be attributed to the fact that 'transportation justice' is a relatively newer and broader framework than environmental justice. Its comprehensive scope (accessibility, affordability, procedural, restorative, and recognition justice) may present challenges for quantitative operationalization, potentially leading researchers to focus on more readily quantifiable dimensions like equity in their quantitative analyses. Studies employing an energy justice framework (Bharati et al., 2023; Boucher & Mérida, 2022; Hennessy & Syal, 2023; Min et al., 2023; Vega-Perkins et al., 2023) were more frequent than transportation justice. This likely reflects the unique position of EVs operating at the intersection of electricity and transport systems. Additionally, the energy justice framework, often referenced by the tenets of distributive,

[1] CalEnviroScreen is a mapping tool designed to identify California communities disproportionately impacted by multiple pollution sources and characterized by heightened vulnerability to pollution effects. It generates census tract scores based on environmental, health, and socioeconomic data, enabling comparative analysis of pollution burden across the state. Higher scores indicate a greater pollution burden. Available at https://oehha.ca.gov/calenviroscreen/about-calenviroscreen

[2] EJSCREEN is an environmental justice mapping and screening tool that offers the U.S. Environmental Protection Agency (EPA) a standardized dataset and methodology for integrating environmental and demographic indicators. Available at https://19january2021snapshot.epa.gov/ejscreen/what-ejscreen_.html

procedural, recognition, and restorative justice, may be perceived as more analytical or practical (Iwińska et al., 2021) than transportation justice for addressing core issues. These tenet-related aspects will be further explored in **Section 3.4.3**.

3.4.1.2 Accessibility, affordability, and equity

A significant portion of the reviewed studies focused on accessibility and affordability, the latter being a principle of energy justice (Sovacool et al., 2016), but also a tool to operationalize equity and justice (Mandolakani & Singleton, 2024). Both concepts are particularly well-suited for quantitative analysis, since data on costs, income, and Geographic Information Systems (GIS) are often available. These studies examined equitable access to charging infrastructure (Carlton & Sultana, 2024; Gazmeh et al., 2024; Halimi et al., 2025; Peng et al., 2024), electricity affordability (Gesevičius et al., 2021), charging costs (Bai et al., 2021), and EV purchase costs (Stefaniec et al., 2025).

In addition, many studies were framed by broader equity concepts (Caulfield et al., 2022; Esmaili et al., 2024; Li et al., 2025; Williams, 2023) and specific applications such as transportation equity (Choi et al., 2024; Halimi et al., 2025; Jiao et al., 2024; Peng et al., 2024; Syal et al., 2024), spatial equity (Guo & Kontou, 2021; Li et al., 2022; Roy & Law, 2022), and horizontal and vertical equity (Halimi et al., 2025; Tsukiji et al., 2023). Equity, in this context, can be understood as the desired outcome of the application of justice frameworks, particularly concerning distributive dimensions. As stated by Ding and Wu (Ding & Wu, 2025), "*equity is a normative principle that assesses justice and leads to distributive outcomes* (Rawls, 1971)". Consequently, transportation, energy, and spatial equity represent specific applications of the broader equity concept to different domains, while still somehow linked to their underlying, more abstract ideas of justice (see Mandolakani and Singleton (2024) for a review of equity and justice theories employed in EVCS accessibility measurement). Many of the literature reviews presented in **Section 3.2.1** focus on equity and quantitative assessments in EV research. Readers are referred to these cited works (Carlton & Sultana, 2023; Gao et al., 2025; Mandolakani & Singleton, 2024; Tsukiji et al., 2023) for further information on the topic.

Nonetheless, while equity, affordability, and accessibility are useful and necessary in quantitative assessments of equity and justice in EV research, relying only on them provides an incomplete picture. Moreover, the conceptual frameworks of equity and justice are not mutually exclusive; they exhibit significant overlap and reinforcement, as evidenced by the numerous studies employing multiple frameworks (Ademulegun et al., 2025; Ding & Wu, 2025; Jha et al., 2025; Jiao et al., 2024; Syal et al.,

2024). Therefore, by operationalizing energy justice (**Section 3.4.3**), we aim to enrich the equity analysis by considering aspects of process, recognition, and history alongside distribution, moving beyond describing disparities to explaining and addressing the underlying injustices.

3.4.1.3 Normative uncertainties

Many reviewed studies employed 'equity' and 'justice' broadly, sometimes without providing clear operational definitions, which can lead to interpretive ambiguity when findings are simply described as 'equitable' or 'fair'. This reliance on implicit understanding is highlighted by Esmaili et al. (2024), who observed that the specific equity theories or standards guiding judgments on EV charging infrastructure distribution often must be inferred from study assumptions and conclusions. Sharma et al. (2023) similarly noted this deficit in explicit definition and operationalization within EV equity research. Furthermore, the relationship between equity and justice is sometimes blurred, with some studies using the terms interchangeably (e.g., (Alshahapy et al., 2025)).

Some studies attempt greater specificity by invoking established equity dimensions. These include distinctions between horizontal equity (equal treatment of similar needs (Delbosc & Currie, 2011), **Table 3-2**) and vertical equity (different treatment based on varying needs (Halimi et al., 2025), **Table 3-2**). Others explicitly differentiated equity from equality, such as Lee et al. (2025), who defined equality as "*treating everyone equally – for example, equal/even distribution of EVs or charging stations (e.g., per capita)*," while equity involves "*acknowledging different needs/challenges that different people or communities may have and addressing them, which may require treating people differently according to their needs/challenges* (Lee et al., 2024)."

However, these distinctions highlight the complexity inherent in equity and justice assessments, which necessitate clearly defining the relevant societal needs or challenges being addressed. The observed lack of conceptual clarity and definitional consistency across studies contributes to normative uncertainty, a finding consistent with critiques in the broader energy justice literature (Van Uffelen et al., 2024). Such ambiguity carries implications, potentially hindering the interpretation of findings and limiting the formulation of targeted policy recommendations. Addressing this requires explicit articulation of working understanding of 'equitable' and 'just' outcomes, including the intended beneficiaries, the spatial and social context, and the comparative benchmarks. The identified diversity in conceptual approaches and critical points regarding definitions provide a foundation for the subsequent analysis of methods, proposed proxies, and energy justice tenets.

3.4.2 Methodological approaches

3.4.2.1 Focus on distributive aspects

Most quantitative studies have emphasized distributional aspects of the EV transition, quantifying the allocation of benefits (e.g., rebates, improved air quality, infrastructure access) and the distribution of burdens (e.g., costs, pollution, inconvenience). This emphasis is consistent with the prevalence of 'equity' as a conceptual framing, and it is partly attributable to data availability and the relative ease of quantifying distributional outcomes, often using well-established metrics such as Gini coefficients (Cai et al., 2024; Guo & Kontou, 2021; Heymann et al., 2019), disparity ratios, and statistical correlations. However, an over-reliance on distributional metrics may obscure underlying inequities rooted in unfair processes or a lack of recognition. This limitation can lead to policies that address the symptoms of inequity rather than its root causes, potentially reinforcing existing power structures and marginalization.

A subset of distributional studies focused on the geographical dimension, employing spatial analysis techniques and methods such as global and local Moran's I (Choi et al., 2024; Esmaili et al., 2024; Jha et al., 2025; Min & Lee, 2020; Min et al., 2023; Roy & Law, 2022), clustering algorithms (Carlton & Sultana, 2022; Romero-Lankao et al., 2022), and location-allocation models (Jha et al., 2025) to identify and quantify spatial disparities in EV adoption and access to EVCI. These methods inherently involve assumptions about spatial relationships and the definition of accessibility. Accessibility measures, for instance, can be classified into four broad categories: gravity-based, opportunity-based, utility-based, and space-time measures (please refer to Li et al (2022) for a detailed description and applications).

Other research developed neighborhood typologies (e.g., micro-urban social typologies – MUSTs (Romero-Lankao et al., 2022), micro-urban typologies (Ding & Wu, 2025)) to analyze the context-specific manifestation of equity issues across urban environments, based on the interplay of sociodemographic, economic, techno-infrastructural, environmental, and governance factors (Romero-Lankao et al., 2022). This classification of regions according to several criteria, including air pollution and health risks exposure, is also found in the differentiation of DAC/non-DAC by the CalEnviroScreen and EJSCREEN tools. Nonetheless, the construction of these typologies relies on choices regarding which socioeconomic and demographic variables to include and how to weigh and classify them (i.e., thresholds).

In addition to spatial analysis and accessibility of EVs and related infrastructure, studies also focused on socioeconomic and demographic disparities among populations (Boucher & Mérida, 2022; Ku et al., 2021). Factors such as median household income, poverty levels, home and vehicle ownership,

employment and education levels, race/ethnicity, age, household size, household structure, and disability status, were often considered in statistical analysis aimed at assessing how these different characteristics influence EV adoption (Canepa et al., 2019; Heymann et al., 2019; Min & Lee, 2020; Romero-Lankao et al., 2022), access to rebates and subsidies (Caulfield et al., 2022; Liu et al., 2022; Williams, 2023), and charging infrastructure accessibility (Khan et al., 2022). Other methodological choices related to distributional aspects encountered in the reviewed literature include agent-based modeling (Lee & Brown, 2021), technology diffusion models (Heymann et al., 2019), probabilistic modeling (Gesevičius et al., 2021), and regression modeling (Ji et al., 2015; Min & Lee, 2020).

3.4.2.2 Multiple scales of justice

The multi-scalar nature of justice necessitates careful consideration of the scale of analysis, as the choice of scale shapes the indicators and conclusions. For instance, equity was often analyzed at the household or census tract level (Steinbach & Blaschke, 2024); however, injustices observed at one scale may be obscured or contradicted at another. For example, studies examining pollutant transfer (Bai et al., 2021; Chang et al., 2023; Ji et al., 2015; Ku et al., 2021; Mejía-Duwan et al., 2023; Peshin et al., 2024; Singh et al., 2024; Visa et al., 2023) explicitly demonstrate how local benefits (e.g., reduced urban air pollution) can generate burdens elsewhere (e.g., increased power plant emissions in rural areas), underscoring the importance of multi-scalar analysis. This point is further emphasized by the "whole systems" approach (Sovacool, Hook, et al., 2019), in which injustices extend beyond the geographic location of the transition, across its lifecycle. Policies formulated based on single-scale analyses may inadvertently produce adverse consequences at other scales (e.g., local EV promotion increasing pollution in power plant-hosting communities), reflecting a prioritization of local over regional or global equity.

Similarly, the temporal dimension of technological decisions warrants attention. Most studies evaluate equity at a specific time (a snapshot) or based on historical data, limiting the scope of indicators to static distribution measures. Fewer studies attempt to predict future equity outcomes (Roy & Law, 2022) or model the dynamic evolution of equity over time (Heymann et al., 2019; Lee & Brown, 2021). Consequently, static analyses may fail to capture the dynamic nature of equity challenges in a rapidly transitioning sector, potentially leading to indicators that underestimate long-term inequities. Nevertheless, proactive, rather than reactive, policy formulation is not necessarily straightforward in equity and justice research. In the case of EVs, this is due to several factors such as the high level of uncertainty in technological development, adoption, geopolitical and economic landscapes. Furthermore, future evaluations of this nature would related to the evolving nature of societal values and moral intuitions,

which may change the understanding of what is fair or equitable as time passes and society evolves (Van Uffelen et al., 2024). However, underscored by intergenerational equity (Sovacool et al., 2016), there is an ethical responsibility to consider future generations and what they will be deprived of due to our past and current actions.

3.4.2.3 Considerations on methodological diversity

This methodological diversity, while enabling context-specific analysis, complicates direct comparisons and synthesis across studies. Crucially, as highlighted by the variability of metrics, policies deemed "equitable" under one metric (e.g., spatial access, operationalized using a specific accessibility index (Loni & Asadi, 2023)) may be deemed inequitable under alternative metrics (e.g., affordability, measured as transportation energy burden (Vega-Perkins et al., 2023)). This underscores that indicators are not neutral representations of reality but are contingent on underlying methodological assumptions and normative commitments.

This observation relates to two critical aspects. First, the trade-offs and synergies that can emerge from different policies and/or technological decisions necessitate carefully considering how to capture these interdependencies and potential value conflicts. This means that not only can one decision enhance, for instance, EVCS accessibility in one region while harming the affordability of charging, but also that the understanding of what is equitable and just is likely to vary among stakeholders. In other words, perceptions of injustice may vary significantly across social groups, underscoring the complexity of energy conflicts (Wood et al., 2024). Second, the definition of the "problem" under investigation significantly influences analytical and methodological choices, shaping the selection and interpretation of indicators, but also the implications of the research.

Moreover, there is the importance of selecting an appropriate baseline for comparison. For example, Williams (2023) argues that new-car buyers, rather than the general population, constitute a more relevant benchmark for assessing the equity of new EV incentives. Likewise, assessing accessibility through distance-based metrics (Jiao et al., 2024), travel time (Carlton & Sultana, 2024), the number of chargers (Peng et al., 2024), or the convenience of charging (Rabinowitz et al., 2023) will significantly affect EVCI expansion planning. Consequently, variations in benchmarks can yield substantially different conclusions and policy interventions related to equity or justice in fleet electrification.

While this review was focused on quantitative approaches, it is important to note that qualitative approaches provide rich contextual understanding, explore lived experiences, and delve into less tangible

dimensions of justice (e.g., mobility justice, procedural justice) within EV research. They provide crucial depth and insight into the underlying drivers of disparities, highlighting the ethical importance of centering marginalized voices. In this sense, mixed-method approaches, notably a minority in the reviewed literature (Syal et al., 2024), offer the potential for a more holistic and ethically informed understanding of EV transitions.

3.4.3 Linking energy justice tenets to quantitative proxies

3.4.3.1 Distributive and cosmopolitan justice

As previously stated, a significant portion of the reviewed studies focused on distributive aspects of EV adoption, specifically concerning the distribution of benefits and burdens related to rebates, technology adoption, charging infrastructure, and pollution exposure. These distributions were analyzed across spatial units (e.g., census tracts, urban/rural areas), socioeconomic strata (e.g., income quintiles), disadvantaged community classifications (i.e., DACs and non-DACs), and demographic groups (e.g., age, race). **Table 3-3** summarizes the key questions associated with distributive justice, relevant quantitative proxies identified in literature, and their limitations. While these metrics capture important dimensions of distributive justice, they necessitate further clarification regarding the definition of a just distribution, the target beneficiaries, and the appropriate comparative benchmark.

Cosmopolitan justice, while not explicitly addressed in any reviewed studies, offers a crucial lens for considering the global implications of EV transitions. We propose that this tenet can be operationalized by examining issues that transcend national borders, such as the global impacts of raw material extraction for battery production. Relevant metrics in EV research could include quantifying raw material flows (e.g., tons of lithium extracted, cobalt mined for EV battery production) and assessing their impact on intergenerational equity, acknowledging that planetary boundaries and biophysical constraints affect all global citizens (e.g., climate change, resource depletion). However, acting on the operationalization of cosmopolitan justice presents substantial challenges, particularly due to the complexities of international governance that often hinder effective action at the global level.

Table 3-3. Operationalization efforts of distributive and cosmopolitan justice.

Tenet	Related questions	Quantitative proxies	Limitations
Distributive justice	- *Who owns EVs? Who receives EV subsidies/rebates/tax credits?* - *Who has access to EVCS?* - *How are benefits/burdens distributed (spatially, socioeconomically, demographically)?*	- Distribution and probability of EV ownership (Boucher & Mérida, 2022; Canepa et al., 2019; Min & Mayfield, 2023; Romero-Lankao et al., 2022); - Distributions of air pollutant emissions, inhalations, and related health costs attributable to EV use (Bai et al., 2021; Chang et al., 2023; Ji et al., 2015); - Accessibility to EVCS (e.g., EVCS density, proximity to charging stations) (Canepa et al., 2019; Carlton & Sultana, 2022, 2024; Loni & Asadi, 2023; Peng et al., 2024; Roy & Law, 2022); - Spatial distribution of household EV charging locations and correlation with income and deprivation index values (Caulfield et al., 2022); - Affordability of EVs (purchase price, charging costs) (Ding & Wu, 2025; Stefaniec et al., 2025; Zhang & Fan, 2025);	- Different definitions of accessibility (opportunity-based, time-based, etc.) and equity (Halimi et al., 2025; Tsukiji et al., 2023); - Limitations of access metrics (e.g., neglecting service quality, travel time variability) (Mandolakani & Singleton, 2024); - Risk of obscuring the causes of distributional disparities (Boucher & Mérida, 2022); - Risk of biases in results due to the scale/aggregation level considered (e.g., region vs. neighborhood);
Cosmopolitan justice	- *What are the impacts of EV adoption on global biophysical elements and environmental conservation?* - *What are the impacts of EV rollout on human rights?*	- Raw material extraction (e.g., tons of lithium extracted, land area deforested) and waste generation; - Global pollutant transport (e.g., transboundary air pollution); - Supply chain labor practices (e.g., prevalence of child labor (Sovacool, Hook et al., 2020), worker wages); - Life-cycle GHG emissions;	- Challenges in quantifying global impacts; - Methodological difficulties in tracing supply chains and assigning responsibility for environmental harm; - Lack of comprehensive data on global labor practices; - Influence of geopolitical factors;

3.4.3.2 Procedural, recognition and restorative justice

Procedural, recognition, and restorative justice are considered together in this section due to their less quantifiable nature. Procedural justice, concerned with fairness in energy-related decision-making processes, encompasses dimensions such as transparency, inclusivity, stakeholder engagement, and access to information (Heffron & McCauley, 2017; Sovacool et al., 2016). While difficult to fully quantify, we contend that proxies for procedural justice could include measures of public participation in transport planning (e.g., number of public hearings held, diversity of attendees), representation of marginalized communities on advisory boards (e.g., percentage of board members from DACs), and accessibility of information regarding EV policies and infrastructure deployment (e.g., availability of information in multiple languages, ease of accessing data portals). However, the inherent challenges in objectively measuring fairness and representation underscore the need for qualitative and mixed-methods approaches to supplement quantitative assessments, as explicitly addressed by Syal et al. (2024) in their work addressing inclusive community engagement for transport planning.

Recognition justice entails acknowledging and respecting the diverse identities, needs, values, and knowledge of different groups (Sovacool, Martiskainen, et al., 2019) affected by EV transitions. While direct quantification of recognition is challenging, certain methodological strategies can support it. The first strategy is disaggregating data by relevant social groups, as performed by many studies, e.g., (Bharati et al., 2023; Esmaili et al., 2024; Hennessy & Syal, 2023). Analyzing metrics separately for groups defined by race/ethnicity, income level, geographic location, and other relevant categories explicitly recognizes that these groups may experience distinct impacts. Only one of the reviewed studies explicitly mentioned the joint operationalization of distributive and recognition justice, Min et al. (2023) stated they "*investigated the level of* DER [distributed energy resources, specifically solar photovoltaics (PV) and EVs] *adoption in light of distributional and recognition justice by grouping spatially defined communities that share similar sociodemographic characteristics*." These metrics, however, do not diminish the necessity of utilizing qualitative methods to document and incorporate perspectives from different communities. This is intrinsically related to epistemic justice, which concerns the right for all communities (e.g., Indigenous communities (Maddox & Ninomiya, 2025)) to exercise self-determination. Epistemic injustice occurs when knowledge production is centralized, excluding and subjugating communities with different knowledge (Maddox & Ninomiya, 2025). It makes us question *how do we know what we believe we know* (Munro et al., 2017). Methodologies must highlight marginalized communities' needs and incorporate their knowledge, perspectives, and contributions.

Restorative justice addresses past and present injustices, aiming to repair harm and compensate affected communities (Heffron & McCauley, 2017). Although also difficult to quantify, we suggest considering metrics that assess the impact of historical injustices or the effectiveness of mitigation measures. Few studies (Hennessy & Syal, 2023; Ku et al., 2021) have explicitly operationalized restorative justice in their methodology. Hennessy and Syal (2023) explored the connection between present-day disparities in access to clean transportation and disinvestment in redlined neighborhoods in California's transition to zero emission vehicles, as a means to pursuing restorative justice. Ku et al. (2021) also point out restorative equity as key to repairing the harm inflicted upon DACs, such as Black, Indigenous, and People of Color (BIPOC) communities in California, as by making clean private vehicles accessible, it is possible to increase job accessibility to these communities and reduce their exposure to environmental pollution. Nonetheless, it is important to note that quantifying the complex and often intergenerational impacts of historical injustices presents significant methodological and ethical challenges.

Table 3-4. Operationalization efforts of procedural, recognition, and restorative justice.

Tenet	Related questions	Quantitative proxies	Limitations
Procedural Justice	- *Who is involved in decisions related to EVs (ICEV bans, mobility options, subsidies, infrastructure, cost)?* - *How are these decisions made?*	- Measures of public participation in transport and EV planning* (e.g., number of public hearings held, diversity of attendees); - Representation of marginalized groups on committees/advisory boards (e.g., share of participation of BIPOC (Syal et al., 2024)); - Accessibility of information regarding EV policies and infrastructure deployment (e.g., availability of information in multiple languages, ease of accessing data portals);	- Risk of tokenism in participation efforts; - Lack of comprehensive data on decision-making processes; - Assumption of fair and objective decision-making processes;
Recognition Justice	- *Whose needs and values are acknowledged in the EV transition?* - *How are they acknowledged?*	- Recognition of DAC and non-DAC (Bharati et al., 2023; Canepa et al., 2019; Guo & Kontou, 2021; Ji et al., 2015; Tsukiji et al., 2023); - Disaggregation of data by race, ethnicity, income, location, etc. (Boucher & Mérida, 2022; Canepa et al.,	- Risk of epistemic injustice in the assumption of interests and values of different groups**; - Difficulty of measuring the effectiveness of recognition efforts;

		2019; Caulfield et al., 2022; Hennessy & Syal, 2023; Ji et al., 2015; Khan et al., 2022; H. Liu et al., 2022; Min et al., 2023; Min & Mayfield, 2023; Peng et al., 2024; Romero-Lankao et al., 2022; Roy & Law, 2022; Williams, 2023);	- Challenge of effectively incorporating diverse perspectives;
Restorative Justice	- *How are past and present injustices (e.g., areas with historical low development and investment) addressed?* - *How are harms repaired?*	- Quantitative analysis of the correlation between historical injustices (e.g., redlining (Hennessy & Syal, 2023)) and current EV/EVCS/subsidies disparities; - Measurement of the effectiveness of remediation policies (e.g., subsidies, rebates, etc. (Guo & Kontou, 2021; Hennessy & Syal, 2023; H. Liu et al., 2022; Williams, 2023));	- Difficulties in establishing direct causality between past injustices and current outcomes; - Challenges in addressing systemic and ongoing injustices, and the long-time scales needed for both harm realization and reparative actions; - Difficulty of agreeing on measures of reparations.

*See Szulecki (2018) for indicators on participatory governance in energy democracy. **Importance of qualitative research to understand diverse perspectives, incorporation of Indigenous knowledge and epistemologies, and participatory research methodologies that empower affected communities in the research process.

3.4.3.3 Flexibility justice

As defined in **Section 3.2.3**, flexibility justice in energy systems concerns the equitable distribution of flexibility capital (Powells & Fell, 2019). It highlights disparities in access to technologies and programs that enable demand-side flexibility, such as decentralized home energy management systems (HEMS) and EVs, emphasizing the need for inclusive policies to address these inequities. In the reviewed literature, flexibility justice was explicitly addressed in two works by Chen, Chen and Tomasik (2024) and Chen, Chen, Tomasik et al. (2024). Chen, Chen and Tomasik (2024)investigated the influence of socio-demographic factors on the adoption of decentralized HEMS and their impact on demand flexibility, focusing on air conditioning (AC) and EV charging. Chen, Chen, Tomasik et al. (2024) examined the influence of factors such as charging anxiety, environmental concern, cost-saving perception, perceived privacy, and trust in utility providers on EV charging behaviors, particularly time-shifting and load-reduction. They also examined disparities in these behaviors across different demographics (income, race, homeownership). Both studies reported that households with lower incomes demonstrated reduced

flexibility (i.e., respondents' willingness to delay (and reduce) energy consumption, such as EV charging or AC usage, to off-peak hours) in adjusting their energy consumption behavior.

Nonetheless, several other reviewed studies implicitly touched upon factors influencing demand flexibility in relation to EVs. These included considerations of equitable participation in smart grid systems and the experience of discomfort and fairness in EV charging optimization (Pournaras et al., 2019), the role of demand-side management programs in mitigating increases in retail electricity prices (Gesevičius et al., 2021), the impact of adaptive tariff policies and proximity to renewable energy sources (RES) on equitable energy distribution (Jayapalan et al., 2022), inequities in the operational convenience of EVs, particularly concerning the availability of home and work charging options (Rabinowitz et al., 2023), and power resilience inequities (Ebbrecht & Chen, 2023).

These studies collectively suggest that vulnerable populations, including low-income households and home renters, face barriers to adopting flexibility-enabling technologies like EVs. Furthermore, they indicate that these populations are disproportionately burdened by the broader adoption of EVs, experiencing diminished grid resilience and increased electricity prices, which are compounded by their limited capacity to modify their energy consumption behaviors. **Table 3-5** summarizes operationalization efforts in relation to flexibility justice.

It is also pertinent to consider the conceptual positioning of flexibility justice withing the energy justice framework. While tenets define the broad categories of justice (the "what"), principles articulate the specific rules or guidelines within those categories (the "how"), they provide "*an inherent normative recommendation regarding how to perceive of justice*" (Van Uffelen et al., 2024). In this regard, it can be argued that flexibility justice operates more as a principle guiding the implementation of distributive, procedural and recognition justice in energy systems (by recognizing the uneven distribution of flexibility capital among different groups and the process by which flexibility programs are developed), rather than a distinct tenet. However, this is a developing area from technological and legal standpoints, with emerging concerns such as data privacy and control in smart grid systems, influencing how demand flexibility and flexibility justice may evolve.

Table 3-5. Operationalization efforts of flexibility justice.

Tenet	Related questions	Quantitative proxies	Limitations

Flexibility justice	- *Who has access to the technologies and programs that enable demand flexibility?* - *Who benefits from the services that demand flexibility provides?* - *Who bears the burdens or costs of providing flexibility?*	- By socioeconomic, sociodemographic, or vulnerable groups: - Access to flexibility: adoption of flexibility-provider technologies (EVs, V2G) (Chen, Chen, & Tomasik, 2024); - Participation in demand-response programs (Chen, Chen, Tomasik, et al., 2024); - Metrics quantifying inconvenience or discomfort (e.g., deviation from preferred schedules) (Rabinowitz et al., 2023); - Power resilience inequity metric, function of power outage frequency and average recovery time (Ebbrecht & Chen, 2023); - Monetary costs/benefits of adjusting energy use (e.g., costs of alternative behavior, savings on electricity bills due to program participation) (Gesevičius et al., 2021)	- Potential for obscuring root causes of disparities in flexibility capital (e.g., social inequalities, capitalism); - Uncertainty in relation to technological development (V2G, smart grids) and related legal and privacy concerns;

3.5 Conclusion

This study has reviewed sixty peer-reviewed works on quantitative assessments of justice and equity in EV research. As discussed in **Section 3.4.1**, the most frequently employed conceptual framing was equity, followed by environmental justice, transportation equity, and energy justice. Other explicit framings include spatial equity, energy equity, transportation justice, and horizontal/vertical equity. However, reflecting the findings of Sharma et al. (2023) on energy equity, few studies explicitly defined justice when referring to it. This highlights a research gap: studies addressing justice or equity would benefit from greater normative clarity. In particular, there is a need to avoid ambiguous or vague references to equity or justice, especially when these terms are selected by authors as defining keywords.

Regarding methods (**Section 3.4.2**), most works focused on statistical and spatial analysis to provide quantitative evidence of distributional injustices by assessing the socioeconomic and spatial distribution of burdens and benefits associated with EV operation or the distribution of subsidies for EV purchase and EVCS installations. In these same analyses, the statistical differentiation or spatial clustering of DAC/non-

DACs, minority, and vulnerable populations is a way to operationalize recognition-based justice by identifying these groups have different needs and limitations. Nonetheless, mixed-methods approaches were a minority in the reviewed literature. This may reinforce risks of oversimplification, epistemic injustice, and biases in quantitative assessments of justice and equity in EV research.

Relating to metrics, the studies encompass a broad spectrum of indicators, ranging from emissions and charging accessibility to differentiation between income levels, race-ethnicity, and household characteristics. However, these metrics are not neutral from an ethical stance; they often reflect underlying (often unstated) assumptions of what is considered equitable or just. It is also important to bear in mind that indicators and quantitative approaches, although important in guiding decision-making and highlighting policy failures, should not be conclusive in isolation, but rather seen as a complement to an interpretative plurality that lies in energy transition conflicts. The fact that scholars can provide quantitative evidence of disparities does not change the fact that justice remains a non-quantitative concept subject to different and multiple definitions.

Based on the reviewed literature, this work also synthesized quantitative proxies to operationalize energy justice tenets in relation to EV technology and its potential limitations (**Section 3.4.3**). It is expected that the proposed operationalization advances the literature on energy justice by supporting its empirical applicability but also by emphasizing the need for situating indicators in a broader contextual perspective. In the case of EVs, mobility justice scholarship offers critical lenses for evaluating the promotion and deployment of EVs (Haas, 2022; Henderson, 2020). It compels a rich contextual examination beyond surface benefits to scrutinize the underlying drivers of EV support, questioning the influence of corporate interests (e.g., automakers) versus broader societal objectives. Furthermore, it foregrounds distributive, procedural, and recognition justice, demanding inquiry of how decisions are made, who benefits, and whose interests (ranging from industry workers (Silva et al., 2023) to marginalized communities (Syal et al., 2024)) are represented and prioritized in decision making. Likewise, a whole-systems approach (Sovacool, Hook, et al., 2019) expands the scope of analysis to include impacts across the full EV lifecycle and multiple spatial and temporal scales. Such inquiries into the context of technological decisions and systemic scope are critical to assess EVs and other low-carbon technologies.

These aspects delineate a future research agenda. First, it is recommended that studies addressing energy justice and related concepts, such as equity, provide explicit definitions. Van Uffelen et al. (2024) have outlined pertinent guidelines for this purpose, including the epistemological assumptions underlying conclusions or policy recommendations concerning justice, the spatial and temporal dimensions

considered, and the relevant stakeholders. This clarity is particularly critical when attempting to operationalize the concept. Second, assuming adherence to such practices in defining and understanding energy justice issues, it is anticipated that there will be increased methodological diversification in the field. This may encompass the development of decision-making tools that take into account the socioeconomic impacts and ethical implications of an accelerated EV deployment. Third, the analytical logic presented in this study to operationalize energy justice tenets in relation to EVs offers a transferable structure to other low-carbon technologies, including solar PVs and onshore wind power. Overall, this review advances the understanding of energy justice within the context of EV research and offers guidance on how researchers might operationalize this complex issue.

4 Integrating social aspects into system dynamics models

This chapter is based on the article titled "*A review of social aspects integration in system dynamics energy systems models*" which has been published in the *International Journal of Sustainable Energy Planning and Management*. The content presented here reflects the key findings and discussions of the original article, with some adaptations to fit the overall structure of this thesis.

A review of social aspects integration in system dynamics energy systems models

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Abstract: The problem of techno-economic approaches to evaluating energy transition pathways has been constantly reported in the literature, while existing research recognizes the critical role played by social aspects in energy systems models. System dynamics has been pointed out among modeling techniques as a suitable tool to evaluate the interdisciplinary nature of energy transitions. This paper explores how energy system-related system dynamics models have incorporated social aspects through a literature review. Models were assessed based on their geographical resolution, time horizon, methodological approach, and main themes: supply-demand, energy-economy-environment (3E), energy-transport, WEF nexus, and consumer-centric and socio-political dynamics. Social aspects considered include behavior and lifestyle changes, social acceptance, willingness to participate, socioeconomic measures, among others. As expected, the representation of social aspects was not standard among the papers analyzed. Socioeconomic aspects were most commonly included in supply-demand and 3E models. Energy-transport and WEF models mainly incorporated changes in travel and consumption habits, respectively. The last theme had a more diverse approach to social aspects that deserves further attention, especially for energy access and justice issues. Other research lines include modeling

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approaches combination, enhanced participatory and transparent processes during model development, and use of SD models in policy-aiding and stakeholders' information processes.

4.1 Introduction

Considering the urgent need to reduce CO_2 emissions and achieve a net-zero economy, consumption patterns, energy technologies and manufacturing processes must change toward sustainable practices. As energy systems are at the core of the global economy, producing energy from low-emission sources, consuming it more efficiently, and lowering demand are key aspects of a successful transition. Nevertheless, the complexity of energy systems has required quantitative modeling techniques to support decision-makers in the challenging task of developing short and long-term transition pathways. Thanks to computational capabilities, the number of energy system models (ESMs) and the complexity captured by them has increased significantly over the last decades (Prina, Manzolini, Moser, Nastasi, & Sparber, 2020). Likewise, review works of ESMs have assessed and categorized developed models while aiding modelers and decision-makers in selecting appropriate tools.

One of the most common classifications separates models into bottom-up and top-down models. Bottom-up or engineering models stress the technical characteristics of energy systems, whereas top-down approaches focus on price and market influences (Spittler et al., 2019). Models can also be classified according to their modeling technique (Spittler et al., 2019), spatial (regional, national, and global) and time dimension (short, medium, and long-term) (Bhattacharyya & Timilsina, 2010). They also have different purposes (e.g., forecasting, exploring, or back casting) and require or include combinations of quantitative, qualitative, disaggregated, or aggregated data elements (Nakata et al., 2011). Another category of models that has become popular to inform large-scale and global climate mitigation pathways (Nilsson et al., 2020) is the Integrated Assessment Models (IAMs). IAMs have been used in the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2008) and European Commission's (2012) assessments and include a wider set of modules than energy systems models alone, such as land use, agriculture, energy, industry, forestry, and climate modules (Blanco et al., 2019).

Regarding underlying methodology, Lopion et al. (2018) differentiated ESMs in optimization, simulation, and hybrid models. Optimization models refer to all linear, mixed-linear and non-linear programming, and equilibrium models solved to optimality (e.g. (Osorio-Aravena et al., 2020; Prina et al., 2020)). On the other hand, simulation models consist of dynamic and stochastic approaches that do not seek optimality

(Lopion et al., 2018) but are concerned with representing overall systems structure and generating insights from policy scenario analysis. On the differences between simulation and optimization archetypes, Lund et al. (2017) compared the two approaches in technical, decision-making, and political terms. The authors argued that optimization models are well-suited for forecasting and prescribing the optimal future, whereas simulation models are fit for back casting and debating the desired future. Hybrid models combine optimization and simulation methodologies. Some works also classify as "hybrid" those models that integrate bottom-up and top-down models (Prina et al., 2020) or use more than one modeling technique (e.g., macro-economic modeling, general economic equilibrium, linear optimization, partial equilibrium, and system dynamics) (Spittler et al., 2019).

Concerning previous review studies, Prina et al. (2020) reviewed bottom-up ESMs and classified them as short-term or long-term models, while Kotzur et al. (2021) and Ridha et al. (2020) reviewed ESMs in terms of their complexity. Ringkjøb et al. (2018) reviewed and classified modeling tools for energy systems with a large share of RES. Connolly et al. (2010) considered 68 and further analyzed 37 computer tools used to evaluate the integration of RES into energy systems. Later, the same methodology was employed in Chang et al. (2021), who surveyed similar review studies and 54 ESMs, including models' application aspects. Alternatively, Fodstad et al. (2022) took a different approach as it reviewed modeling frameworks according to the main challenges faced by ESMs, namely, (i) the handling of several energy carriers, (ii) the integration of different time and spatial scales, (iii) uncertainty, and (iv) the integration of energy transition dynamics.

Also, Fattahi et al. (2020) analyzed nineteen IAMs used at national levels and unfolded an interesting discussion on current and future low-carbon energy system modeling challenges and how to address them. Moreover, this last work also recognized how social aspects are commonly neglected in ESMs, given their predominant techno-economic nature (Fattahi et al., 2020). The latter aspect was also highlighted by Süsser et al (2022) who argued for the relevance of integrating social and environmental factors into energy models. The authors showed how ignoring these aspects could lead to misleading policy recommendations in terms of the speed of the energy transition and technological options.

Particularly, system dynamics is a simulation-based modeling technique that has been successfully used for energy system modeling (Bolwig et al., 2019) since the seminal works of Sterman (1981) and Fiddaman (1997). In contrast with linear models, system dynamics captures the complex dynamics of energy systems through feedback loops and endogenously models system behaviors commonly absent from other modeling techniques (Spittler et al., 2019). System dynamics modeling can account for market

failures, delays in feedback loops, the absence of complete information and deal with several uncertainties present in energy systems, such as human behavior and perceptions (Mutingi et al., 2017). Reddi et al. (2013) reviewed system dynamics models targeting RES and combined heat and power generation. Leopold (2016) extensively reviewed energy-related system dynamics models from 2000 to 2015 in terms of their general purpose, time horizon, regional frame, and main conclusion. The author underscored that system dynamics models have been applied to diverse situations within the energy sector, but gaps in transformation processes and transition research through consumer-centric perspectives remained (Leopold, 2016).

Nonetheless, Papachristos (2019) emphasized the potentiality of system dynamics simulations for the study of socio-technical energy transitions (STET) as a way to catalyze learning and decision making in complex systems. Also, Li et al. (2015), when reviewing STET models, stated that, even though agent-based models (ABMs) are the most employed when it comes to incorporating the heterogeneity of actors, dynamics simulation approaches seem to be as successful as ABMs in representing key characteristics of socio-technical systems. Additionally, Bolwig et al. (2019) stressed the potential of system dynamics to "*capture the co-evolution of economic, policy, technology, and behavioral factors over sufficiently long periods, which is necessary for the analysis of transition pathway dynamics*". The authors also presented how system dynamics models integrate sustainable transition concepts, such as strategic niche management (SNM) (Schot & Geels, 2008), learning effects, consumer behavior and values (Bolwig et al., 2019).

A broad number of frameworks and theories have been used to conceptualize the social processes behind the energy transition, such as MLP, Technological Innovation Systems (TIS), SNM, and Transition Management (TM), with some of these frameworks being well represented in system dynamics models (Martin et al., 2020). Moreover, recent debates on JETs and energy justice have shed light on the preoccupation of how to transition to a low-carbon system without reinforcing current socioeconomic inequalities but rather diminishing them. This leads to the question of how to incorporate social aspects and metrics into quantitative ESMs appropriately, which has contributed to the development of frameworks and indicators within a trend towards further incorporation of social sciences into energy analysis (Süsser et al., 2022). Even though this is not a new problematic, as social metrics have been a source of discussion since the rise of sustainability and welfare concepts, it is still subject to improvement. Krumm et al. (2022), for instance, reviewed how different types of energy models (i.e., IAMs, ABMs, ESMs, and computable general equilibrium models) represent social factors. The authors concluded that

13 out of the 23 reviewed energy models incorporated social aspects, mainly public acceptance, and behavioral and lifestyle choices, being ABMs the only ones to partially address public participation and the heterogeneity of actors (Krumm et al., 2022). However, none of the reviewed models consisted of system dynamics models.

From this background on ESMs reviews, system dynamics, and the incorporation of social aspects into quantitative modeling, the present work aims to identify how system dynamics energy system-related models incorporate social aspects without placing a particular focus on the literature about STET. To the best of the authors' knowledge, this is the first work in literature to approach this gap. A review of energy-system related system dynamics models available in the peer-reviewed literature was conducted and main social aspects incorporated in models were identified. Within social aspects, it was considered socioeconomic, demographic, behavioral, socio-political, wellbeing, and social acceptance aspects, as described in **Section 4.2.2**. Henceforth, these aspects are simply referred to as "*social*" for the sake of simplicity. Ultimately, we aim to contribute to the research on social perspectives of energy transitions and a better representation of social dynamics in system dynamics ESMs.

4.2 Methodological approach

This work was based on a literature review of system dynamics energy system-related models conducted in three databases, Scopus, Science Direct, and Web of Science, on the 12th of September 2022. The search string consisted of a combination of the words "*energy system*", "*model*" or "*modeling*", and "*system dynamics*". Considering works published after 2012, this search string led to 240, 92 and 73 results on Scopus, Science Direct, and Web of Science databases, respectively. Books, book chapters, conference papers, review articles, and documents other than research articles, as well as non-English documents, were excluded. After abstract screening and duplicates removal in the reference manager Mendeley, 69 works remained. Most studies excluded in the abstract screening stage consisted of research on power control systems. In the full-paper screening stage, only papers that (i) could be retrieved, (ii) contained a representation of the system dynamics model (e.g., model structure, CLDs, SFDs), (iii) applied the model to real case studies, and (iv) made future simulations were considered. This led to the exclusion of 24 other works and a final portfolio containing 45 works. The literature review process is presented in **Figure 4-1**.

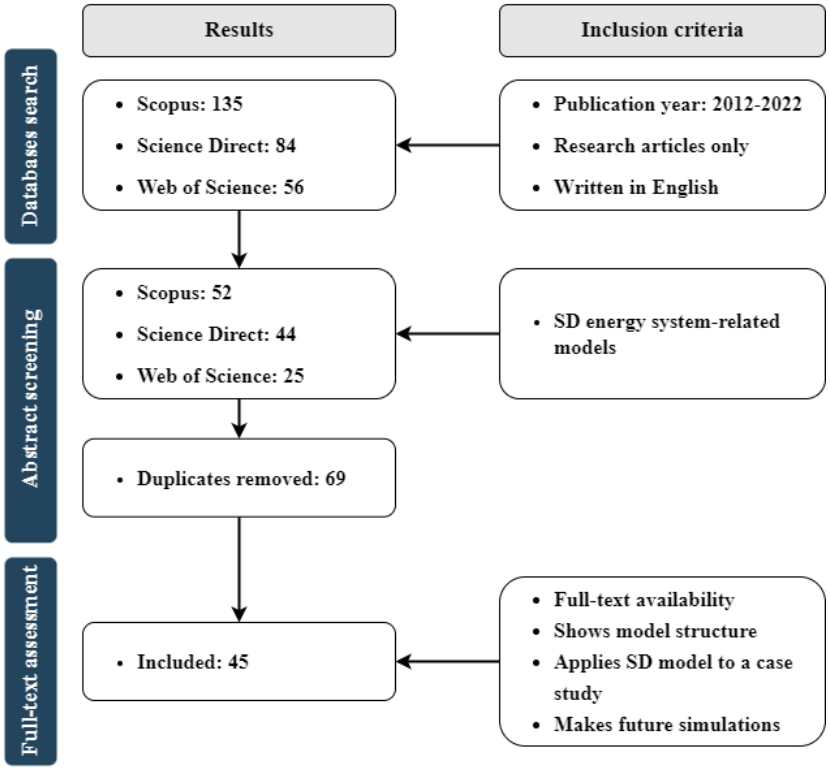


Figure 4-1. Literature review process.

4.2.1 Main themes

The final collection of 45 works was assessed based on the location of case studies, geographical resolution, time horizon, methodological approach, and main themes. Concerning main themes, supply-demand models were concerned with representing the feedback processes that affect production, mainly from specific sources (e.g., natural gas, hydrogen, biomass), and energy consumption. Models in the 3E topic were concerned mainly with macro-economic aspects, energy production, and emissions, including IAMs (e.g., (Perissi et al., 2021)). Energy-transport models integrated both energy and transport sectors. The WEF nexus evaluated the dynamics across the water, energy, and food spheres. Sometimes, the analysis was restricted to two aspects (e.g., water-energy (De Stercke et al., 2018)) or extended to others (e.g., society (Zeng et al., 2022)). Finally, consumer-centric and socio-political dynamics models were more diverse and mostly incorporated feedback focused on consumer behavior, technology adoption, and household-level dynamics.

4.2.2 Social aspects

As it is beyond the scope of this study to systematically review energy-related social aspects, we framed as 'social aspects' the concepts commonly linked to the energy transition. Since 'Limits to growth' (Meadows et al., 1972), economic and biophysical models have underscored the dangers of unstoppable economic and population growth (Dale et al., 2012). This motivated us to consider population and gross domestic product (GDP) growth in the search for socioeconomic aspects representation. Next, given concerns over a JET (García-García et al., 2020) and the dynamics of job creation and destruction from fossil fuels phase out (IEA, 2021), employment and income were also pondered. Particularly, employment impacts can be perhaps deemed as the socioeconomic aspect most commonly incorporated in ESMs, regardless of the modeling approach (e.g., (Lund & Hvelplund, 2012; Lund et al., 2022)). Behavioral aspects have also been commonly investigated in energy research (Bishoge et al., 2021), and include individual consumption habits, socio-cultural preferences, and lifestyle changes (Clora & Yu, 2022).

Social acceptance and perception of RE and energy efficient technologies are also key determinants of the adoption of alternative technologies and the pace of low-carbon transition (Menges & Beyer, 2014; Roddis et al., 2018; Rygg et al., 2021), being linked to levels of public awareness (Koirala et al., 2018). There is also reference to the public participation and ownership of energy transitions, and the potential of inclusive perspectives (Marczinkowski, 2022). When not taken into consideration, the absence of these aspects can negatively affect investments in RES, especially in rural communities (Butu & Strachan, 2022). Next, there are socio-political factors such as institutional structures (Selvakkumaran & Ahlgren, 2017), trust in infrastructures and services, as well as the heterogeneity of actors involved in energy systems (Krumm et al., 2022).

Last but not least, we looked into well-being issues in light of how energy systems affect people's lives. These include quality of life and health and environmental hazards as a result of technology choices and consumption habits (Samarakoon, 2019). Given the growing concern on achieving SDG7, energy justice, and these effects on socioeconomic development, we also assumed energy access as a social aspect (Gladkykh et al., 2021). These aspects are represented in **Figure 4-2**. Therefore, by assessing models' structures and looking for the aforementioned aspects, it was possible to identify which and how they were modeled in system dynamics models. Main social dynamics that included these social aspects were then represented in CLDs for each modeling theme. CLDs were chosen as a visualization tool because, together with SFDs, they are the most common and easiest way to visualize system dynamics models

and represent feedback processes (Sterman, 2000). Nonetheless, it is worth having in mind that presented CLDs are simple representations of much more complex models.

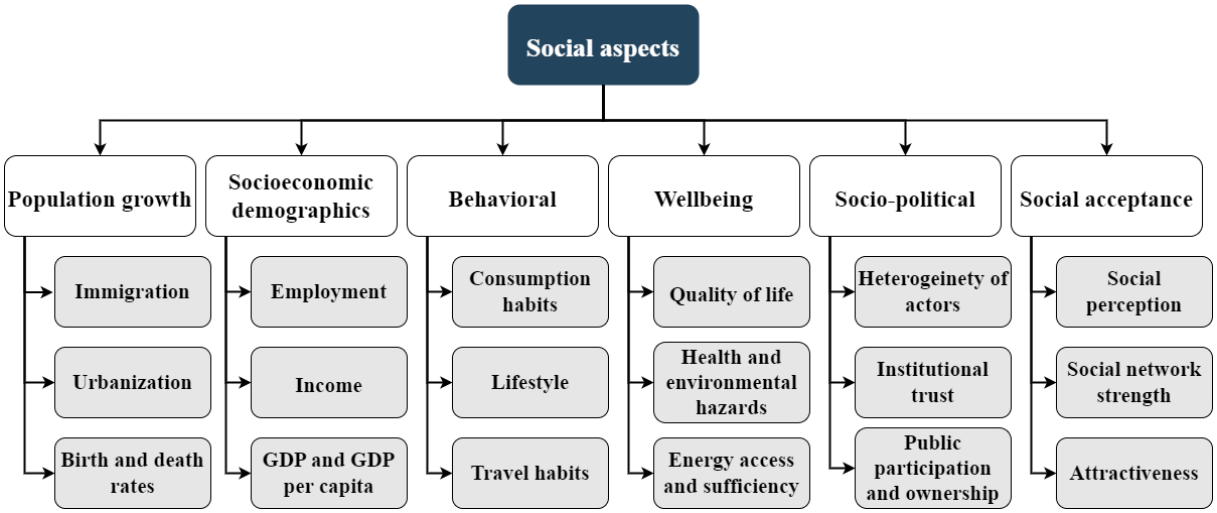


Figure 4-2. Social aspects related to the energy transition.

4.2.3 Limitations

The literature review process was not based on the review of system dynamics models themselves, being entirely based on secondary information published in the peer-reviewed literature. Therefore, even though the most relevant feedback loops and variables were commonly discussed in papers, identifying social aspects and describing dynamics could be different. Different search strings would have different results (e.g., "*energy*" AND "*system*" instead of "*energy system*"). However, an overlapping "*system dynamic*" concept in the electric and electronic fields required initial search restrictions to avoid a large number of unrelated works. The search string and inclusion criteria were used to filter a diverse and broad literature on the topic that is far from being extensively reviewed in this paper. However, this is not considered an impediment to fulfilling this research's objectives. While the location, geographical resolution, time horizon, and methodological approach are objective classifications, works could have been grouped into different main themes. Nonetheless, we carefully considered the identified problems and hypotheses mentioned in the studied models to select appropriate categories aligned with existing literature.

4.3 Descriptive results

Concerning the methodological approach, out of the 45 reviewed works, two (Pakere et al., 2022; Wu & Ning, 2018) combined system dynamics with GIS in order to evaluate results both temporally and spatially. In Pakere et al. (2022), the GIS model provided data on land suitable for wind turbines, which was used as a limiting input in the system dynamics model. In Wu and Ning (2018), GIS software was used to visually analyze the results of the system dynamics model representing Beijing's districts. Five other works (Akhtar et al., 2013; Daneshzand et al., 2019; Eker & van Daalen, 2015; Karunathilake et al., 2020; Wu & Xu, 2013) combined system dynamics to multi-objective optimization modeling to evaluate supply-demand and 3E dynamics. Among them, the ANEMI model (Akhtar et al., 2013) consists of an integrated optimization-simulation model that solves an optimal allocation problem within each simulation time step without considering future projections (i.e., it generates an endogenous path for energy supply). Also, Daneshzand et al. (2019), Wu and Xu (2013), and Eker and van Daalen (2015) considered multi-objective optimization methods to find optimal values of policy variables. Karunathilake et al. (2020) employed a fuzzy optimization approach to find optimal energy mixes according to different performance objectives, which were used as input in their life-cycle-based system dynamics model. Lastly, Blanco et al. (2019) bi-directionally soft-linked the system dynamics model "*Powertrain Technology Transition Market Agent Model*" (PTTMAM) (Harrison et al., 2016) of the passenger transport sector with TIMES to simulate the development of fuel cell vehicles in Europe. The remaining 37 works employed pure system dynamics models.

In terms of spatial resolution, one model was global (Akhtar et al., 2013), three papers (Blumberga et al., 2016; Gladkykh et al., 2021; Sheykhha & Madlener, 2022) evaluated a group of countries, 27 models had a national scope, and nine other papers analyzed regions within countries. Most models were simulated up to 2050, given the year's relevance for climate action plans as a landmark for achieving a net-zero global economy (IEA, 2021). Regarding model development, only Blumberga et al. (2022) and Strapasson et al. (2020) mentioned the performance of workshops to gather insights on systems structures and stakeholders' expectations. Concerning the employment of models to aid policy-making, only Blumberga et al. (2022) reported on the development of an open Internet-based policy-aiding tool.

4.4 Social aspects and dynamics

This section brings which and how social aspects have been incorporated into system dynamics models concerning energy systems according to the main identified themes. First, social aspects found in models are synthesized in tables for each theme, after the ways by which these aspects were influenced in the models are discussed along with visual representations in simplified CLDs. In CLDs, variables are related by causal links (arrows). Links can have positive (+) or negative (-) polarity that shows how the dependent variable changes with the independent one. A positive link means that if the cause increases, the effect also increases; and if the cause decreases, the effect also decreases. On the other hand, a negative link means that if the cause increases, the effect decreases; and if the cause decreases, the effect increases (Sterman, 2000). Particularly, CLDs do not differ between stocks (i.e., accumulations in the system), flows (i.e., rates of change in and out stocks), and converters, which are all components of system dynamics models. Important feedback loops are also shown in CLDs, and they can be denoted as balancing or reinforcing. Balancing or negative loops counteract a change, pushing in the opposite direction. Conversely, reinforcing or positive loops sustain and "reinvest" in a change. In terms of behavior, balancing feedback loops bring stability to the system, while reinforcing feedback loops produce behaviors such as exponential growth.

4.4.1 Supply-demand

Table 4-1 displays the works reviewed in this category, their investigation topic, and considered social aspects. Models targeted RE, natural gas, electricity generation and flexibility, and whole energy systems. Economic and population related aspects were most commonly included in models, followed by income and employment, social acceptance of technologies and human health.

Table 4-1. Supply-demand thematic and considered social aspects.

Reference	Topic	GDP	Population growth	Urbanization rates	Income	Employment	Social acceptance	Environmental awareness	Human health	Consumption habits
(Aslani et al., 2013)	RE development									

(Qudrat-Ullah, 2013)	Electricity generation	x								
(Eker & van Daalen, 2015)	Bioenergy						x			
(Szarka et al., 2018)	Bioenergy		x			x				
(Aslani et al., 2018)	Natural gas	x	x							
(Jin et al., 2019)	Bioenergy	x				x			x	
(Daneshzand et al., 2019)	Natural gas	x	x	x	x					
(Karunathilake et al., 2020)	RE development	x	x				x		x	
(Spittler et al., 2021)	Electricity generation									
(Sheykhha & Madlener, 2022)	Electricity generation and flexibility	x						x		
(Insuasty-Reina et al., 2022)	Hydrogen production									
(Blumberga et al., 2022)	Energy system	x	x							x

While some models incorporated different social concepts through exogenous and endogenous variables and policy levelers, other technology-based models did not include any social aspects (Aslani et al., 2013; Spittler et al., 2021). These models were very technical and considered exogenous energy demand projections together with technological availability, efficiency, energy sources, and associated costs in the supply side. GDP and population growth were represented as drivers of energy demand in (Aslani et al., 2018; Qudrat-Ullah, 2013; Sheykhha & Madlener, 2022). Residential energy demand, in particular, was calculated through exogenous urbanization rates and household income (Daneshzand et al., 2019). From a technological perspective, demand was also influenced by the share of energy efficient and inefficient consumers (Blumberga et al., 2022). Energy efficiency interventions are presented in **Figure 4-3** as a result of technological development and behavior changes (Blumberga et al., 2022). Information campaigns influenced the latter. As can be seen, social aspects were commonly represented exogenously. There are four reinforcing (R) feedback loops in **Figure 4-3**. R1 and R3 demonstrate how higher GDP levels lead to higher energy demand, investment, and production, which in turn positively affect GDP growth (Aslani et al., 2018). R2 represents the relationship between energy capacity depreciation and

new installed capacity (Spittler et al., 2021), while R4 indicates the cause-and-effect relationship between GDP, household income, energy demand, up to energy production. Variables in a grey ellipse indicate social aspects.

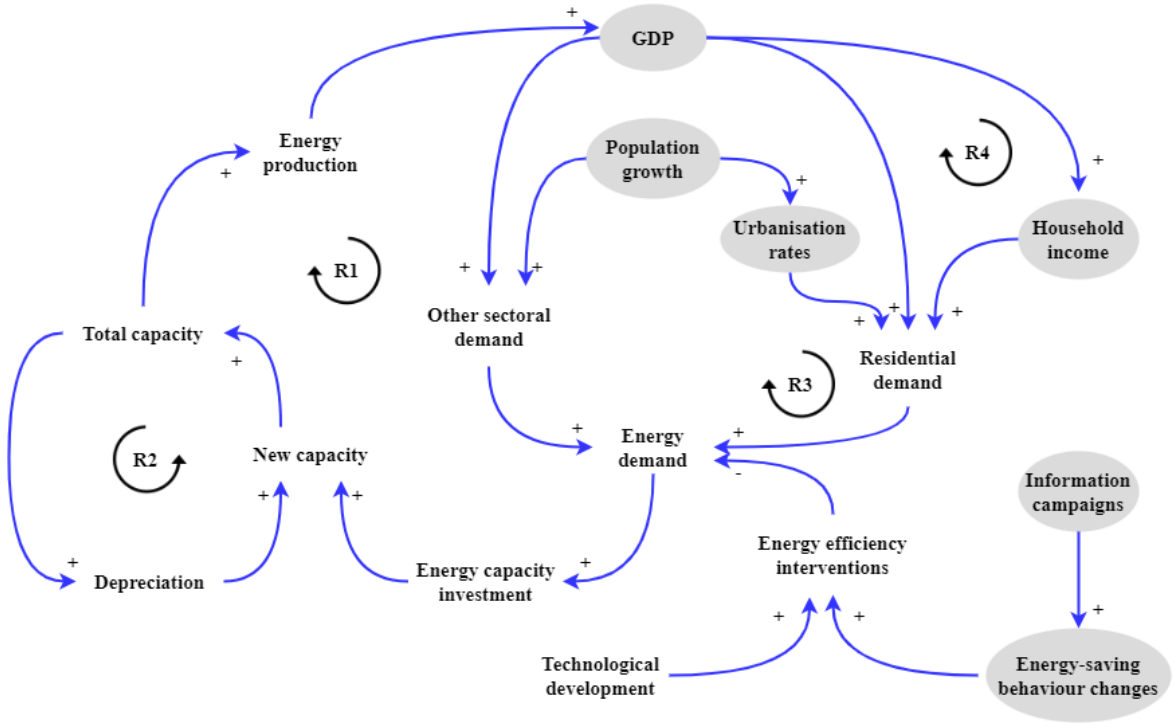


Figure 4-3. Representative CLD of social dynamics influencing energy demand in supply-demand models (R – reinforcing loop). Adapted from: (Aslani et al., 2013; Blumberga et al., 2022; Daneshzand et al., 2019; Spittler et al., 2021).

Moreover, given the pursuit of a less carbon-intense energy matrix, overall energy demand was commonly split into fossil fuel and RES. RE development was dependent on the social acceptance of technologies (Eker & van Daalen, 2015) and the effects of policies (Szarka et al., 2018), whereas the suitability of RE projects was seen as a consequence of lifecycle impacts on human health and emissions (Karunathilake et al., 2020). Increasing energy demand requires a matching production capacity, which can offer employment opportunities across project lifecycles (Jin et al., 2019). If RE capacity increases, a reduction in CO_2 emissions is expected, which can be linked to the social cost of carbon (i.e., non-commercial impacts of emissions on health and the environment) and consequent savings (Jin et al., 2019), as shown in **Figure 4-4Figure 4-4**. The reinforcing feedback loops, R1 and R2, link GDP and energy demand to investment in fossil fuels and RE, respectively. The other two reinforcing feedback loops, R3 and R4, refer

to how investment in RES can reduce emissions and lead to more investment in RES while reducing health and environmental hazards through the social cost of carbon.

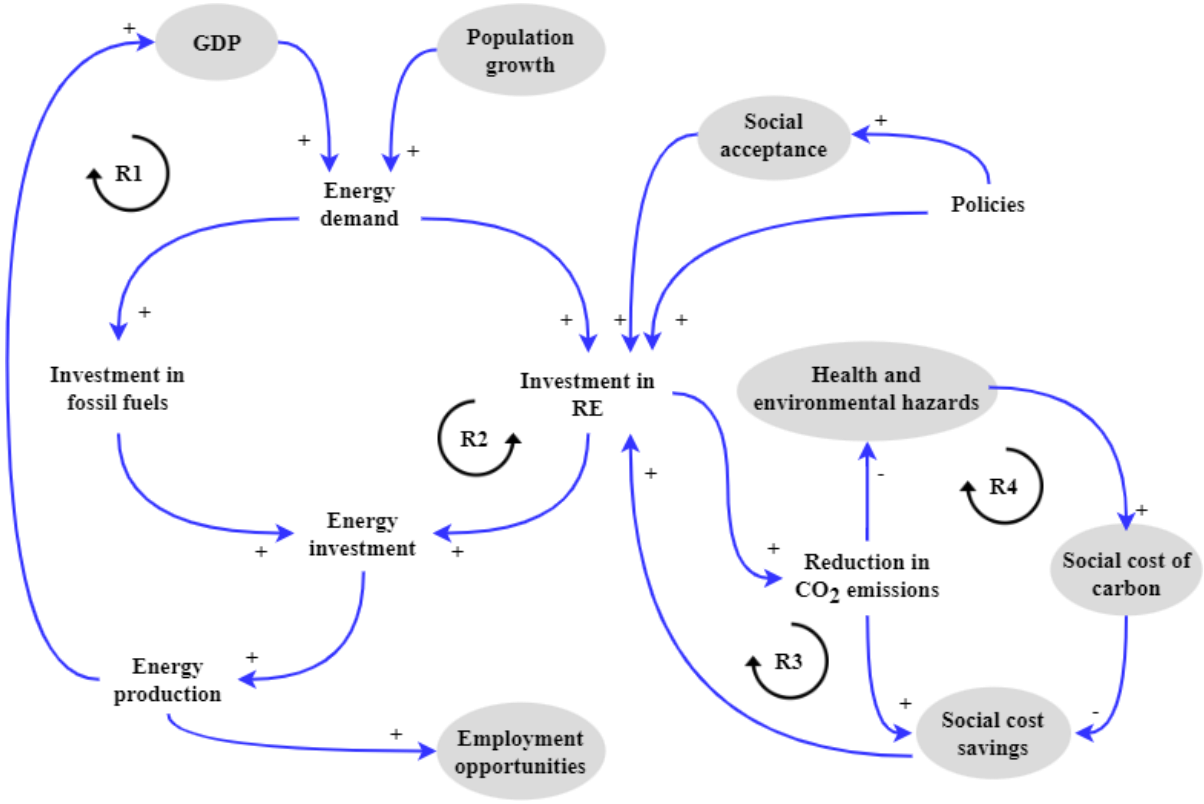


Figure 4-4. Representative CLD of social dynamics influencing renewable energy (RE) in supply-demand models (R – reinforcing loop). Adapted from: (Eker & van Daalen, 2015; Jin et al., 2019; Karunathilake et al., 2020; Szarka et al., 2018).

4.4.2 Energy-economy-environment

Commonly, 3E models observed socioeconomic aspects, as can be seen in **Table 4-2Table 4-2**. The relative absence of other social aspects can be explained by the underlying purpose of these models in representing top-down system structures and their particular concern with emissions resulting from energy systems and other sectors. In particular, 3E system dynamics models that did not emphasize any social dynamics (Blumberga et al., 2016; Laimon et al., 2022) were again technical-based models concerned with the investments and depreciation of capacities under different policy scenarios.

Table 4-2. 3E thematic and considered social aspects.

Reference	Topic	GDP	Population growth	Income	Employment	Consumption habits	Life expectancy
(Akhtar et al., 2013)	Climate-biosphere-economy-energy	x	x	x	x	x	x
(Wu & Xu, 2013)	Energy-economy-emissions	x	x				
(X. Liu et al., 2015)	Energy-economy-emissions	x	x				
(Blumberga et al., 2016)	Energy-emissions						
(Roberts et al., 2018)	Energy-economy-emissions	x			x		
(Wu & Ning, 2018)	Energy system	x	x				
(Akhtar et al., 2019)	Climate-biosphere-economy-energy	x	x				
(Wu et al., 2021)	Development scenarios	x	x				
(Perissi et al., 2021)	IAM	x	x				
(Hafner et al., 2021)	Energy-economy-emissions	x	x	x		x	
(Laimon et al., 2022)	Energy system						

Similar to supply-demand models, 3E systems considered population growth and economic development as drivers of energy demand. Distinctly, population growth was modeled endogenously as a result of fertility and death rates resulting from climate change in the ANEMI model (Akhtar et al., 2013; 2019). Economic development was also linked to employment opportunities (Roberts et al., 2018). In some cases, labor dynamics were understood as a demand-supply feedback, in which households provided labor to the market, and the resulting household income led to an average consumption of goods (Akhtar et al., 2013; Akhtar et al., 2019; Hafner et al., 2021). In another approach, Laimon et al. (2019, 2022) considered employment opportunities generated by increasing energy production capacity as a driver of immigration and, therefore, population growth. Population growth drove energy demand and, consequently, energy production, creating a reinforcing feedback loop. Moreover, conflicting objective

functions have been reported, in which there is no common solution for maximizing GDP or minimizing energy consumption, pollution and emissions (Wu & Ning, 2018; Wu & Xu, 2013).

Figure 4-5 represents the aforementioned 3E dynamics together with four reinforcing (R1, R2, R3, and R4) and two balancing feedback loops (B1 and B2). B1 and B2 refer to how GDP growth leads to higher investment in science and technology, resulting in technological progress towards more efficient technologies. This reduces energy consumption linked to GDP in B2 and to energy demand, capacity expansion, employment, and GDP in B1. R1 indicates that GDP growth brings employment opportunities and, R2, higher energy consumption. R3 links GDP and population through emissions and global temperature, while R4 shows how GDP growth can be reinforced through investment in more efficient technologies even when economic development restrictions are in place.

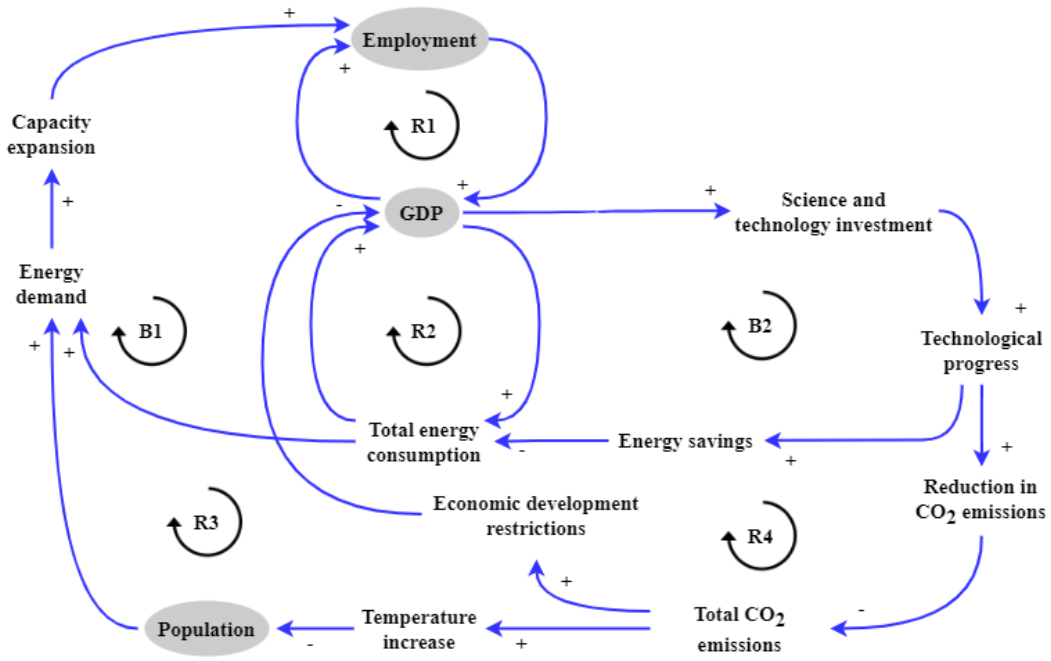


Figure 4-5. CLD representing the relationship between GDP, employment, emissions, and energy consumption. (R – reinforcing loop; B – balancing loop). Source: Adapted from (Akhtar et al., 2013, 2019; Laimon et al., 2019, 2022; Wu & Xu, 2013).

4.4.3 Energy-transport

Table 4-3 summarizes the social aspects within energy-transport system dynamics models. GDP and population were modeled exogenously as drivers of energy and transport demand (Spittler et al., 2020).

Behavioral aspects, such as vehicle use (i.e., travel demand) and the social acceptance of alternative options, were also commonly considered.

Table 4-3. Energy-transport thematic and considered social aspects.

Reference	Topic	GDP	Population growth	Travel demand	Social acceptance	Heterogeneity of actors
(Shafiei et al., 2014)	Low-carbon transport development	x	x	x		
(Shafiei, Davidsdottir, Leaver, Stefansson, & Asgeirsson, 2015b)	Alternative fuels market	x	x	x		
(Shafiei, Davidsdottir, Leaver, Stefansson, & Asgeirsson, 2015a)	Alternative fuels market	x	x	x	x	
(Shafiei et al., 2016)	Supply-push strategies for biofuel vehicles	x	x	x		
(Shafiei, Leaver, & Davidsdottir, 2017)	Cost-effectiveness of low-carbon transport	x	x	x		
(Shafiei, Davidsdottir, Leaver, Stefansson, & Asgeirsson, 2017)	Hydrogen and electricity fueled vehicles	x	x	x		
(Blanco et al., 2019)	Soft-linking system dynamics transport model and optimization-based energy system model			x		x
(Spittler et al., 2020)	Geothermal electricity production and transport demand	x	x	x		

Seven out of eight works on energy-transport dynamics were based on the UniSyD model (Leaver et al., 2012). This model incorporates social aspects related to consumers' travel behavior and perceived utility of a particular modal choice and AFVs. Shafiei et al. (2015b) particularly pointed to assessing social network strength on consumers' consumption and further technological adoption but did not consider its effects in the modeling. These aspects can be seen in **Figure 4-6**, where three reinforcing loops (R1, R2, and R3) are identified. Besides R1 and R2 linking energy production and capacity, there is a potential loop (R3) between the social network strength, the attractiveness of a particular technology, and its actual

adoption. Especially, Blanco et al. (2019) softly linked PTTMAM (Harrison et al., 2016), a simulation model that considers the major stakeholders (i.e., users, authorities, infrastructure providers, and manufacturers) in the light-duty passenger transport, to TIMES (Nijs & Ruiz Castello, 2021), a widely known optimization model. Therefore, the heterogeneity of actors was also incorporated into the system dynamics model (i.e., socio-political-technical).

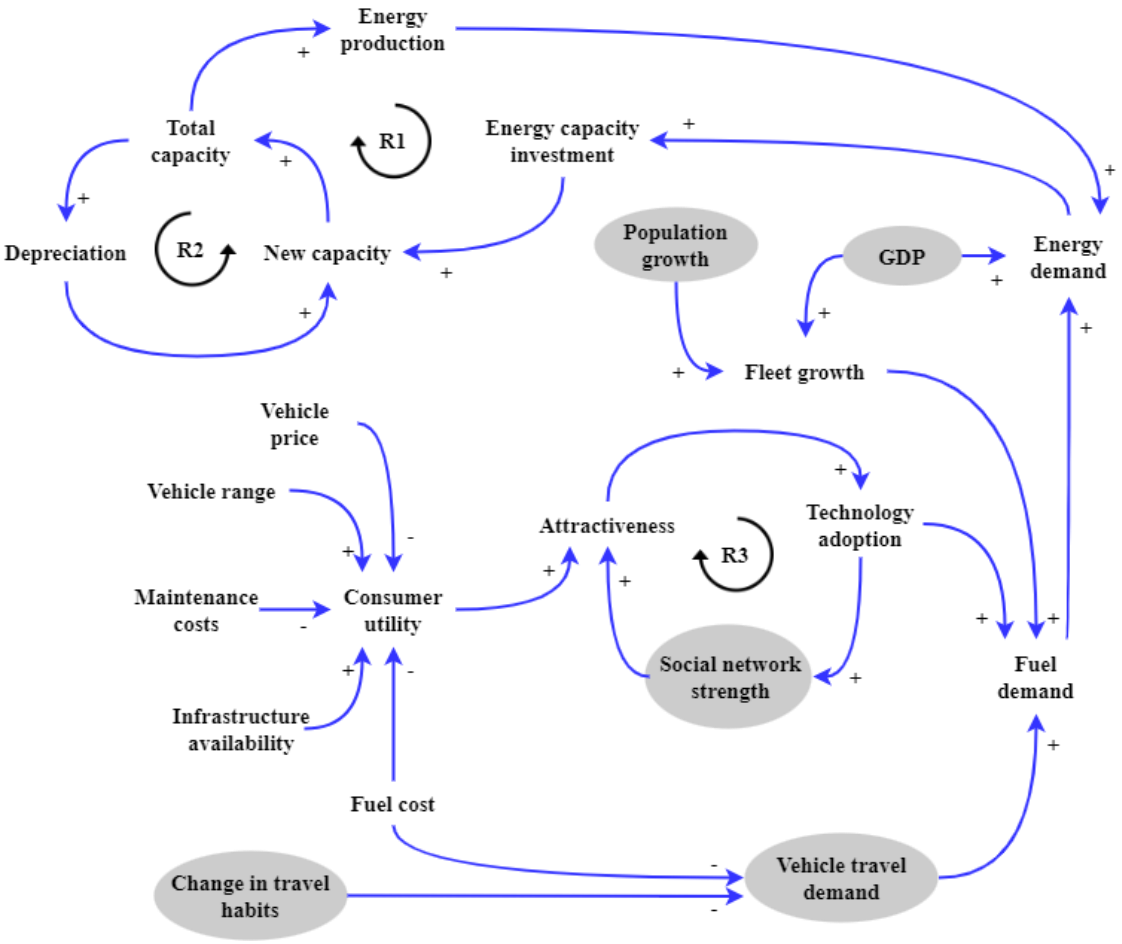


Figure 4-6. CLD representing the relationship between change in travel habits and vehicle adoption (R – reinforcing loop). Source: Adapted from (Shafiei et al., 2015a; Spittler et al., 2020).

4.4.4 Water-energy-food nexus

WEF models were concerned with the macro-economic and population dynamics driving water, energy, and food demands, and how changes in consumption habits and lifestyle could impact these demands. In two instances, quality of life (De Stercke et al., 2018) and environmental awareness (De Stercke et al., 2018; Zeng et al., 2022) were also considered, as shown in **Table 4-4**.

Table 4-4. Water-energy-food thematic and considered social aspects.

Reference	Topic	GDP	Population growth	Consumption habits	Quality of life	Environmental awareness
(De Stercke et al., 2018)	Water-energy		x	x	x	x
(Strapasson et al., 2020)	Energy-food-climate-land		x	x		
(Mobaseri et al., 2021)	Energy-food	x	x	x		
(Keyhanpour et al., 2021)	WEF	x	x	x		
(Zeng et al., 2022)	Water-energy-food-society	x	x	x		x

Within WEF models, economic and population growth influenced the demand for food, energy, and water (Mobaseri et al., 2021). The relationship between these resources supply and demand was labelled as 'security' (Keyhanpour et al., 2021) or 'shortage' (Zeng et al., 2022). Water, energy, and food shortages influenced the population's environmental awareness (Zeng et al., 2022). Food security affected agricultural development, the area under cultivation and, consequently, food supply. The cultivated area also impacted on the amount of water needed for agriculture, which, along with urban, industrial, and energy sector demand for water, composed the water demand variable. While agricultural water demand is also linked to energy requirements in irrigation systems, water is also required for hydroelectric energy generation. Life quality was modeled as a result of water, energy, and water-energy end uses in urban systems (De Stercke et al., 2018). Quality of life, in turn, affected population growth, which then impacted demand for energy and water along with pressure to reduce consumption. Behavioral aspects were also considered through diet habits (Strapasson et al., 2020), more specifically, meat consumption and overall calories. The latter was represented in **Figure 4-7** through 'lifestyle and consumption changes' along with the main dynamics influencing social aspects in the WEF nexus.

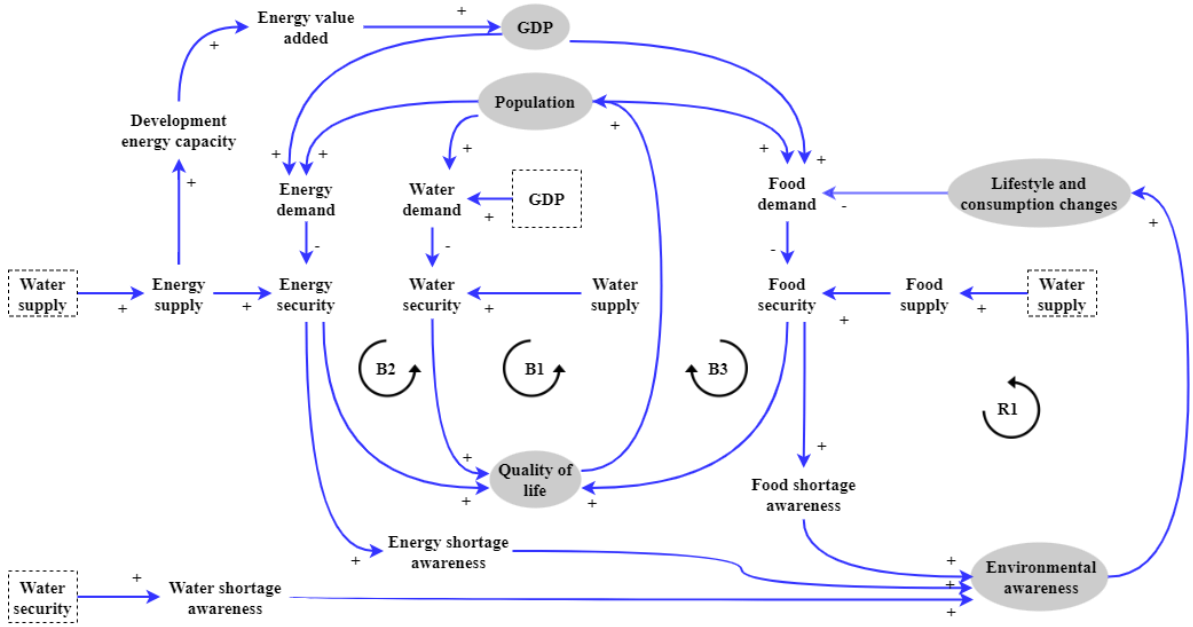


Figure 4-7. CLD representing the relationship between economic and population growth and WEF demand. Source: Adapted from (De Stercke et al., 2018; Mobaseri et al., 2021).

In **Figure 4-7**, we can notice the following feedback loops. In R1, lifestyle and consumption habits change with environmental awareness, decreasing food demand, and raising food security and awareness. The other three balancing feedback loops, B1, B2, and B3, show how population growth increases demand for water, energy, and food, respectively, which decreases security indicators. Lesser life quality lowers population growth levels.

4.4.5 Consumer-centric and socio-political dynamics

In general, models within this category incorporated the largest number of social aspects given their underlying representation of consumer-centric and socio-political dynamics, as can be seen in **Table 4-5.**

Table 4-5. Consumer-centric and socio-political dynamics and considered social aspects.

Reference	Topic	GDP	Population growth	Urbanization rates	Income and Employment	Environmental awareness	Human health	Social perception	Consumption habits	Willingness to participate	Heterogeneity of actors	Energy sufficiency

(Toka et al., 2014)	Technology adoption					x						
(Bažbauers et al., 2015)	Electricity savings	x			x				x	x		
(Kubli & Ulli-Beer, 2016)	Distributed generation					x		x				
(Blumberga et al., 2018)	Building renovation					x		x	x		x	
(Gladkykh et al., 2021)	Energy sufficiency		x	x								x
(Freeman, 2021)	Socio-political-technical feedbacks							x		x	x	
(Pakere et al., 2022)	RE development							x		x	x	
(Eftekhari et al., 2022)	Distributed generation				x							
(Shari et al., 2022)	Technology adoption			x	x		x	x	x			

Clean and RET adoption at household levels was represented through the Bass innovation diffusion model (Sterman, 2000) in (Freeman, 2021; Shari et al., 2022; Toka et al., 2014), where, besides reinforcing feedback loops (R1 and R2) among adopters (**Figure 4-8**), external influences included environmental awareness and social acceptance of technologies (Toka et al., 2014). Concerning effects on demand, energy efficiency takes place through technological development and more efficient technologies, which are influenced by investment in research and development (R&D), and behavior changes in energy consumption (Blumberga et al., 2018). This can be affected by the level of consumers' environmental awareness and social acceptance (Blumberga et al., 2018). These two aspects could be influenced by information campaigns and governmental policies, which could also affect inconvenience costs (Pakere et al., 2022), describing social aspects affecting production costs, such as lack of knowledge and trust in RETs.

Inconvenience costs of RET expansion were also included as 'public awareness' influencing consumers' reliance on contractors (Eftekhari et al., 2022) and perceived utility (Kubli & Ulli-Beer, 2016). Moreover, demand for more sustainable technologies was represented as a result of several other aspects, such as income, educational levels, socio-cultural differences and preferences, household size, urban-rural adoption, environmental and health hazards, and cost subsidies (Shari et al., 2022). Notably, there is a reinforcing effect on education, income, and socioeconomic impacts represented by R3 (**Figure 4-8**). The further expansion of RE capacity was modeled as influencing employment opportunities and rural-urban migrations (Eftekhari et al., 2022). Considering the heterogeneity of actors involved in the energy transition, socio-political factors' influence on the feasibility of the UK's carbon budgets was also represented using system dynamics (Freeman, 2021). Social political factors included political capital, policy ambition, public willingness to participate, and pushbacks. Pushback is an information feedback that notifies governments about the public acceptance of governance and influences the political capital for the energy transition and the ambition of policies (Freeman, 2021).

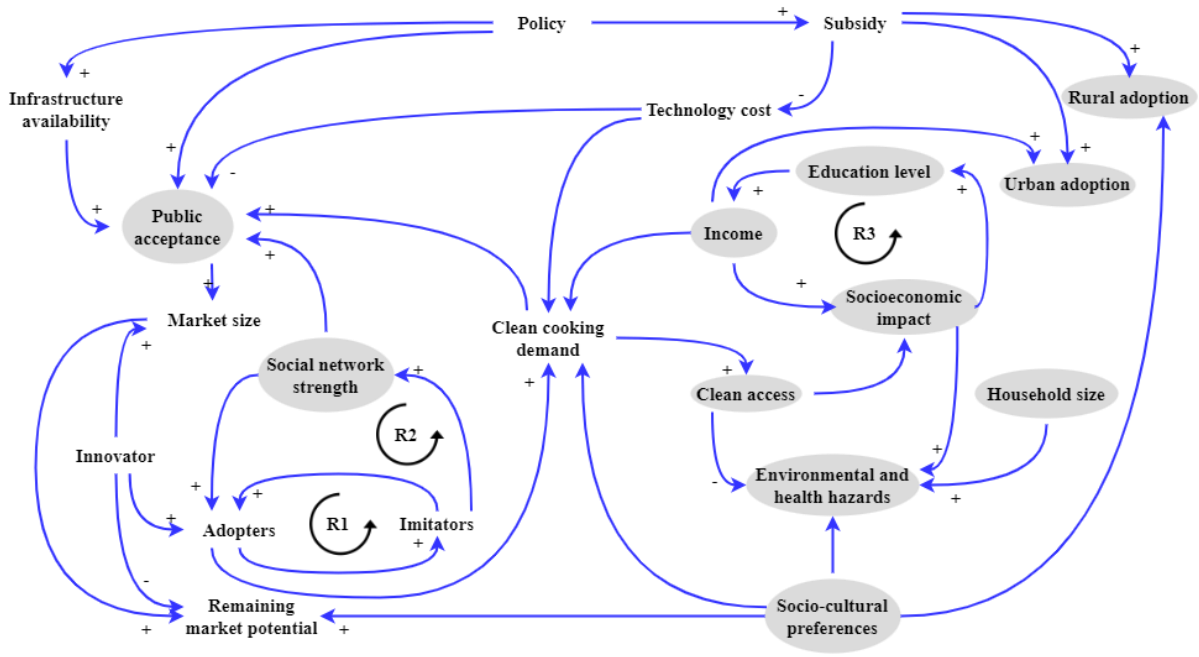


Figure 4-8. CLD representing the relationship between policy effects and clean cooking demand (R – reinforcing loop). Source: Adapted from (Shari et al., 2022).

Consumer behavior choices were also modeled as a result of the willingness to undertake energy efficiency measures, environmental awareness, electricity and income ratio, and changes in consumption

habits as a result of the use of electrical appliances (Bažbauers et al., 2015). This is shown in **Figure 4-9**, along with a balancing loop (B1) between electricity consumption and changes in habits and appliances. Low- and high-income households were considered given different perceptions, consumption behaviors, and disposable income (Bažbauers et al., 2015). Apart from behavioral and socioeconomic aspects, the concept of 'energy sufficiency' was also defined and modeled to evaluate urban and rural household electricity provision in Sub-Saharan Africa (Gladkykh et al., 2021). Energy sufficiency corresponds to "*a maximum desired amount of energy per capita to be produced and consumed*" and is linked to energy justice and SDG7 (Gladkykh et al., 2021).

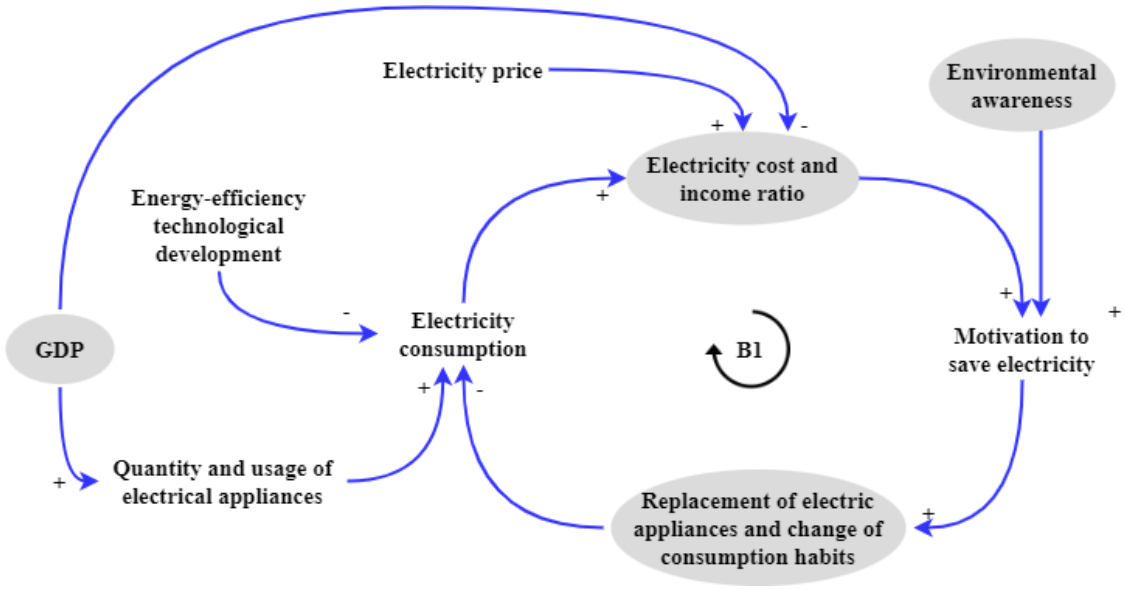


Figure 4-9. CLD representing the relationship between GDP and electricity consumption parameters (B – balancing loop). Source: Adapted from (Bažbauers et al., 2015).

4.5 Main findings and conclusion

As pointed by Lund et al. (2017) when reviewing simulation versus optimization models, each modeling approach has its own advantages and disadvantages. Therefore, each problem must be carefully evaluated before a methodological choice is made. In any case, challenges will follow. Particularly, this paper reviewed how flexible and resourceful system dynamics energy system-related models are, as they have been applied to a diverse range of topics and case studies from regional to global levels. These results are in agreement with those obtained by Bolwig et al. (2019). Additionally, different actors (e.g., households, infrastructure investors and providers, energy suppliers, and governments) and sectors (e.g.,

residential, industrial, and agricultural) were represented in the models, which highlights the potential of system dynamics models to incorporate the heterogeneity of actors in the energy transition (Krumm et al., 2022). Nevertheless, as Blumberga et al. (2022) discusses, it is necessary to pay attention to the political dimension of models and policy processes. Still, the underlying top-down approach of system dynamics as a simulation model seems also fit to represent the socio-environmental-energy nexus and approach the problem of integrated sustainability (Cappellaro et al., 2019).

The combination of system dynamics with other modeling techniques, even though minority, seemed capable of symbiotically approaching the energy transition from more than one front: bottom-up and top-down, geographically and timely, simulation and optimization. The potential of methodological combinations has been already highlighted in the literature as they forward to overcome some of the obstacles in the path towards more realistic quantitative modeling of transitions (Bolwig et al., 2019). The participatory development of models considered in a few works (Blumberga et al., 2022; Strapasson et al., 2020) and the conversion of models into accessible policy-aiding tools (Blumberga et al., 2022) can help develop inclusive pathways and enhance the public sense of ownership and participation while acknowledging the variety of actors that affect and are affected by the energy transition. Even though minority, participatory development and decision-making approaches could contribute to co-creation initiatives (Cappellaro et al., 2019), reducing the chances of atomistic approaches leading to increased social inequality and environmental injustice (Qarnain et al., 2020).

Regarding social dynamics incorporated in system dynamics models, supply-demand models have mainly integrated GDP, population, and the social acceptance of technologies. 3E models focused on population and economic growth, labor and consumption aspects, whereas energy-transport models included behaviors in relation to travel and the utility of vehicle choices. WEF models considered population and GDP as drivers of food, energy, and water consumption, while environmental awareness and lifestyle changes balanced it. In consumer-centric and socio-political models, many social aspects were considered, including urbanization rates, household income and employment, social acceptance, willingness to participate, environmental awareness, and behavioral aspects. In contrast with socioeconomic factors, well-being aspects (e.g., environmental and health hazards, quality of life) were less often considered, which can be explained by the challenges of representing social welfare and well-being and its various dimensions through quantitative metrics (Scott et al., 1996). The incorporation or not of social aspects remains subject to the modelers' choice of how to approach a certain problem within each model's purpose and focus.

As for future avenues of research in system dynamics modeling, we would like to highlight (i) the combination of system dynamics with other modeling techniques and (ii) the participatory development of models and conversion of models into accessible policy-aiding tools. Our review indicated that incorporating social metrics in system dynamics energy systems models is far from being standard, as also concluded by Krumm et al. (2022) when reviewing other types of energy-related models. Selecting appropriate social indicators and shifting from a techno-centric perspective remains a challenge in quantitative energy modeling but indeed a requirement for successful transitions (Süsser et al., 2022). We underpin the importance of further and bridging research on social and engineering sciences as well as STET.

The array of models targeting consumer-centric dynamics and the different incorporated social variables suggest there are research opportunities on the use of system dynamics models to quantitatively assess the impacts of energy access and the (in)justice of energy transitions. Moreover, the offset of job opportunities from fossil fuels to renewables as a result of the energy transition could be further explored through system dynamics models as well as dynamics involving disposable income, energy prices, and energy poverty issues. Given the richness of models and topics, we argue for further and in-depth reviews of system dynamics models in each one of the main identified themes so conclusions about the real influence of social aspects and their exogenous or endogenous nature can be captured.

5 Case study context: Energy justice issues in Portugal's EV transition

This Chapter presents the case study context for the empirical components of this thesis, focusing on energy justice issues associated with Portugal's transition to EVs. It builds on the theoretical and methodological foundation laid in the previous chapters, namely, the conceptual framework linking energy justice tenets to the EV lifecycle (**Chapter 2**), the identification of quantitative proxies for justice-related concerns (**Chapter 3**), and the review of system dynamics approaches to modeling social aspects in energy systems (**Chapter 4**).

The choice of Portugal as a case study is motivated by its ambitious decarbonization agenda (Simões & Erbach, 2025), the strategic importance of domestic lithium resources for the EU's battery supply chain (Lebedeva et al., 2017; Wolters & Brusselaers, 2024), and the uneven socio-spatial dynamics surrounding EV adoption and infrastructure deployment. These features make Portugal an instructive setting to examine how energy justice concerns manifest across different stages of the EV transition, from resource extraction to everyday use.

Section 5.1 provides an overview of Portugal's energy and transport transitions, outlining the role of EVs in national policy and EV-backing narratives. **Section 5.2** examines two key justice issues in greater depth: the socio-environmental conflicts surrounding lithium mining in the Barroso region, and the spatial and socioeconomic disparities in EV ownership and access to charging infrastructure in the country. These two topics form the basis for the modeling exercises presented in **Chapters 6 and 7**. This Chapter concludes with a discussion of how the justice concerns identified here are translated into system dynamics modeling (**Section 5.3**).

5.1 Portugal's transition to a low-carbon transport system

In this thesis, EVs refer specifically to light passenger vehicles powered by battery-stored electricity, namely BEVs and PHEVs. The case of EVs in Portugal is particularly relevant for several reasons.

First, the country has committed to reducing transport-related GHG emissions by 40%, a significant target given that the transport sector currently accounts for 31.4% of national emissions (Simões & Erbach, 2025). In line with this commitment, the Portuguese Government approved the Green Mobility Package in 2024, a policy framework aimed at decarbonizing passenger and freight mobility. This includes direct subsidies for EV purchases and investments in charging infrastructure (Portuguese Government, 2024a).

However, Portugal presents several structural challenges that complicate the transition. It has one of the oldest vehicle fleets in Europe, and its car market is heavily reliant on used vehicle imports (IMT & INE, 2022). These dynamics may introduce barriers to a rapid and equitable fleet renewal process and raise concerns about distributional justice, particularly in terms of access to new, cleaner technologies.

Furthermore, upstream and downstream socio-environmental concerns associated with EVs, such as mining impacts and the uneven distribution of charging infrastructure, are critical for assessing the justice implications of this transition (Sovacool, Hook, et al., 2019; Sovacool, Hook et al., 2020). To better understand these issues in the Portuguese context, extensive documentary analysis was conducted, including reviews of national low-carbon plans and policy documents (DGEG, 2019; Portuguese Government, 2024b, 2024a; Simões & Erbach, 2025), industry reports (Deloitte, 2020; IAPMEI, 2022; Jordão & Fernandes, 2022; Madruga, Rodrigues, & Ferreira, 2023), and statistical data (EAFO, 2024; IMT & INE, 2022; INE, 2022).

The political support for EVs has drawn criticism, both in Portugal and more broadly across Europe. Critics argue that the dominant policy discourse continues to prioritize private car ownership and the interests of the automotive industry over more sustainable, collective mobility solutions (Haas, 2022; Henderson, 2020). At the EU level, EVs are embedded in a broader techno-optimistic imaginary of green reindustrialization, in which their contribution to sustainability is often overstated and insufficiently scrutinized (Di Felice et al., 2021). These critiques are also applicable to the Portuguese case.

In Portugal, the automotive sector holds significant economic relevance due to its multiplier effects on employment and industrial activity. In 2020, the sector's[1] Gross Value Added (GVA) totaled EUR 1,643.8 million and contributed approximately 0.8% to national GDP, employing over 47,000 workers, mainly in component and parts manufacturing (INE, 2024c). This economic weight has led to explicit support from government actors for expanding EV manufacturing in Portugal, framing it as part of a broader project of "green European reindustrialization" and an entry into the so-called "electrification era" (Portuguese Government, 2025). These narratives are accompanied by aspirational claims of fostering "accessible and sustainable mobility" (Portuguese Government, 2025), though the underlying assumptions and distributional consequences often remain unexamined (Di Felice et al., 2021).

[1] Instituto Nacional de Estatística (INE). Activity 29 of the National Classification of Economic Activities (CAE), "Manufacturing of motor vehicles, trailers, semi-trailers, and components for motor vehicles"

The Green Mobility Package exemplifies this duality in policy discourse. It allocates EUR 20 million to support the acquisition of a range of electric and non-electric low-emission transport options, including light EVs, bicycles, motorbikes, mobility devices, and charging infrastructure (Portuguese Government, 2024a). The package also outlines additional measures, such as: (i) enhanced access to public transport for vulnerable populations (e.g., elderly, unemployed, youth, people with disabilities); (ii) expansion of cycling infrastructure and bike parking; (iii) improvements in the public transport user experience; (iv) reductions in external costs in freight rail transport; and (v) support for municipalities in digital and sustainable mobility transitions.

While these measures suggest an openness to multimodal and inclusive mobility, they are at different stages of implementation. Public transport infrastructure, in particular, tends to evolve more slowly than financial incentives for private vehicle acquisition. This temporal asymmetry, along with the heavier political emphasis on EV uptake, raises concerns about a potentially skewed transition that risks reinforcing existing inequalities, especially in rural and economically disadvantaged areas[2].

The techno-optimist narrative also extends upstream to raw material extraction. Lithium mining has become central to the government's framing of the energy transition, described as vital for achieving national and EU-level "green energy goals" (Araújo et al., 2022). The Barroso region in northern Portugal has been identified as a key site for lithium extraction, but the project has sparked significant opposition from local communities, who contest the environmental, social, and procedural implications of the mine. While the government presents mining as a path to national development and European integration, local actors often experience it as an imposition, leading to what some scholars describe as "green extractivism," "extractivist violence," and a threat to social welfare (Canelas & Carvalho, 2023; Dunlap & Riquito, 2023).

In summary, the Portuguese government actively supports the diffusion of EVs, the expansion of the automotive sector, and lithium mining, framing these actions within a broader green growth strategy that aligns with EU policies and the European Green Deal (European Commission, 2024). The justifications provided highlight job creation, technological advancement, and environmental benefits. However, this framing risks overlooking the socio-cultural and political complexities of transition processes (Di Felice et

[2] Several studies have found asymmetries in EV adoption and access to charging infrastructure among urban and rural residents and socioeconomic classes. See for instance Carlton and Sultana (2024) on EV charging equity and accessibility in the US and Hennessy and Syal's (2023) analysis of the distribution of rebates and EV ownership in California US.

al., 2021), particularly the tensions between national economic priorities and local environmental justice claims.

5.2 Justice issues in the EV Lifecycle in Portugal

As discussed in **Chapter 2**, EVs raise a variety of energy justice concerns across their lifecycle, from production and consumption to end-of-life, each corresponding to distinct temporal and spatial scales (Sovacool, Hook, et al., 2019). This section explores those concerns most relevant to the Portuguese context.

Within the production stage of EVs, which encompasses resource extraction and processing as well as the manufacturing of EVs and related components, studies have underscored: (i) asymmetries of knowledge and power among stakeholders, such as the forced delocalization of native populations and conflicts with local communities arising from mining projects; and (ii) disparities in the distribution of benefits (economic gains, job opportunities) and burdens (environmental pressure, biodiversity losses, health hazards, job losses) that accompany decisions to develop mining activities or to expand manufacturing capacities (Dall-Orsoletta, Ferreira, & Gilson Dranka, 2022). These issues are mainly linked to the lack of fair and inclusive processes, which relates to procedural and recognition justice, the unequal spatial distribution of costs and benefits (distribution justice), and the restoration of unavoidable harm (restorative justice). Additionally, from a global resource perspective, the production of EVs also has implications for resource availability and lifecycle GHG emissions (cosmopolitan justice).

In the consumption stage, which encompasses the re-charging and operation of EVs, several issues have emerged associated with the energy justice tenets. Main concerns refer to job losses in the fossil fuel industry and retail, the affordability of EVs, the uneven uptake of EVs across socioeconomic groups, regions (e.g., urban-rural), and countries (e.g., North-South divide), the second-hand market of ICEVs, the marginalization of other forms of mobility, emissions offset from tailpipe to power plants (Dall-Orsoletta, Ferreira, et al., 2022; Sovacool, 2021; Sovacool, Hook, et al., 2019; Sovacool, Hook et al., 2020; Sovacool, Lipson, et al., 2019; B. K. Sovacool, Martiskainen, et al., 2019), and the uneven distribution of flexibility capital (Chen, Chen, Tomasik, et al., 2024), which limits the participation in demand-response programs. Additionally, justice-related issues can emerge regarding the availability and equity in access to EV charging infrastructure, a topic addressed by several studies (Beyazit et al., 2024; Khan et al.,

2022), and the effects of EVs on electricity tariffs or charging tariff structures (Ademulegun et al., 2025; Jayapalan et al., 2022).

In relation to the end-of-life stage, much attention has been devoted to environmental and health hazards arising from the inappropriate disposal of EV, particularly when adequate recycling or disposal practices are lacking. These concerns are primarily distributional in nature, as they tend to disproportionately affect marginalized communities. This main concern is often addressed, at least rhetorically, by the so-called circular economy principles, which would also reduce impacts at mining stages thanks to improved material recycling efficiency (Bonsu, 2020).

In the specific context of Portugal, relevant information has been gathered from academic literature, industry and government reports, media coverage, and historical data. In terms of resource extraction, lithium mining projects such as the Barroso Mine in northern Portugal have sparked significant concerns. These include recognition and procedural injustices related to inadequate engagement with affected communities, as well as distributive injustices stemming from uneven exposure to environmental risks and limited access to economic benefits (Canelas & Carvalho, 2023). Although plans have been announced to construct lithium refineries domestically (Lusa, 2024b), no concrete developments have yet taken place.

In relation to the automotive manufacturing industry, it has been promised that the production of new EV models in the country will create jobs and economic growth (Portuguese Government, 2025). It is unclear, however, how this will impact the existing jobs in the fossil fuel industry and retail in the country. It is estimated that Portugal's motor vehicle fuel retailing sector employed approximately 16 thousand people in 2024 (Ibis World, 2024). Likewise, motor vehicle and motorcycle sales, maintenance, and repair activities generated a GVA of EUR 1,445.4 million in 2012, employing more than 93,000 people (INE, 2024c).

As for the operation phase of EVs, EV ownership disparities were noted between urban and rural regions in Portugal (Morrison & Wappelhorst, 2022). Rural areas in Portugal had a much lower BEV adoption rate (closer to 0 %) compared to the national, intermediate and urban regions' average (approximately 12.5 % and 5.0 %, respectively) (Morrison & Wappelhorst, 2022). Likewise, there seems to be a spatial disparity when comparing the number of public chargers available in urban and rural regions in the country (Dall-Orsoletta, Oosthuizen, et al., 2025). In relation to home charging, EV owners may face restrictions when home renters and/or living in multi-family units (Varghese et al., 2024), an aspect that becomes relevant given that more than 20% of dwellings are occupied by tenants in Portugal (Eurostat, 2021).

In relation to tax benefits and purchase incentives, Portugal offered full tax exemption on BEVs; a 75% reduction for PHEVs if the all-electric range is greater than or equal to 50 km and the emission intensity is less than 50g CO2/km; and a 40% reduction on hybrid electric vehicles (HEVs) under the same conditions (ACEA, 2023). Additionally, it currently offers EUR 4,000 for private users who buy a light passenger EV for up to EUR 38,500, as part of a scrapping scheme for ICEVs over 20 years (Portuguese Government, 2024a). These benefits have supported an increase in EVs in the country, with 33,749 BEVs and 92,422 HEVs registered by 2020, representing an increase of 42% and 39%, respectively, compared to the previous year (IMT & INE, 2022). It is unclear, however, who benefits from these incentives due to the absence of data on the sociodemographic profile of recipients.

One positive aspect of Portugal's transition is the potential for significant emissions reductions in the transport sector, given the country's relatively low-carbon electricity mix. In 2021, RE accounted for 60% of final electricity consumption (INE, 2024c), a share expected to rise to 80% by 2030 (DGEG, 2019)). As for the management of EV battery residues, while there are several strategies at the EU level for enhanced resource efficiency and circular economy (Bonsu, 2020), it is unclear how these efforts will be implemented domestically.

Therefore, there is robust evidence of energy injustices in Portugal's EV transition, particularly in relation to lithium mining, most notably the Barroso project, and the uneven distribution of EV ownership and charging infrastructure between urban and rural populations. Additional concerns, such as potential job losses in the fossil fuel sector, disparities in flexibility capital, effects on electricity tariffs, and the risks associated with battery disposal, have also been identified. However, these latter issues warrant further investigation due to limited available evidence.

Table 5-1 provides an overview of the justice-related challenges associated with EV uptake in Portugal, which are analyzed in greater detail in **Chapters 6 and 7**. It contains the respective EV lifecycle stage, the system boundary or the boundary of analysis, the spatial scale of the issue[3], and the related energy justice issue.

[3] Sovacool, Hook et al. (2019) conceptually framed the spatial scale of energy justice as *micro* ("within communities and close to infrastructure"), *meso* ("at the national and supra-local level"), and *macro* scales ("transational and beyond any single country").

Table 5-1. Summary of whole-systems energy injustices of EVs in Portugal.

Lifecycle stage	System boundary	Spatial scale	Energy justice issue
Resource extraction and processing	Lithium mining in "Mina do Barroso-Alvão", Northern Portugal	Micro	Procedural, recognition-based, and distributional injustices associated with the Barroso lithium project as reported by Canelas and Carvalho (2023)
Operation	EV ownership and charging infrastructure between urban and rural populations	Meso	Distributional injustice associated with the uneven uptake of EVs between urban and rural populations reported by (Morrison & Wappelhorst, 2022). Spatial density analysis of public charging stations pointed to unequal distribution of charging infrastructure (Dall-Orsoletta, Oosthuizen, et al., 2025).

To complement the case study analysis and enrich the interpretation of justice dimensions in Portugal's EV transition, a face-to-face participatory workshop was conducted in Braga, Portugal on January 13th, 2025. The workshop convened 17 participants from diverse backgrounds, including users and non-users of EVs, with the aim of fostering a broader understanding of the systemic justice implications associated with EV transitions, both within Portugal and in global contexts. Although the workshop was conducted after the primary documentary identification of injustices, focused on lithium mining and EV operation, it served as an important opportunity for reflection, validation, and triangulation of the research findings. **Figure 5-1** provides an overview of the activities conducted during the workshop.



Figure 5-1. Face-to-face workshop conducted in Portugal on January 13, 2025.

In addition to the workshop, an online seminar was held in February 2025, offering a platform to disseminate the study's findings to a broader audience and engage in dialogue on the challenges of operationalizing justice in energy system modeling. Informal discussions during the seminar provided input for some of the points discussed in the limitations (**Section 8.2**) and future research agenda (**Section 8.3**). Particularly, future research directions in system dynamics modeling, transport systems, and justice concerns, and limitations with regards to the lack of participatory approaches and the inclusion of marginalized perspectives in the developed models were discussed in detail.

5.3 Translation of justice concerns into system dynamics modeling

Justice concerns in Portugal's EV transition materialize in (i) the environmental and social impacts of lithium mining in the Barroso region and (ii) disparities in EV ownership and public charging infrastructure between urban and rural populations. This section illustrates how system dynamics modeling was employed to assess these justice-related concerns, both conceptually and quantitatively.

It is argued herein that system dynamics modeling can be a key tool for evaluating justice in low-carbon transitions. First, it supports conceptual understanding through CLDs (as presented in Appendix I and

demonstrated in **Chapter 4**), which help map the interdependencies and feedback loops[4] underlying observed asymmetries. CLDs clarify how different elements interact to reinforce or mitigate these asymmetries and are particularly effective in participatory research contexts (Galende-Sánchez & Sorman, 2021; McGookin et al., 2021). **In Chapter 6**, a CLD was used to structure stakeholder perspectives on the dynamic relationship between social acceptance and mining project developments. The CLD was developed based on semi-structured interviews with mining experts, environmental non-governmental organizations (NGOs), and researchers specializing in environmental, social, and governance (ESG) and mining governance, which were conducted between July and December 2023.

Second, system dynamics models allow for the integration of justice-related indicators and quantitative proxies, enabling the simulation of how these indicators evolve under different policy or development trajectories. In the case of the Barroso Mine (**Chapter 6**), energy justice issues were operationalized using indexes (0-10) representing environmental impacts, socioeconomic impacts, and procedural justice. Environmental impacts were based on water depletion and land disturbance, whereas the socioeconomic impacts reflected local employment and reinvestment. Procedural justice was represented as a scale variable (0-10) incorporating a "sticky-slippery" dynamic to capture the asymmetry between rapid deterioration and slow recovery of public perception (Verrier et al., 2022). Scale values from 0-10 were estimated from the available literature and attempt to translate qualitative evaluations into a quantitative scale: Very low [0-2), Low [2-4), Medium [4-6), High [6-8), Very high [8-10]. This is a stylized representation that did not benefit from stakeholder input or resulted from applying a questionnaire or survey.

Furthermore, system dynamics allows for the consideration of different stakeholder groups (aka, agents, transition actors) based on, for example, income levels, political influence, region (e.g., urban, rural), educational level. In the lithium mining case, government's, company's, and community's interests were considered separately, although they were not directly contacted. Also, in **Chapter 7**, EV adoption and equitable access to EVCI was considered between two population groups: urban and rural. Although both instances refer to simplified representations of more complex, multi-agent decision systems, they represent the capacity of system dynamics models to consider and integrate different stakeholders into models.

[4] For methodological guidance on how to build a CLD, refer to Sterman (2000, Chapter 5).

In Chapter 6, the quantitative model simulated how levels of social acceptance affect the long-term viability of the mining project under two concession periods (11 and 31 years). Technical data were sourced from the Barroso lithium project (Savannah Resources, 2021a, 2023), and parameter values were based on recent studies (Araújo et al., 2022; Canelas & Carvalho, 2023; Dunlap & Riquito, 2023; Ribeiro et al., 2021). The model underscored the dynamic nature of justice concerns by showing how trust plays a critical role in project development, and how mismatches between governmental and community's interests can lead to project disruptions, revealing key leverage points for policy and stakeholder engagement. A detailed model description and discussion on limitations are presented in **Chapter 6**.

In Chapter 7, a second application of system dynamics modeling focused on national-scale equity concerns related to EV ownership and charging infrastructure. Here, the justice dimension was framed around disparities between urban and rural areas, using two core indicators:

- **EV ownership disparity:** Tracked by the percentage share of EVs in urban versus rural populations over time.
- **Charging infrastructure equity:** Measured using two density indicators, charging stations per 1,000 km^2 (spatial equity) and per 100,000 people (population equity), combined into a ratio (urban-to-rural) where values near 1 signal more equitable distribution.

This model was calibrated using historical data from 2010 to 2021 (Mobi.E, 2024; Morrison & Wappelhorst, 2022) and projected forward to 2050. It simulated the impact of different policy scenarios on EV adoption and access equity, revealing for example how subsidies, although well-intentioned, can exacerbate existing inequalities between urban and rural populations. The model illustrated that while national EV growth may appear positive in aggregate terms, justice concerns may persist beneath the surface, especially if scrapping policies are not effective. A detailed model description and discussion on limitations are presented in **Chapter 7**.

The decision to develop two separate system dynamics models (one focused on lithium mining at the local level in **Chapter 6** and the other on national EV equity in **Chapter 7**) was driven by both conceptual clarity and methodological rigor. These models operate at different levels of abstraction, a term that refers to the degree of generalization or simplification used to represent a system's components, structure, and behavior (Sterman, 2000). Abstraction levels guide the scope of a model by determining what is included, what is omitted, and how much detail is appropriate for the questions being asked. In **Chapter 6**, the

local model of the Barroso lithium mine emphasizes site-specific socio-environmental dynamics, such as procedural justice in stakeholder engagement and distributive impacts on local communities. In contrast, in **Chapter 7**, the national model on EV ownership and charging infrastructure adopts a broader abstraction level suited to systemic equity concerns across Portugal's urban and rural populations. It abstracts from individual-level dynamics or specific locations and instead uses aggregate indicators (e.g., EV shares, charging station densities) to assess macro-level policy effects and regional disparities. By maintaining model separation, each justice concern is addressed at the appropriate scale and with the appropriate level of detail.

Table 5-2 summarizes the reasons behind the utilization of system dynamics as the computational modeling approach employed in this thesis.

Table 5-2. Rationale for the utilization of system dynamics as the computational modeling approach to explore justice concerns in the energy transition.

Characteristic	Comment
Representation of stakeholders involved in energy and low-carbon decisions	Justice concerns are highly contextual and vary according to stakeholders' perspectives over what is fair or just. The ability of system dynamics to represent different stakeholder groups and their decision dynamics is crucial to build understanding over energy transition asymmetries.
Representation of dynamics generated by feedback loops and delays	Human capacity is very limited when it comes to accounting for the consequences of feedback loops and delays for the overall system behavior. Humans often underestimate their effects and perform poorly in managing complex dynamic systems. In this regard, system dynamics figures as a tool to build understanding on the effects of feedback loops and delays involved in the energy transition, related policies and technologies' adoption.
Experimentation and learning through participatory model building, policy and scenario testing	In the energy transition context, justice-related concerns often arise from impartial, mis-informed, or uninformed decisions and policies. The participatory development of system dynamics models and CLDs can enhance understanding over potential or current issues associated with a certain low-carbon technology or policy. Different from other modeling approaches, system dynamics is highly visual, facilitating its understanding by lay users. A finalized model (i.e., implemented and calibrated) can serve as a "flight simulator" in which policies and scenarios can be tested in a protected, virtual environment, rather than in practice.
Problem-oriented approach	Particularly, system dynamics models can be developed to address a particular problem, requiring well defined boundaries and problem understanding. This relates directly to having appropriate abstraction levels or, in the case of justice concerns, appropriately capturing context-relevant dynamics.

Nonetheless, across both cases, system dynamics modeling served not as a predictive tool, but as a method to explore the dynamic complexity of justice concerns in the EV transition. By incorporating feedback loops, policy delays, and stakeholder perceptions, system dynamics models may help reveal how injustices can become self-reinforcing over time. However, these models should be interpreted with caution. As emphasized in the literature, the goal is not to precisely replicate societal dynamics, which remain too complex for formal models (McDowall & Geels, 2017), but to enable learning and reflection about the conditions under which justice issues arise and evolve.

6 Modeling lithium mining project dynamics in Portugal

This chapter is based on the article titled "*How does social acceptance affect transition minerals production in Europe? A system dynamics approach and case study in Portugal*" which has been published in *The Extractive Industries and Society*. The content presented here reflects the key findings and discussions of the original manuscript, with some adaptations to fit the overall structure of this thesis.

How does social acceptance affect transition minerals production in Europe? A system dynamics approach and case study in Portugal

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Abstract: Against the backdrop of competing interests between mining developments, energy transition minerals procurement, and local communities striving to preserve their heritage and livelihoods, this paper delves into the dynamics between mining and social acceptance. Drawing from a participatory approach, the study offers qualitative and quantitative insights into this complex relationship. Cause-and-effect links surrounding social acceptance and mining activities are represented in a CLD, which illustrates how social acceptance is affected by trust, perceived procedural fairness, socioeconomic and environmental impacts, and (mis)alignment between government and community's interests. The conceptual diagram aided the development of an adaptable quantitative system dynamics model, which is applied to a case study, the Barroso lithium project in Northern Portugal. Analysis reveals how low levels of social acceptance during initialization and across the project lifecycle can lead to a significant decrease in operational performance and the amount of lithium recovered, while attempts to obtain the social license to operate (SLO) are highly dependent on building genuine trust. The relevance of trust-

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building delays for decarbonization agendas is also discussed. The paper concludes by delineating a future research agenda that points to embedding community engagement as core rather than side practice to leverage industry and policy decision-making towards JETs.

6.1 Introduction

Research on mining-community relationships is gaining increased attention in Europe after the European Commission supported the expansion of raw materials extraction and the establishment of a sustainable supply chain within Europe (Lesser et al., 2021). This expansion comes as a response to an increased demand for energy storage technologies, EVs, and grid development, all crucial for the decarbonization of the energy system, and increasingly, energy security. The IEA forecasts that globally, the number of EVs could reach 350 million by 2030 and nearly 2 billion by 2050 (IEA, 2021a). This represents an estimated 30- and 200-fold increase compared to 2020 levels. Despite the fast development of alternative technologies, lithium-ion batteries are currently regarded as the most efficient and reliable (Miao et al., 2019), thereby driving increased demand for lithium worldwide. According to IEA's Global Critical Raw Materials Outlook (IEA, 2024a), global lithium demand could reach 1,700 kt by 2050 in the Net-Zero Scenario, a tenfold increase from 2024 levels, largely due to the growth in the EV industry demand. Lithium has been labelled a critical raw material by both the European Commission (European Commission, 2022a) and the US Geological Survey (US Geological Survey, 2021) due to its economic importance and supply risk.

In this regard, "*recycling is indispensable to the security and sustainability of critical minerals supply for clean energy transitions*" (IEA, 2024c), and several studies have assessed the potential of lithium recycling for decreasing raw material extraction. For instance, a recent study by Bruno and Fiore (2024) has forecasted the amount of lithium that could be recovered from end-of-life EV lithium-ion battery in Europe. Accordingly, the European lithium-ion battery recycling could receive 175 t of lithium in 2030, of which 96% could be recovered by hydrometallurgy. Nonetheless, the authors also mention that the treatment capacity of European recycling plants could supply as much as 2% of the weight required to meet European lithium-ion battery production in 2030 (Bruno & Fiore, 2024). In other words, recycling, although of high importance for reducing lifecycle emissions and reducing the demand for raw materials, will not stop the need for increased raw materials extraction in the current global low-carbon transition.

The IEA forecasts that China (responsible for 23% of the global lithium production), Chile (12%), and Australia (33%) will remain the largest global lithium producers by 2030, whereas China (57%), Chile (15%), and Argentina (13%) figure as the world's largest refiners of lithium (IEA, 2024a). Nevertheless, different extraction techniques are required according to the reserve type. In Chile and other parts of the Lithium Triangle, lithium is extracted from underground saltwater brines found in salars (Fornillo & Lampis, 2023). This process involves pumping brine to the surface and allowing it to evaporate in large ponds, leaving lithium-rich solutions that are then further processed (Flexer et al., 2018). In contrast, in Australia, lithium is typically mined from hard rock deposits, particularly spodumene, through open-pit or underground mining, which includes drilling, blasting, crushing, and processing the ore to extract lithium concentrates (Bos et al., 2024). Each method presents unique challenges and environmental impacts, such as water-intensive process for brine extraction and habitat disruption from mining activities (Flexer et al., 2018). The geographical concentration of lithium and cobalt mining and refining, critical raw materials for EV batteries, in specific countries is discussed in Dall-Orsoletta, Dranka, and Ferreira (2022) from the perspective of energy justice (Sovacool & Dworkin, 2015). In an attempt to meet forecasted demands and reduce lithium supply dependency of external sources, several new mining projects are being proposed across Europe. Some of Europe's most prominent lithium projects include the Barroso lithium project in Northern Portugal by the British company Savannah Resources[6], the Imerys' EMILI project in France[7], the Sibanye-Stillwater's Keliber project in Finland[8], and the European Metals' Cinovec in the Czech Republic[9]. All these projects boast estimated lithium reserves exceeding 100 million tons of lithium carbonate equivalent (LCE). Nonetheless, new mine developments are likely to have competing interests, values, and visions with local communities trying to preserve their heritage and livelihoods (Mononen et al., 2022). Recent anti-mining protests in Serbia against the Rio Tinto lithium mining project in the Jadar region illustrate the socio-environmental tensions inherent in resource extraction for the energy transition (Vasovic et al., 2024). Although the project was initially halted in 2022 due to environmental concerns, widespread protests have resurged following the Serbian government's decision to reinstate Rio Tinto's license. According to Rio Tinto, the license would enable the development of Europe's largest lithium, with the potential to meet 90% of the continent's lithium demand (DW, 2024).

[6] Savannah Resources, Barroso Lithium Project [webpage], https://www.savannahresources.com/project/barroso-lithium-project-portugal/, (accessed on 30 January 2025).
[7] Emili Imeris, EMILI Project [webpage], https://emili.imerys.com/en/emili-project-overview, (accessed on 30 January 2025).
[8] Sibanye-Stillwater, Keliber lithium project [webpage], https://www.sibanyestillwater.com/business/europe/keliber/, (accessed on 30 January 2025).
[9] European Metals, Cinovec vertically integrated battery metals project [webpage], https://www.europeanmet.com/cinovec-project-overview/, (accessed on 30 January 2025).

In this context, Stuehlen and Anderl (2024) analyze the emergence of the anti-mining resistance movement in the Jadar region, highlighting the tensions between top-down policies and bottom-up concerns, exemplifying the complex intersection of global and local interests. On one hand, the EU Green Deal emphasizes the strategic importance of securing "green" energy resources like lithium to support decarbonization goals. On the other hand, local communities voice significant concerns over ecological degradation and community well-being in face of potential disruptions to traditional livelihoods.

From this perspective, power dynamics between mining companies and local communities play a relevant role in the extent of mining impacts and the trajectory of mining project development. The concept of a SLO has emerged as a crucial factor in ensuring positive outcomes from mining projects. The SLO is mainly conditioned by the existence of trust in mining companies and government, coupled with adherence to principles of procedural fairness (Lesser et al., 2021). Nonetheless, despite its potential to mediate conflicts, the SLO does not negate the substantial environmental and social disruptions often caused by mining. Critics have pointed to the risk of "greenwashing of mining" (Bolger et al., 2021), where environmentally harmful practices are rebranded as necessary for the energy transition. Additionally, the concept of "resource justice" (Marin, 2024) highlights the need to prioritize reducing resource and energy demand to fulfil societal needs, as opposed to perpetuating material extraction and consumption. These debates are particularly relevant in the context of policies like EU's pursuit of supply chain resiliency (Bolger et al., 2021).

Based on the presented narrative, this paper aims to explore the complex dynamics of mining developments and social acceptance, employing both qualitative and quantitative approaches. The paper explores how social acceptance is influenced by the environmental, social, and economic impacts of mining activities, and conversely, how social acceptance impacts the development of mining projects activities. The qualitative approach utilizes a participatory process to develop a conceptual model that visually represents the cause-and-effect links among system components, based on the systems thinking methodology. Then, a system dynamics model is employed to quantitatively explore these dynamics in the context of a lithium mining case study in Portugal. Building on this, the research translates into the following research questions: "*What are the interdependent relationships between social acceptance and mining activities?*" and "*How may social acceptance affect the development of the Barroso Lithium Project in Portugal?*".

This study offers a two-fold contribution to existing literature. First, it advances the existing literature on complex sociotechnical aspects of mining by focusing on the participatory identification of feedback loops

between social acceptance and mining activities. Secondly, it contributes to the literature on the quantitative analysis of social aspects by advancing the developed conceptual diagram towards a quantitative system dynamics model that explores a real-world case study of lithium mining in Northern Portugal, the Barroso mine project, one of the first quantitative analyses of social acceptance dynamics in this specific context. The research topic is particularly timely and relevant considering the EU Green Deal and targeted policies meant to build supply-chain resiliency on one side, and the potential generation of conflicts with local communities on the other. This work also underscores the dynamic relationships that must be considered by stakeholders when working on strategic mine planning and community engagement practices and sheds new light on the development of the controversial Barroso lithium project.

The remainder of this paper is organized as follows. **Section 6.2** presents relevant literature on the impacts of mining activities, the SLO and its related factors, and the application of systems thinking and systems dynamics to mining. The research methods are then presented in **Section 6.3**, while **Section 6.4** presents and discusses the results. Finally, **Section 6.5** concludes this work with the main findings, limitations, and a future research agenda.

6.2 Literature review

6.2.1 Social, economic, and environmental impacts of mining activities

Mining can have significant economic as well as ESG consequences, influencing how communities perceive and respond to mining projects. The extent and nature of a mining project's impacts vary depending on several factors, including the type of ore being extracted, the technologies used in the extraction and processing stages, the vulnerability of the area, and the regulation and compliance with social and environmental standards. Nevertheless, the mining sector remains historically linked to environmental impacts, such as soil contamination, air and water pollution, deforestation, and loss of biodiversity (Muhirwa et al., 2023). Mining can also lead to the displacement of communities (Muhirwa et al., 2023), which presents serious risks for the livelihoods, health, and social ties of its members (see (Marshall, 2023) analysis of Vale's coal mines and their extensive footprint in Mozambique). Indigenous people are frequently disproportionately affected by mining activities, often forced to leave their heritage and land behind (Conde & Le Billon, 2017). Neighboring communities are also more susceptible to suffer

from the negative health impacts of mining pollution as evidenced by Dibattista et al. (2023) in the region of Boké, Republic of Guinea. The economic, political or social marginalization of communities can exclude people from participating in the decision-making processes associated with the project (Conde & Le Billon, 2017).

Furthermore, the mining process itself can be resource-intensive, demanding high levels of energy (see (Kolie et al., 2024) assessment of energy and water infrastructure management in the Republic of Guinea), water (see (Damonte et al., 2021) for mining-generated water insecurity), and labor (Marshall, 2023). Depending on the extraction method, reagents, and techniques, mining can also place significant biophysical pressure on the environment (see (Boldy et al., 2021) for the impacts of mining on ecosystem services) and compete for resources with local communities. However, recent advancements in regulations and technologies are paving the way for less environmentally damaging mining practices (UNDP and UN Environment, 2018). Mining projects can also create a dependency between the community and the company's jobs, revenue, or benefits stemming from Corporate Social Responsibility (CSR) Programs (Mononen et al., 2022). Additionally, mineral extraction can bring economic benefits at the national level, potentially increasing export earnings and government revenue through taxes and royalties (see, e.g., (Lundstøl, 2022) analysis of Zambia and Tanzania mineral revenues from 2000 to 2013). On the other hand, the anticipation of future resource extraction revenues can also have detrimental effects to countries' political and economic stability, as showcased by Frynas and Buur (2020) with the "presource course" in African countries.

In summary, whether mining activities contribute to socioeconomic development or not is subject to a series of factors, such as the existing political and governance capacity (Lamas, 2023), the preparedness of local and national governments to manage resources revenues (Frynas & Buur, 2020), and the local socioeconomic context (Conde & Le Billon, 2017). It must be clear, however, that the existence of natural resources is not equivalent to economic prosperity, the so called "resource curse" (Lundstøl, 2022; NRGI, 2015). **Table 6-1** summarizes the main impacts often associated with large-scale mining, as presented in a recent study commissioned by the Policy Department for Citizens' Rights and Constitutional Affairs for the Committee on Petitions about the social and environmental impacts of mining activities in the EU (Mononen et al., 2022).

Table 6-1. Positive and negative impacts of large-scale mining. Source: Adapted from (Mononen et al., 2022).

Impact Category	Positive Impact	Negative Impact
Environmental	-	Changes and loss of biodiversity; Soil, air, and water pollution; Land degradation; Water scarcity/depletion; Noise pollution and vibration; Changes to land, topography, and landscape (i.e., aesthetic degradation);
Economic	Creation of local employment; Contracting opportunities; Revenue sharing from taxes and royalties; Infrastructural development; Positive impacts on existing livelihoods (e.g., hospitality services);	Negative impacts on existing livelihoods (e.g., agriculture); Economic risk of local dependency;
Social	Revitalization of areas: new people and activities;	Health issues; Land and resource use competition; Negative impacts of migration to mining area; Disputes and conflicts; Loss of sense of place and traditional practices; Displacement;

6.2.2 Social acceptance, trust, and procedural fairness

It has been increasingly recognized that meeting legal requirements related to the environment is no longer sufficient to meet societal expectations concerning mining activities (Bridge, 2004; Moffat & Zhang, 2014). The SLO can be defined as "*an informal social contract that aims to bridge the gap among the views of the most important stakeholders involved in mining activities*" (Komnitsas, 2020). In other words, when mining companies obtain their SLO, they mitigate potential conflicts and minimize business risks (Prno, 2013). In this vein, calls for increased community participation in decision-making processes are seen as crucial for achieving an SLO, as they help to mitigate project risks (Prno, 2013).

In mining, the SLO necessitates broad and sustained societal acceptance (Joyce & Thomson, 2000; Thomson & Boutilier, 2011). As pointed by Dobele et al. (2014), it is "*imperative to build trust and social legitimacy within the local community*" for stakeholder engagement and management towards CSR. However, securing social acceptance at both the community and public levels can be challenging due to inherent ESG trade-offs between economic growth and environmental conservation, (trans-)national interest against local benefits, and diverging future expectations (Lesser et al., 2021).

Critiques regarding the practical application of the SLO have raised concerns about legitimacy (Brueckner & Eabrasu, 2018) and coverage (Pedro et al., 2017). One criticism concerns the usage of the terms 'license' and 'social' and their potentially misleading nature (Pedro et al., 2017); a business-driven approach to avoid public opposition (Owen & Kemp, 2013); and the lack of clear definition supported by "*the normative complexity surrounding the SLO construct*" (Brueckner & Eabrasu, 2018). The replacement of the SLO with a "sustainable development to operate" or SDLO, has been suggested to contribute more comprehensively to the achievement of the UN's SDGs (Pedro et al., 2017).

Despite the criticisms raised, a substantial body of literature explores the SLO, encompassing conceptual frameworks (e.g., (Lesser et al., 2021; Prno & Slocombe, 2014)) as well as case studies (e.g., (Cesar & Jhony, 2021; Cruz et a., 2021; Litmanen et al., 2016)). In practice, the SLO has been established as part of mining developments, especially in North and South America and Australia. However, in Europe, the concept is "*still in early maturation and acceptance*" (Lesser et al., 2021). Studies considering the SLO in the European context include Jartti et al. (2020) and Litmanen et al.'s (Litmanen et al., 2016) assessment of the preconditions of the SLO in the Finnish context, and Mononen and Sairinen (2021) reporting on a successful SLO case in medium-sized Kylylahti multi-metal mine in Eastern Finland. Taking the case in Norra Karr in Sweden, Barakos and Mischo (2021) discussed the importance of considering the SLO in the early evaluation of mining projects as a means to determine their viability.

Most studies explored various aspects when trying to assess and quantify the SLO, including trust in the company and government's regulatory capacity (Thomson & Boutilier, 2011), procedural justice (i.e., how the community participates in the decision-making process (Besley, 2010)), and the perceived impacts of mining, as proposed by Moffat and Zhang (2014). These aspects can interact and influence each other in complex ways, depending on the specific cultural and political context under analysis (Cruz et al., 2021; Lesser et al., 2021; A. Zhang et al., 2015).

6.2.3 Systems thinking, system dynamics, and mining projects

Systems thinking can be understood as a way of comprehending the complex nature of the world that differs from a linear and disaggregated perspective. The concept of systems thinking is founded on the principle of complexity, which asserts that "*a system is more than a collection of its parts*" (Meadows, 2008). Due to its systemic nature, systems thinking has gained recognition as a highly suitable approach to tackling society's complex challenges (CST, 2020). Particularly, system dynamics is a simulation-based modelling technique based on systems thinking, which has been applied to a wide variety of fields (e.g.,

energy systems (Bolwig et al., 2019)). By capturing complex dynamics of systems through feedback loops and endogenous behaviors (Spittler et al., 2019), system dynamics models enable an improved understanding of how the system behaves over time and provide valuable insights for effective system management (Ford, 1999). Furthermore, system dynamics models have been increasingly suggested as a resourceful tool for sustainable TM (Bolwig et al., 2019), particularly due to their ability to incorporate complex and delayed dynamics and social aspects (Dall-Orsoletta, Uriona-Maldonado et al., 2022). System dynamics has been already linked to the socio-technical transition literature, socio-political domains of the transition (de Gooyert et al., 2016; Freeman, 2021; Verrier & Strachan, 2024), and other theoretical frameworks such as the multi-level perspective and strategic niche management (Martin et al., 2020).

System dynamics simulation models applied to mining include Sverdrup's global lithium cycle model (Sverdrup, 2016), and earlier works for other metals, such as rare earths (Kifle et al., 2012), copper (Sverdrup et al., 2014), silver (Sverdrup et al., 2014), and aluminum (Sverdrup et al., 2015). Exemplifying system dynamics application in management decisions, Jafarpour and Khatami (2021) developed a system dynamics model to evaluate how incorporating environmental costs associated with different green mining strategies, such as water recycling, can impact the total mining costs of a copper mine in Iran.

In an advancement of the representation of mining socio-technical aspects from a systems perspective, Verrier et al. (2022) proposed a system dynamics model to quantify the dynamics amongst the use of cyanide in gold leaching operations, environmental impacts, community and public trust, and operational productivity. The authors linked the effect of community and public trust on overall mining operations' productivity, employing both "soft and hard data". Among avenues for improvement, the authors highlighted the inclusion of other "perceived" variables such as "actual impacts vs. perceived impacts" and "mistaken interpretations by media and public" (Verrier et al., 2022). A user-friendly tool was also created for the model, which is available online for experimentation[10].

Complementing quantitative system dynamics modeling, CLDs offer a qualitative systems-thinking-based tool that visually depicts the interdependencies between variables within a system. A CLD is a simple word-and-arrow diagram used to indicate causal relationships among system variables (Ford, 1999).

[10] Isee Exchange, The cyanide socio-technical learning lab [website], https://exchange.iseesystems.com/public/smijkmrc/the-cyanide-socio-technical-learning-lab/index.html#page1

These relationships are denoted by a polarity (+ or -) that indicates the reinforcing or opposing nature of the relationship. A positive polarity (+) indicates that "*if X increases so does Y*", and "*if X decreases so does Y*". On the other hand, a negative polarity (-) means that "*if X increases, Y decreases*", and "*if X decreases, Y increases*". CLDs are often used to represent dynamic relationships in complex systems, as in (Janipour et al., 2022) and (Salim et al., 2020). Additionally, the employment of participatory methods to develop CLD has been consistently referred to as an adequate approach to capture different stakeholders' perspectives on problems, reduce modelers' biases, and support a shared learning process (McGookin et al., 2021). Examples of techniques include group model building (Eker et al., 2018) and interviews (Perrone et al., 2020). In the mining context, Alozie's Ph.D. thesis (Alozie, 2019) proposed a participatory framework based on systems thinking for the sustainable management of mineral resource-active regions. The author underscored how the tool could avoid conflicts and support collaboration among stakeholders.

Prno and Slocombe (2014) developed a systems-based conceptual framework to investigate the determinant factors in obtaining the SLO. The proposed framework comprises four main components: system characteristics, multi-scale variables, local variables, and SLO outcomes (Prno & Slocombe, 2014), which can be interconnected through feedbacks loops, reflecting the principles of systems thinking. Local variables include those involved in mining-community relationships, such as mining technology, community engagement performance, and the needs, aspirations, and expectations of local people (Prno & Slocombe, 2014).

Building upon the literature reviewed in the previous sections, the following four central aspects can be highlighted. First, mining activities can have a wide array of environmental, economic, and social impacts, at different scales. Secondly, concerns over the social impacts of mining activities have received growing attention in the past decades, especially from a CSR perspective and the obtainment of the SLO. However, existing research on SLO primarily focuses on pre-conditions for obtaining it, neglecting the dynamics of social acceptance over time. Thirdly, conceptual models developed within the mining sector can further benefit from participatory methods given the complex and conflicting nature of mining developments. Lastly, targeted quantitative system dynamics models focus on technical and economic aspects of mining. Recent efforts to employ a systems perspective and incorporate social factors into modelling deserve further exploration.

6.3 Research methods

Recognizing the multifaceted nature of social acceptance of mining projects, a mixed-methods approach was employed to achieve the research objectives. The research design comprises a three-phase process (**Figure 6-1**): the development of a conceptual diagram supported by literature and interviews, a case study investigation, and finally the development of a quantitative SD model. The following sections will describe each phase in more detail.

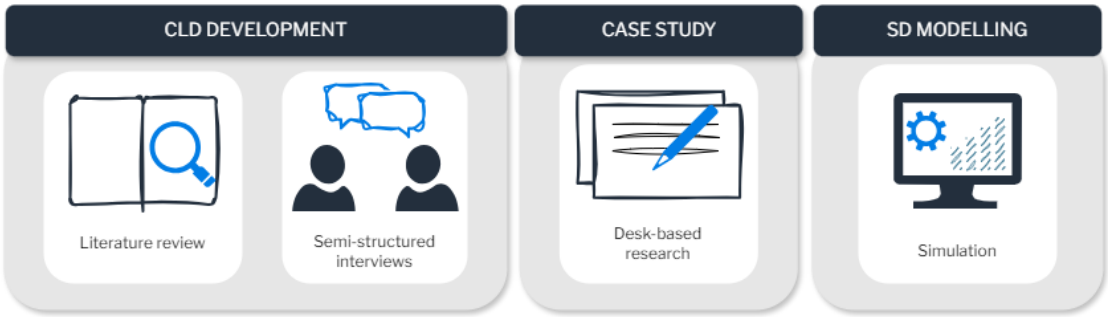


Figure 6-1. Research design phases.

6.3.1 CLD development

Semi-structured interviews were used to establish links within the mining-social acceptance nexus and iterate the CLD in a participatory way. CLDs allow to capture the non-linear nature of socio-technical systems and their feedback loops, where both physical materials (e.g., environmental impacts) and information (e.g., community perceptions) flows influence each other over time. A participatory CLD development reduces the risk of author bias, assembles the perspectives of different stakeholders into one diagram, and can enable a shared learning process by visually representing complex interdependencies (McGookin et al., 2021). In-depth semi-structured interviews were conducted with seven mining specialists and relevant stakeholders (**Table 6-2**) from July to December 2023, following a snowballing approach (H. K. Salim et al., 2020). The interview process specifically targeted stakeholders representing a variety of perspectives on mining, including academia, industry, government, and civil society. Importantly, civil society voices were included through NGOs directly involved in the representation of local communities affected by the case study and broad environmental issues in Portugal. The selection strategy ensured the inclusion of individuals with expertise in diverse areas such

as mining sustainability, process optimisation, socio-environmental conflicts, constitutional law, community investment, and grassroots concerns and advocacy (see **Table 6-2**).

Interviews were held online in Portuguese and English and lasted for approximately one hour. The interview process itself consisted of going through the links and variables depicted in the CLD and collecting suggestions and feedback from interviewees. Therefore, each subsequent interview was based on the reviewed and updated CLD resulting from the previous interview. New participants were invited until no significant new information emerged, indicating data saturation (Salim et al., 2019). The first interview relied on an initial CLD drawn by the authors based on the literature. CLDs were built using Vensim v10.0.0 and Stella Architect.

Table 6-2. Participatory CLD development interviewees.

N.	Participant Role	Stakeholder Group	Experience	Country [Home/ Current]
1	Director of Research Centre	Industry, Academy, Government	+20 years in mining operations, especially in process optimization	Iran / Australia
2	Professor	Academia	+5 years in mining sustainability	Brazil/ Portugal
3	Postdoc Researcher	Academia, Industry	+5 years in energy and emissions budgeting and reporting in mining	South Africa/ Australia
4	Senior Manager	Industry	+10 years in mining impact management, sustainability reporting, and community investment	Chile
5	Director of NGO	Civil society	+10 years in environmental and social issues	Portugal
6	Postdoc Researcher	Industry, Academy, Government	+10 years in socio-environmental conflicts, rights, and constitutional law	Canada/ Netherlands
7	NGO Manager	Civil society	+5 years in environmental and social issues related to mining in Portugal	Portugal

6.3.2 Case study

Portugal has a longstanding history of lithium production for the ceramics and glass industries (Domingues, 2022), reaching a production of 600 metric tons in 2022 (Statista, 2023). However,

increasing global demand for lithium, driven by rise of EVs and energy storage technologies, has prompted strategic evaluations of Portugal's mineral deposits. This effort was spearheaded by the "Grupo de Trabalho 'Lítio'" (Lithium Working Group - GTL), established by the Directive n.º 15040/2016 (RCM nº 11/2018, 2018). In 2016, GTL identified nine regions with significant lithium deposits in Portugal, among which the Barroso-Alvão region in the Northern region. In a subsequent Strategic Environmental Assessment conducted under the "Programa de Prospeção e Pesquisa do Lítio" (Lithium Prospecting and Search Programme - PPP Lítio), eight regions were assessed for potential development. Following a reduction in their original areas, six were approved for the tender process. Notably, the Barroso-Alvão region was excluded from this evaluation as it had already been conceded to Savannah Resources. Additional concessions had been granted in Argamela (to Neomina in 2021) and Montalegre (to Lusorecursos), although both projects have faced obstacles: Neomina failed to deliver an Environmental Impact Assessment (EIA) in face of biodiversity concerns (Ferreira & Gabriel, 2024), and Lusorecursos encountered intense local opposition (Lusa, 2024a).

Alongside "Mina do Romano" in Montalegre, the Barroso Mine, located in the Barroso-Alvão region, represents one of the most advanced projects for mining battery-graded lithium in Portugal. The British company Savannah Resources claims that the mine contains the largest lithium reserves in Western Europe (Domingues, 2022). The company commenced prospecting drills in 2017 (Araújo et al., 2022) and argues the development of open-pit mining activities in the Barroso Mine would reach a reserve of approximately 28 million tons (Mt) containing 293,400t of Li_2O, equivalent to 725,521t of LCE[11] (Savannah Resources, 2023). Approximately 63% of this resource is located in the Grandão orebody, within the current Mining Lease. Additionally, the mining operations in the Barroso Mine will yield quartz and feldspar products that can be used in the ceramics and glass industries.

After processing the ore, the company plans to transport the spodumene lithium concentrate (≥ 5.5% Li_2O) to the port of Leixões, from where it will be exported to China. Nonetheless, the construction of a refinery in the region of Porto is also being considered (Savannah Resources, 2023), which would add value to the exported product in the form of lithium carbonate (Li_2CO_3) and potentially increase supply security in Europe. Separately, plans for a lithium refinery in Setúbal in the Metropolitan Area of Lisbon,

[11] JORC Mineral Resource Estimate for Lithium (June 2023, 0.5% Li_2O cut-off).

an initiative by the energy company Galp and the Swedish Northvolt, were recently cancelled (Lusa, 2024b), highlighting the challenges of establishing downstream lithium infrastructure in the country.

Despite receiving a conditional Positive Declaration of Environmental Impact by the Portuguese Environmental Agency (APA) following an initial rejection, the Barroso mine has faced significant resistance (Araújo et al., 2022). Many organizations and individuals in the public consultation process opposed the project, citing its location within a Globally Important Agricultural Heritage System (GIAHS) recognized by the United Nations Food and Agriculture Organization (FAO) (APA, 2023; Instituto do Ambiente e Desenvolvimento, 2022). The conditional approval requires Savannah Resources to implement extensive mitigation and compensatory measures.

The project has experienced delays, with mining operations initially expected to begin in 2023 but now anticipated to start in 2026. These delays are partly due to a public investigation into corruption and malfeasance related to the mine's concession process. The concession of the Romano Mine in Montalegre was also part of the investigation, which contributed to the resignation of former Portuguese Prime Minister António Costa in November 2023. This controversy has further complicated efforts to secure a SLO for the Barroso Mine, amplifying public scrutiny and resistance. **Table 6-3** summarizes the key technical and economic characteristics of the Barroso lithium project.

Table 6-3. Barroso lithium project: Techno-economic aspects. Sources: (Carballo-Cruz & Cerejeira, 2020; Savannah Resources, 2023).

Location	Northern Portugal, near the town of Boticas; 145km by road from the deep-water port of Leixões near the city of Porto
Mining lease	3 blocks (A, B, C), including Mine C-100 and the Aldeia exploration area, valid until 2036 and extendable for 20 years
Concession area	681,3 ha
Mining technique	Open pit mining
Mineral resource estimate	28Mt containing 293,400t of Li2O at an average grade of 1.05% Li2O (725,521t lithium carbonate equivalent, "LCE") across five orebodies as of June 2023
Life of mine strip ratio	5.9:1 (waste:ore)
Initial life of mine	14 years at 1.5 Mtpa throughput rate
Processing route and recovery rate	Crus-grind-dense media separation-flotation (73% recovery)
Average annual production	175,000 tons of lithium spodumene (6% Li_2O)

	400,000 tons of feldspar/quartz 100,000 tons of low grade pegmatite
Initial investment	EUR 98.11 million
Total costs (over 11 years)	Operation costs: EUR 510 million Freight: EUR 140 million Royalties: EUR 40 million
Community measures	EUR 40 million
Income (over 11 years)	EUR 1,420 million (85% from international sales)
Employment	Development: 300 workers Exploitation: 120 workers
Net Present Value	EUR 327 million (before taxes) EUR 221 million (after taxes)
Payback	1.7 years

Consequently, the Barroso Lithium Project is expected to exploit what Savannah Resources (2023) claims to be the most significant resource of hard rock spodumene lithium in Europe. However, similar claims have been made by other companies regarding projects such as the Jadar project in Serbia (DW, 2024), suggesting that such statements should be interpreted more as a promotional rhetoric that as definitive estimates. Achieving social acceptance is crucial for the project's development, as extensively documented in the literature (see **Section 6.4.2**). Public demonstrations across the country, combined with significant local opposition and project delays, underscore the Barroso Mine's social and political relevance, making it a compelling case study for this research. Secondary data on the project was collected from the academic literature, industry reports, and government publications, including results from the public consultation process (APA, 2023). Additionally, insights from interviews with representatives of an NGO that has direct contact with the local population have provided valuable perspectives on how residents perceive the project and their expectations. This blend of sources helps ensure a comprehensive understanding of the multifaceted social dynamics surrounding the case study.

6.3.3 System dynamics modeling

The quantitative modeling process included the development of a SFD, which consists of three types of elements: stocks (a.k.a., levels or state variables), flows, and auxiliary variables (**Figure 6-2**). Stocks represent accumulations in systems, aspects that have a history and are influenced by their past behavior. They can be tangible (e.g., recovered lithium) or intangible (e.g., community trust in mining companies).

Flows govern the level of stocks over time through output (outflows) and input (inflows), represented through rates (e.g., liter/second, EUR/month, change in trust levels/month). The last type of variables is called auxiliary or converters. They include constants, graphical functions, unit conversion factors, etc., and they help establish the interdependencies between different model elements.

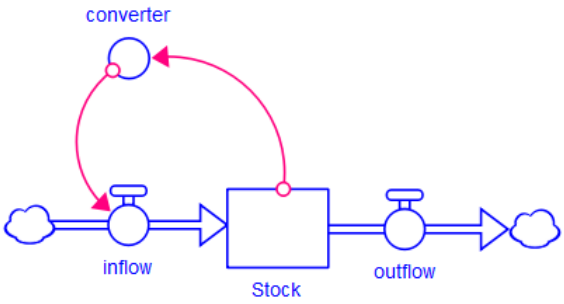


Figure 6-2. An example of stock, input and output flows, and converters. Source: Authors, built in Stella Architect 3.5.

The developed model was based on the relationships identified in the CLD and the literature, as well as data about the case study. The model was built on Stella Architect v3.5 and parametrised with technical and financial data retrieved from the company's website (Savannah Resources, 2023), a report conducted by a Portuguese Higher Education Institution (Carballo-Cruz & Cerejeira, 2020), and the literature (Domingues, 2022). Estimates for community perceptions were also gauged from the literature investigating social opposition to the project (Araújo et al., 2022; Canelas & Carvalho, 2023; Chaves et al., 2021; Domingues, 2022; Dunlap & Riquito, 2023; Ribeiro et al., 2021). Nonetheless, due to the absence of real data on the effect of social acceptance on mining developments the system dynamics model is exploratory in nature and describes stylised results. The full model structure is publicly available on the ISEE Exchange platform[12]. The validation process included parameter analysis, extreme-test validation, and sensitivity analysis to ensure behaviour consistency, as suggested by Sterman (2000). The simulation's time horizon runs through the project planned operation lifecycle, from the current development stage to mine closure, considering current and extended concession periods of 11 and 31 years, respectively.

[12] Isee Exchange, "An exploratory model: The Barroso Lithium Project" [webpage], https://exchange.iseesystems.com/models/player/alaize-orsoletta/barroso-lithium-project

The system dynamics model aims at answering "*How may social acceptance affect the development of the Barroso Lithium Project in Portugal?*" and shed light on the medium and long-term effects of prioritising different stakeholders' interests. The developed model incorporates over 180 variables, including 27 stocks, distributed across six modules: mining, financial aspects, socioeconomic development, environmental impact, and social acceptance (**Figure 6-3**). A detailed description of each module is provided as follows.

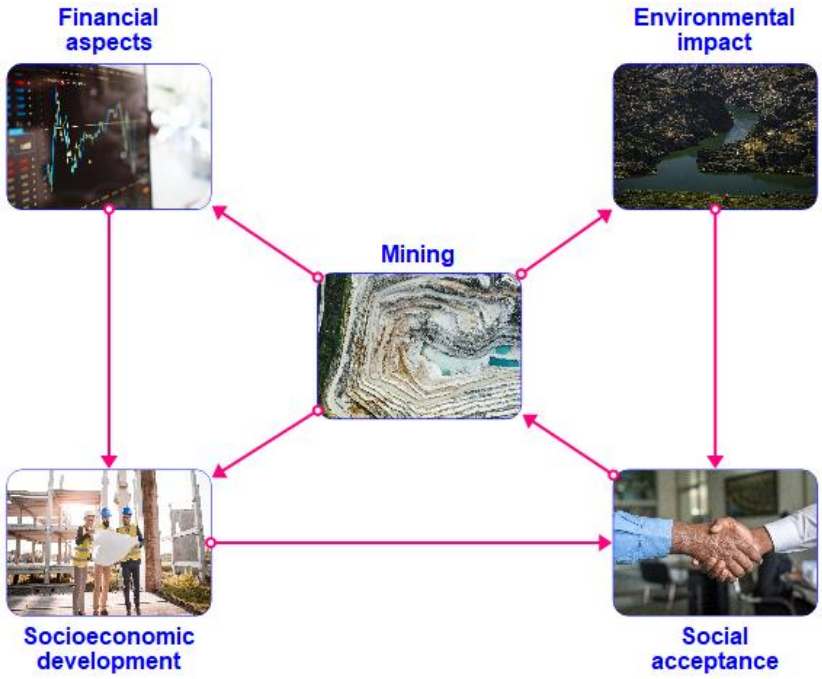


Figure 6-3. Top-level interaction of modules in the system dynamics model.

Module 1. Mining: This module, illustrated in **Figure 6-4**, entails the mining process from the start of the operations to ore extraction and processing, including waste rock and tailings management. The mine life is initially set at 132 months, with the potential for a 20-year extension (total mine lifetime = 372 months). A strip of mine ratio of 5.9:1 led to an approximate 0.17 share of ore in the mined material. Valuable materials were divided into lithium spodumene (LiS) and co-products, comprising feldspar, quartz, and low-grade pegmatite. The company's integrated waste landform was used to model the waste rock and tailings management. Tailings will be dewatered, stacked, and then transported to final storage in waste rock and tailings composite (3:1 ratio), which is expected to reduce the risk of water and soil contamination. The processing plant is expected to recycle 85% of the water used. Given local concerns

over water scarcity, water availability was also considered and accounted for seasonality effects. Mining and processing rates were calibrated according to the company's values (e.g., *company*: 16,000 and 41,600 t/month of LiS and co-products v. *model*: 17,400 and 44,700 t/month of LiS and co-products, respectively). Several time delays were considered in processing mining operations, recovering LiS and co-products, and managing tailings.

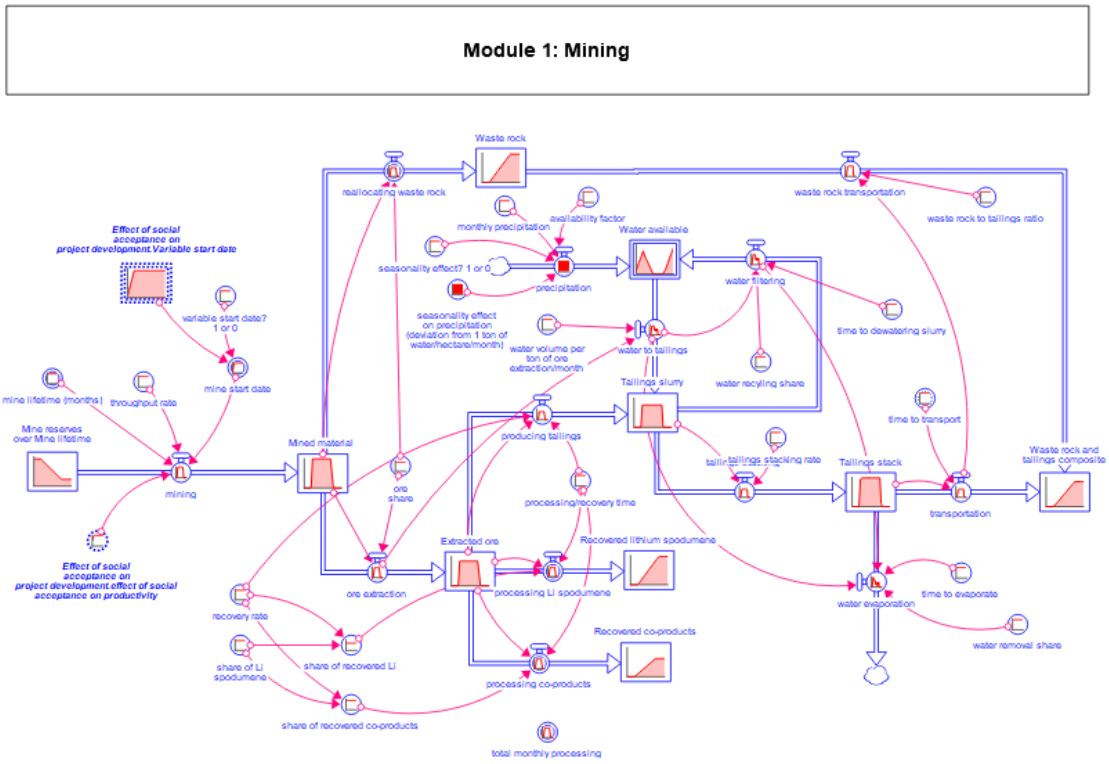


Figure 6-4. Illustrative representation of stock-and-flow (SFD) diagram for Module 1 – Mining.

Module 2. Financial aspects: This module represents economic aspects of the project including initial investment, revenues from sales, freight costs, operational costs, royalties and taxes, community development monthly expenses, and closure costs. These different variables were combined through equations to feed three stocks: Cumulative government receipts, Cumulative community receipts, and Cumulative (company) profit, calibrated according to publicly available values. The local community is expected to receive approximately EUR40 million from the project directly through the Good Neighbour and Sharing Benefits Schemes described earlier. The government (no differentiation between local or national government) is expected to receive EUR40 million from royalties plus EUR258 million in the form of taxes. The company expects a revenue of US$4.2 billion over the duration of the operations (i.e., 11

years). It assumes an average 5.5% Li_2O grade spodumene price of US$1,464/t (or EUR1,330/t assuming EUR1 = US$1.1) over the same period (Savannah Resources, 2023). This value is highly uncertain with current prices around US$800/t (Benchmark Source, 2024). For co-products, the average price of feldspar/quartz of US$110/t (or EUR100/t) was used (Savannah Resources, 2023). The company also foresees EUR510 million and EUR140 million in operational and freight costs over 11 years, with an initial investment of EUR98.11 million.

Module 3. Environmental impacts: The purpose of this module was to represent the community's main concerns over environmental impacts. Unlike the previous modules, there were no numerical estimates to support calibration. From the literature, three types of environmental impact were considered: incident-caused pollution, water scarcity, and land use. Effects of biodiversity, although relevant for the ecosystem, and pollution resulting from daily operations (i.e., non-incident-caused) were not included in the model. Land use impact was modelled as a function of the disturbance (reallocating waste rock) over the concession area and restoration efforts. Although it is known that the effects of mining activities spread beyond the concession area towards nearby roads and land, the company's concession area of 8.36 km^2 (approx. 800 hectares) was considered as a means of simplification. Water scarcity is estimated by considering the effect mining operations have on an initial water availability stock. Lastly, the risk of incident-caused pollution was modelled as a function of the average maintenance performance (rating from 0 to 10) and the probability of incident per time step, as in Verrier et al. (2022). The "calculated" environmental impact is estimated as the maximum value among the three categories of impacts. The model incorporates an asymmetrical perception regarding environmental impact (i.e. it takes less time for the community to adjust its perception negatively than to increase it positively, in a "slippery-sticky perception", as detailed for the notion of trust in Verrier et al. (2022)). It is worth noting that a high environmental impact (closer to 10) represents a more severe negative impact.

Module 4. Socioeconomic development: This module captures the main local socioeconomic impacts from mining operations. The uncertainty concerning whether the practical impact would be positive or negative in current socioeconomic activities led to a stylised assessment of the local socioeconomic development based on: additional local expenditure from community receipts, local procurement, and monthly income reinvestment. Together with job opportunities occupied by locals, these aspects are combined to estimate the resulting socioeconomic development (stock, from 0 to 10),

which follows a goal-seeking behaviour. Around 250 workers were considered to be required over the mine's lifetime. In this module, four exogenous variables are of particular relevance, namely local hiring share, the share of local contracting and services, the share of income locally reinvested, and pre-mining local spending. The initial perception of the local community indicates a potential low expected socioeconomic development (i.e., closer to 0).

Module 5. Social acceptance: Following the relationships described in the CLD, this module comprises four stocks (with values that range from 0 to 10) that present a goal-seeking behaviour: company's engagement performance, perceived procedural fairness, community trust, and social acceptance. Values closer to 10 indicate positive performances. Company's engagement performance responds to changes in social acceptance and causes changes in the perceived procedural fairness together with substantive fairness, the latter influenced by the relationship between government interests and social acceptance. If government interests in mining are much higher than the local community, substantive fairness is closer to zero and reduces procedural fairness, as pointed by the interviewees. Community trust is affected by both perceived procedural fairness and social acceptance, the latter a function of socioeconomic and environmental impacts as well as trust. Trust and perceived fairness also display a "slippery-sticky perception" behaviour, since adjustment times are different for positive and negative changes. The relevance of each one of these three stocks in the calculation of social acceptance is given by weighting factors.

It was assumed that social acceptance could affect the project development in two ways. Firstly, social acceptance can affect mining productivity through a multiplier factor used in mining (t/month). Secondly, social acceptance levels determine the project start date through a conditional formulation. Although the SLO is not a tangible aspect, it is assumed herein that a "SLO issued" is equivalent to a social acceptance value of 7 or higher. From this value onwards, the effect of social acceptance on mining production stops being detrimental. While a stylised representation, it allows for the consideration of social acceptance effects on pre-mining and mining stages.

6.4 Results and discussion

This section presents and discusses the results obtained from the conceptual CLD development and the case study-based system dynamics modelling. **Section 6.4.1** presents and discusses the CLD variables and their interconnections. In **Section 6.4.2**, the case study perspective is discussed qualitatively by tying feedback loops to the project's reality, then quantitatively through the model structure and simulation results (**Section 6.4.3**). **Section 6.4.4** discusses insights and emerging trends.

6.4.1 Feedback mechanisms and social acceptance

The CLD resulting from the literature analysis and interviews is shown in **Figure 6-5**. This conceptual diagram does not directly capture the details of the case study: it is meant to be adaptable to different context and commodities. The variables included in the CLD focused on technical, socioeconomic, and environmental aspects influencing the development of mining projects through social acceptance. Social acceptance in this case functions as a proxy for the SLO, which aligns with the literature (Mercer-Mapstone et al., 2018).

In the CLD, social acceptance is affected by trust and perceived procedural fairness in addition to socioeconomic and environmental impacts. Although trust can be a relatively hard-to-grasp aspect, its concept is often portrayed as a component and pre-condition of the SLO (Lesser et al., 2021). Trust has a direct impact on social acceptance, and both of the previous are influenced by procedural fairness (Mercer-Mapstone et al., 2018; Zhang et al., 2015), which refers to the fair and impartial treatment of all stakeholders in the decision-making process, assisting in the prevention of conflict and disputes. Since the SLO implies having trust amongst stakeholders so that negative environmental and social impacts can be mitigated while ensuring raw material supply (Komnitsas, 2020), it is necessary to have appropriate engagement strategies to cultivate mine-community partnerships (Prno, 2013). However, it is also important that involved parties understand the purpose of consultation process for genuine engagement (Deonandan et al., 2024).

According to one of the NGO interviewees that has worked closely with local communities affected by the Barroso Mine, there is a deep feeling of distrust towards the mining company. Overcoming this mistrust is likely to require significant time and sustained community engagement efforts. However, as highlighted by the interviewees, the risk of social opposition can also act as a driver for improving company's engagement performance with the local community. Cruz et al. (2021) supported the investment of

companies in building more transparent relationships for the empowerment of local communities, and Zhang et al. (2018) stressed the importance of initial engagement practices in the community members' attitudes toward mining developments.

Nonetheless, despite what seems to be an enhancement in companies' engagement practices over time, evidence suggests that community-mining operation conflicts have simultaneously intensified (Hodge, 2014). This raises critical questions about the feedback loops represented in **Figure 6-5**, particularly loops B3 and B4, which are directly influenced by the company's engagement actions with the local community. For instance, in the case of Barroso Mine, delayed efforts by the company to foster acceptance were perceived by the local population as insincere gestures or "bribes" and those that engaged in the discussion perceived as "traitors", exacerbating feelings of resentment (e.g., see Sami organizations in Sweden (Mononen et al., 2022; Poelzer et al., 2020)). These outcomes highlight the critical importance of timing in community engagement processes, as well as the inherent delays in building trust. This dynamic is represented by the delay markers ("| |") over the corresponding links in the CLD, underscoring the principle that earlier engagement with local communities significantly enhances the prospects for trust-building and social acceptance.

Additionally, government interests in advancing mining were also related to substantive fairness by interviewees. When "*state lacks the capacity and/or the legitimacy to protect the public good*" (Hamann, 2014), substantive and procedural justice deteriorates. One interviewee also underscored how mining company's positive financial performance supports domestic procurement, reinforcing national socio-economic development. Particularly, domestic procurement tends to be costlier for mining companies, but it often contributes significantly to the country's economic development and fosters stronger relationships amongst stakeholders. In the CLD, the inclusion of "perceived variables" allows for the incorporation of communities' perception of environmental impacts (e.g., based on local needs or environmental awareness) as well as the procedural fairness of the historical and current mining-community relationship. A brief description of the CLD's main feedback loops is presented in **Table 6-4**.

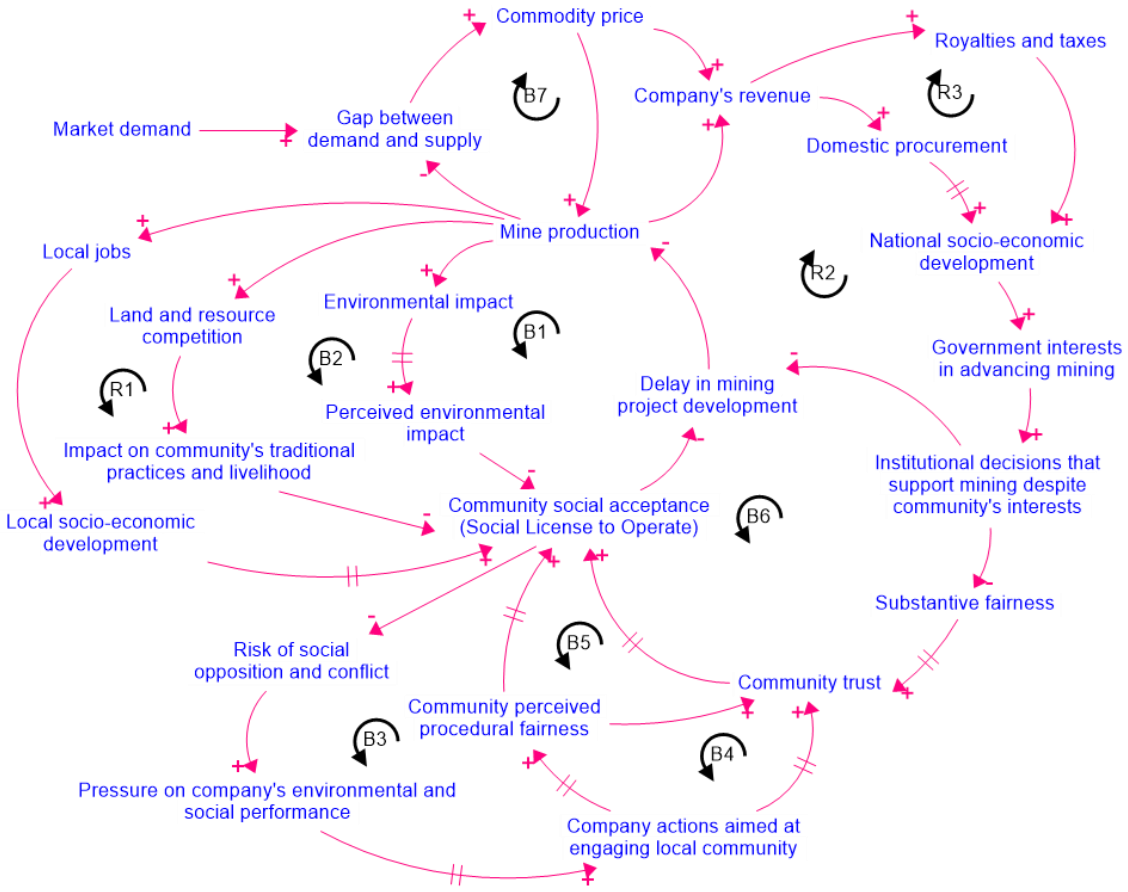


Figure 6-5. The interrelationship between mining developments and social acceptance. "| |" denotes time delay in the causal relationship between two variables.

Table 6-4. Description of balancing (B) and reinforcing (R) feedback loops identified in the CLD.

Feedback loop	Comment
B1	B1 illustrates the dynamics between mining production, environmental impact, and social acceptance. As mine production increases, so does the environmental footprint, which affects how the community perceives the project. High environmental impacts can lead to decreased social acceptance. This, in turn, can cause delays in the development of mining projects, hindering production.
B2	As mine production increases, it often intensifies competition for land and resources, potentially disrupting traditional practices and livelihoods of nearby communities. This can lead to a decline in social acceptance, resulting in delays in project development, and ultimately affecting mine production.
B3	Lack of social acceptance within the local community heightens the risk of opposition and conflict, which can negatively impact the mining company's operations. However, this pressure also incentivises the company to improve its environmental and social performance. By taking actions to engage with the local community, the perceived procedural fairness is improved, consequently fostering greater social acceptance.

B4	Similar to feedback loop B3, as the company takes actions to engage with the local community, it builds trust, which further strengthens social acceptance.
B5	Similar to feedback loops B3 and B4, as the company takes proactive steps to engage with the local community, it promotes procedural fairness, leading to the development of trust. This increased trust, in turn, reinforces community social acceptance.
B6	A lack of social acceptance often leads to delays in project development, subsequently affecting mine production and potentially reducing the company's revenue. However, mining revenue contributes to domestic procurement, supporting national socio-economic development and aligning with government interests in advancing the mining sector. Despite community concerns, institutional decisions may prioritise mining, leading to perceptions of substantive unfairness, decreasing trust and social acceptance.
B7	As mine production increases, it creates job opportunities for the local community, leading to socio-economic development. This, in turn, fosters community social acceptance of the mining operation, as it may be beneficial to the local area.
R1	As mine production increases, it generates revenue for the company, contributing to domestic procurement and bolstering national socio-economic development. This aligns with government interests in advancing the mining sector, leading to institutional decisions that support mining activities, despite potential opposition from local communities. These decisions tend to advance the project and further support mine production.
R2	The company's revenue responds to increases in mine production, leading to higher royalties and taxes paid to the government. These financial contributions, in turn, support national socio-economic development and align with government interests in advancing the mining sector. Consequently, institutional decisions may prioritise supporting mining activities, even if they conflict with community interests.
R3	B1 illustrates the dynamics between mining production, environmental impact, and social acceptance. As mine production increases, so does the environmental footprint, which affects how the community perceives the project. High environmental impacts can lead to decreased social acceptance. This, in turn, can cause delays in the development of mining projects, hindering production.

6.4.2 Case study dynamics

This section ties the feedback loops identified in the CLD (**Figure 6-5, Table 6-4**) to key aspects of the case study, emphasizing the interconnected factors influencing social acceptance and project development.

The proximity of the Barroso Mine to an agricultural heritage site and important hydrological resources, aesthetic impacts on the landscape, risks of soil, air, and water pollution plus water scarcity are frequently cited concerns (Canelas & Carvalho, 2023; Chaves et al., 2021; Domingues, 2022). These environmental risks correspond to the “Environmental impact” and “Perceived environmental impact” variables in the feedback loop B1 of the CLD, which links environmental concerns to reduced social acceptance.

The government's pro-industry discourse rooted on a climate-reductionist agenda (Dunlap & Riquito, 2023) has disregarded local perspectives, thereby intensifying conflicts between the perception of the local population and the government's (Araújo et al., 2022). This tension is reflected in feedback loop B6, where institutional decisions that prioritize mining projects over local concerns diminish trust and perceptions of fairness, further undermining social acceptance. This conflicting agenda has also been discussed by Stuehlen and Anderl (2024) in relation to the Jadar project in Serbia.

A lack of meaningful community engagement in decision-making process, coupled with insufficient transparency regarding exploration plans and potential impacts (Canelas & Carvalho, 2023; Ribeiro et al., 2021), has eroded procedural fairness and trust in the mining company. This corresponds to feedback loops B3, B4, and B5, where effective community engagement and enhanced procedural fairness are shown to reduce the risk of social opposition and conflict, improve trust, and foster social acceptance. Nonetheless, it is important to emphasize that it is not only the act of engaging with the community that matters ("what") but also "how" and "when" this engagement is initiated, as showcased by Mononen and Sairinen (2021) and Barakos and Mischo (2021). Barakos and Mischo (2021) exposed the fact that "*the earlier the parameters for gaining and maintaining a SLO are taken into account, the better for the overall viability of a mining project*". However, as depicted in loop B6, the alignment of institutional decisions with national economic priorities often undermines efforts to address community grievances, perpetuating perceptions of substantive unfairness and eroding trust.

In an effort to address these concerns, Savannah Resources has implemented several initiatives, including a "Benefit Sharing Plan" and a "Good Neighbor Plan". These programs aimed to enhance community welfare by prioritizing local procurement, providing shared transportation services, and supporting education, employment, and social support activities (Savannah Resources, 2021b). Such initiatives are central to feedback loops B3, B4, and B5, which emphasize the role of community engagement in building social acceptance. Nonetheless, existing resentment towards the company and political scandals are likely to undermine these efforts. The initial discourse surrounding lithium extraction in Portugal was also a critical aspect for the lack of social acceptance (Araújo et al., 2022). In this regard, one may question whether Portugal also suffered from a "presource curse" (Frynas & Buur, 2020).

Additionally, the project is anticipated to generate over EUR 258 million in taxes and charges, a portion of which may be allocated to the surrounding municipalities (Domingues, 2022), potentially improving infrastructure and social services. Employment creation, with estimates of 300 direct and 500-600 indirect jobs (Domingues, 2022), could also contribute to socio-economic development, as represented

in reinforcing feedback loops R1, R2, and R3, where socio-economic benefits promote greater social acceptance of the project. Nonetheless, the disruption of traditional livelihoods, such as local agro-pastoral activities and ecotourism, caused by resource competition with mining operations, is another major source of contention (Canelas & Carvalho, 2023; Chaves et al., 2021). These dynamics are captured in feedback loop B2, where such competition diminishes social acceptance and leads to project delays.

In summary, the developed CLD is capable of depicting the major dynamics at play in the case study and the complexity involved in its lacking social acceptance. Nevertheless, it does not explicitly include aspects such as the familiarity or history of local communities with mining activities (Tuija Mononen & Sairinen, 2021), configurations of power (Johnson et al., 2024), legitimacy (Brueckner & Eabrasu, 2018), or governance (Deonandan et al., 2024). Likewise, it does not differentiate between the community and public acceptance as proposed by Lesser et al. (2021) and Verrier et al. (2022).

6.4.3 Simulation results

The model is intended to shed light on the effects of changes in social acceptance before and while mining operations occur. **Table 6-5** shows the values of exogenous community-based variables for the baseline case.

Table 6-5. Environmental impact, Socioeconomic impact, and Social acceptance modules: Main exogenous variables for the baseline case.

Variable	Range	Initial value	Comment*	Reference
Initial perceived environmental impact	0-10	8	Very high. Local community concerns.	(Canelas & Carvalho, 2023) (Araújo et al., 2022) (Dunlap & Riquito, 2023) (Ribeiro et al., 2021)
Initial expected socioeconomic development	0-10	3	Low. Local community expects the project to damage ecotourism and agricultural activities.	
Initial perceived procedural fairness	0-10	1	Very low. Lack of transparency, communication, and inclusion has been constantly reported in the literature.	
Initial community trust	0-10	1	Very low. The literature also points to very low trust levels from the community towards the company.	
Initial social acceptance	0-10	3	Low, but not as low as perceived procedural fairness and trust, given	

			the local population is somewhat polarized concerning the advancing of the project	
Company's initial engagement performance	0-10	3	Low. Company's efforts have happened although not effectively. It would be 'Very low' if no effort had been recognized.	
Government interest in advancing mining	0-10	10	High government interest.	
Environmental impact weighting factor (on social acceptance)	0-1	0.35	The sum of these three weight factors is equal to 1 in all cases. A higher value for the trust weighting factor is supported from comments from Interviewee 7 (who directly worked with surrounding communities of Mina do Barroso). Considering the local community's context, it is assumed that the socioeconomic impact is the least important factor for social acceptance.	
Socioeconomic development weighting factor (on social acceptance)	0-1	0.15		
Trust weighting factor (on social acceptance)	0-1	0.5		

*Very low [0-2), Low [2-4), Medium [4-6), High [6-8), Very high [8-10].

The effect of social acceptance on project performance: The simulation results indicate that social acceptance plays a critical role in influencing operational performance. To explore this effect, two scenarios were analyzed, assuming a mine lifetime of 132 months. The first scenario (Run 1) assumes high levels of social acceptance, trust, and procedural fairness throughout the whole project, whereas the second scenario (Run 2) reflects a forced project initiation without securing a SLO six months into the simulation, based on the values provided in **Table 6-5**). In Run 2, operational and financial performance are significantly compromised, as shown in **Table 6-6**. For instance, lithium recovery rates are reduced by up to 70% compared to Run 1. Likewise, company's cumulative profits decrease by approximately 33%.

Table 6-6. The effect of low acceptance levels on project productivity and financial indicators.

Run	Average throughput rate (kt/Month)	Recovered LiS (Mt)	Recovered co-products (Mt)	Cumulative community receipts (M€)	Cumulative government receipts (M€)	Cumulative profits (M€)
1	481.06	2.19	5.63	37.82	356.45	2,314.87
2	341.39	1.55	4.00	26.46	245.54	1,541.68

These results align with the findings of Verrier et al. (2022), who considered the detrimental effect of low trust levels on mining project productivity in their system dynamics model. Moreover, the economic implications of reduced throughput and productivity emphasizes the importance of social acceptance for assessing mining projects' feasibility, as suggested by Barakos and Mischo (2021), and how fundamental it is to evaluate the current status of the SLO and its determining factors in a case-by-case manner (Cruz et al., 2021). This consideration of the SLO in early stages of project planning can help minimize the risks of social conflict and address social concerns comprehensively (Prno, 2013). Importantly, the simulation does not account for cases of project cessation due to social opposition, which is a likely outcome considering the current situation of the Barroso Mine and the Romano Mine in Montalegre.

Challenges in achieving a social license: This section examines the feasibility of securing a SLO before commencing mining, using the baseline assumptions outlined in **Table 6-5**. Across 285 simulations, in which environmental, socioeconomic, and trust weighting factors on social acceptance were varied, 16 scenarios resulted in the successful issue of a SLO within the mine's operational lifetime (Social acceptance ≥ 7). These 16 scenarios were contingent upon high trust weighting factors (equal to or higher than 0.7) and the continuous effort of the company to build up community trust through engagement, communication, and transparency. These findings reinforce the idea that the SLO is conditioned by even greater degrees of trust in the European context (Lesser et al., 2021). The results also suggest that delays in trust-building efforts can severely undermine the likelihood of achieving community acceptance against the current European plans for transition mineral extraction and supply chain. Nevertheless, it is worth acknowledging "*the fragile nature of trust*" (Hitch & Barakos, 2021) and the complexity of the SLO (Brueckner & Eabrasu, 2018). In this regard, it is recommended that the time required to engage with the local community be considered in mining project planning and governmental plans, consistent with the feedback dynamics described in **Figure 6-5** (loops B3 and B4).

Impact of government interest on social acceptance: The relationship between government interest in advancing mining projects and community social acceptance was also explored. Two scenarios were simulated: one assuming low initial government interest and the other high, using baseline exogenous variable values from **Table 6-5**. The scenario with high government interest in mismatch with

the communities' is representative of the initial Barroso Mine situation, however, recent changes in government positions due to accusations of corruption and malfeasance and the increased public attention to the project may have an impact on the government's position and interest in advancing the project. The results reveal that discrepancies between government interests and community acceptance can undermine substantive fairness and trust, which, in turn leads to lower social acceptance over the project lifecycle (**Figure 6-6**). High government interest, particularly when perceived as prioritizing corporate benefits and an international agenda over community well-being, has a detrimental impact on trust, consistent with findings from Stuehlen and Anderl (2024). These findings align with propositions of Gozluklu and Sterman (2023), who argue that misaligned policy priorities can inadvertently create barriers to project development despite well-intentioned government decisions .

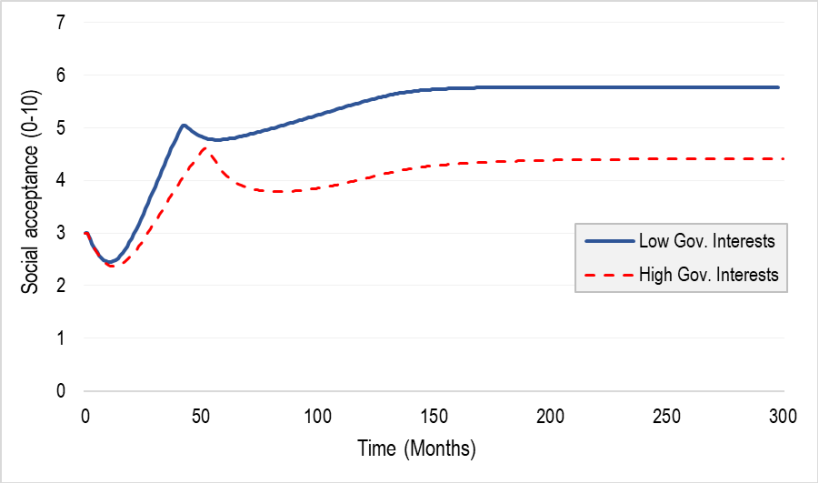


Figure 6-6. Social acceptance over time: The effect of high (red) and low (blue) government interest in advancing mining against low initial social acceptance.

6.4.4 Insights and emerging trends

This study offers a visual representation of the feedback relationships between mining and social acceptance in a CLD that was developed through a participative process. Amongst notable opposing dynamics, the creation of local jobs and an increase in domestic procurement (i.e., positive socioeconomic impacts) can sustain social acceptance of mining processes in the long term, while land and resource usage competition in conjunction with environmental impacts (i.e., negative socio-environmental impacts) increases opposition, conflicts and delays, and could profoundly affect mining

production locally and at larger scales over time. Additionally, the creation of local jobs, an increase in domestic procurement, royalties and taxes from mining production increases government interest in advancing mining, which leads to institutional support and incentives. On the other hand, government interests, if misaligned with the community's, can decrease substantive fairness and, consequently, social acceptance. Significant delays in the trust-building process, as well as changing perceptions over environmental and socio-economic impacts were also identified in the CLD.

The simulation results provide critical insights into the dynamics of social acceptance and their implications for mining projects. They underscore the necessity of early and sustained engagement with local communities, echoing themes from the literature on procedural fairness (Cruz et al., 2021; Mercer-Mapstone et al., 2018; Zhang et al., 2018) and trust (Lesser et al., 2021; Verrier et al., 2022). Moreover, the findings illustrate how exogenous factors, such as government interest, interact with community perceptions to shape the trajectory of social acceptance. Here, these interactions were understood through the lens of SD, which captures the feedback and delay mechanisms inherent in trust-building process. Engaging with the local community during the initial phases of project planning is of paramount importance, a step that was notably absent in the Barroso case. If the engagement process begins poorly with local communities, it is highly likely that, irrespective of subsequent efforts, an SLO will never be issued.

Regarding trust-building delays, it is worth noting that decarbonization agendas often overlook the potential delays caused by social conflicts arising from the anticipation of mining projects, clashes of stakeholder interests, and the "green energy rush" (Haag et al., 2024). This oversight is specially concerning from a justice perspective, since "green extractivism" can create sacrifice zones (Fernandes, 2024) and undermine procedural and recognition-based justice (Heffron, 2020). Such controversies within the energy transition discourse have been increasingly discussed in the literature (Lapeyronie & Szedlacsek, 2025), particularly in the context of lithium mining (Ciftci & Lemaire, 2023; Wolters & Brusselaers, 2024). These emerging discussions underscore the need for more inclusive and just approaches to resource extraction and ultimately call for a rethinking of established policy agendas. It also underscores the importance of treating community engagement not as a peripheral concern but as a central tenet of energy transitions.

6.5 Concluding remarks and limitations

Returning to the contributions stated at the outset, this study offers a two-fold advancement to existing literature. Firstly, it deepens our understanding of the sociotechnical complexities in mining by identifying feedback loops between social acceptance and mining activities in a participatory approach. Secondly, it bridges a significant gap in the quantitative analysis of social aspects in mining projects, advancing a conceptual system dynamics diagram into a quantitative model. By applying this dynamic perspective to the Barroso mine project, the research not only provides a case-specific exploration of social acceptance dynamics but also offers transferable insights for other resource extraction contexts.

Nonetheless, it is expected that this study's contributions extend beyond academic literature to the practical ecosystem of stakeholders in mining projects. For policymakers, the findings highlight the need for supportive governance frameworks that strike a balance between advancing strategic mining initiatives and protecting local communities' interests. For mining companies, the results provide a compelling case for prioritizing transparent and inclusive engagement strategies from the earliest stages of project development. For local communities and NGOs, this research underscores the importance of advocating procedural fairness and ensuring that community voices are meaningfully integrated into decision-making processes. It also demonstrates how local resistance can influence mining project outcomes, reinforcing the power of collective community action in shaping governance and corporate behavior.

While participatory development reduces biases by collecting different perspectives, it is important to acknowledge that the proposed model is a simplified representation of a complex social system, and the specific weighting factors and social acceptance dynamics may vary depending on the specific project context. The study is an exploratory analysis that does not aim to make exact predictions, especially because of the lack of data and high uncertainty in model parameters. This is an intrinsic limitation of the problem at hand, which depends on socio-technical effects that are not easily quantified with no historical data available. These limitations point to a future research agenda that includes further advancement of the model to this case study and applications to other mining developments, especially in Europe. The enhancement of the model could include further participatory and consultation processes with mining companies, governments, and local communities' representatives. The development of dedicated interfaces would be a relevant tool in communication, participatory decision-making, and knowledge-dissemination actions. Further research can foster culturally sensitive dialogues and balancing the interests of both companies and communities (Hamann, 2014) and account for the time delays involved

in the process of building trust, a crucial although less explored step towards achieving energy security in Europe.

7 Modeling disparities in EV adoption in Portugal

This chapter is based on the article titled "*A quantitative modeling approach to energy justice in electric vehicle adoption*", which has been submitted to an international journal of high impact factor. The content presented here reflects the key findings and discussions of the original manuscript, with some adaptations to fit the overall structure of this thesis.

A quantitative modelling approach to energy justice in electric vehicle adoption

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Abstract: EV adoption is a key component of the global low-carbon transition, yet it may also give rise to social and ethical issues derived from its widespread adoption. Nonetheless, there is limited research on how justice issues can be integrated into EV-related decision-making, particularly from a quantitative modeling perspective. This study employs a system dynamics model to simulate the effects of various policies on EV adoption and charging infrastructure, incorporating quantitative proxies for distributive justice, an energy justice tenet. The model is parametrized and calibrated for the case of Portugal. The results reveal disparities in charging station distribution and EV ownership between urban and rural areas, with ownership parity delayed in scenarios involving increased vehicle demand. The 2050 EV share ranges from 25.51% in the baseline scenario to 82.87% in the policy mix scenario considering growth projections in vehicle ownership. Additionally, EV subsidies appear to benefit urban populations disproportionately, leading to delayed ownership parity in rural areas (2045 vs. 2033 in the base case). The area-based urban-to-rural ratio of public charging stations reaches values from 2 to 7 by 2050 across scenarios, indicating an improvement from 2030 values although disparities remain. This study contributes to the emerging literature on energy justice by providing insights into the complexities of equitable EV adoption and suggesting that justice issues must be carefully integrated into decision-making

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tools to avoid unintended consequences of technological substitution, supporting just and sustainable transitions.

7.1 Introduction

While adopting EVs offer a promising solution for reducing road transport emissions (Raugei & Winfield, 2019), their environmental sustainability and social equity implications are complex, making them not inherently sustainable or just (Dall-Orsoletta, Ferreira, et al., 2022). From an environmental sustainability perspective, several works have shown that battery manufacturing and electricity generation sources are critical to determine the potential reduction of lifecycle GHG emissions when transitioning from traditional ICEVs to EVs (e.g., (Krause et al., 2020; Moro & Lonza, 2018)). In China, for instance, Hao et al. (2017) found that EV manufacturing produced higher GHG emissions than ICEVs. In this sense, the country's electricity mix and the vehicle operational time dictate whether the positive impacts of ICEV-EV substitution are realized (Hawkins et al., 2013). However, this "*impact accounting process*" is not the only one that can provide insights into technology sustainability. From a systems-thinking perspective, one can identify several delayed feedback loops that will impact EVs' long-term sustainability and unintended consequences. In the words of Dangerman & Schellnhuber (2013), when addressing the "Success to the Successful" archetype (Kim, 2000) in the interplay between conventional and alternative energy-technology complexes: "*...it is clear that, if that alternative system grows, becomes more coherent, and gains critical mass, its negative influence on and disturbance of the environmental system may be bigger than now anticipated.*"

In this regard, one may question the social and ethical considerations behind EVs as a technological choice and their further adoption. While mentions of "*just transitions*" have become more common in governmental agendas, what justice means is not always clear (Van Uffelen et al., 2024). Hence, employing a theoretical or normative framework when addressing justice within energy and technological decisions is crucial. In this work, the tenet-based energy justice framework (Jenkins et al., 2014) is employed to address problematic aspects that arise during EVs' operational stage, more specifically the distributive justice issues (Sovacool, Kester, et al., 2019) associated with the ownership and charging accessibility. Building on this background, this study makes significant contributions to both the literature and practice by conducting an initial attempt towards modeling the equitable distribution of benefits and burdens associated with EV adoption. It represents a pioneering effort to frame energy justice issues

related to EVs and evaluate them using a quantitative system dynamics model and simulation. The analysis is focused on Portugal, marking the first such assessment of the country in the literature. Portugal serves as a relevant case study due to its status as a small European nation, supported by the Just Transition Fund (European Commission, 2022b), and characterized by one of the oldest vehicle fleets and a high volume of imports in Europe (IMT & INE, 2022). This study seeks to advance understanding by addressing the following research question: "*How can system dynamics modeling be used to assess the energy justice implications of EV adoption in Portugal, considering factors such as consumer demographics, charging infrastructure accessibility, and policy interventions?"* In addition to its theoretical contributions, this study has practical implications related to the provision of decision-making tools that facilitate the formulation and evaluation of energy and technology policies within just transition plans, taking into account the existence and emergence of injustices over time.

The remainder of this study is organized as follows. **Section 7.2** presents the theoretical background of this study related to system dynamics and justice issues and the research gap that is being addressed. **Section 7.3** contains the research methods. **Section 7.4** presents the results, which are critically discussed in **Section 7.5**. **Section 7.6** concludes this work with a summary of main findings, limitations, and a future research agenda.

7.2 Theoretical background

7.2.1 System dynamics and electric vehicles

System dynamics modeling is a simulation-based approach used to understand and analyze the behavior of complex systems over time. The key components of system dynamics models include stocks (accumulations in a system), flows (rates at which stocks change over time), feedback loops (closed causal chains), and time delays (Sterman, 2000). System dynamics models have been developed and applied to a wide variety of contexts, such as energy policy simulation (Qudrat-Ullah, 2017), the integration of waste heat into district heating (Ziemele & Dace, 2022), and natural gas subsidies phasing-out (Daneshzand et al., 2022). The development of AFVs market has also been largely assessed through SD models.

Examples of works that built system dynamics models to simulate the diffusion of AFVs include (Gnann & Plötz, 2015) and (Hardman et al., 2018), who studied the interaction between the consumer, market

diffusion of AFVs and their refueling infrastructure. Gómez Vilchez & Jochem (2019) reviewed AFV market diffusion models based on system dynamics. The authors compared the degree of variable endogenization, consumer choice behavior' structures and numerical assumptions adopted in models. The authors are also responsible for other studies, e.g., assessing the impact of powertrain technologies on GHG emissions (Gómez Vilchez & Jochem, 2020) and a hybrid simulation-optimization model assessing transport and energy systems (Blanco et al., 2019). Additionally, Shafiei et al. (2012) proposed an integrated framework to analyze the diffusion of AFVs, where they included the interaction between all the players in the EV market (i.e., the automotive industry, energy supply systems, consumers, and government). The authors are also responsible for other works studying the AFV market, such as (Shafiei et al., 2014, 2015b, 2015a, 2016; Shafiei, Davidsdottir, et al., 2017; Shafiei, Leaver, et al., 2017). Keith et al. (2020) developed a generalized system dynamics model to explore the diffusion of AFVs, focusing on the interactions between consumers, charging infrastructure, and vehicle research and development. Onat et al. (2016) broaden the analysis of sustainability performance of EVs by integrating the dynamics that exist between the economic, environmental and social dimensions. Other examples include (Lopez-Arboleda et al., 2023) who proposed a system dynamics model for the sustainable integrated car-ownership transition to EV (i.e., SICOTEV). In her doctoral thesis, Pillay (2018) considered income as an endogenous factor of its system dynamics model to determine the provincial affordability of EVs in South Africa.

Although far from an extensive literature review, these studies demonstrate the utility of system dynamics approaches in modeling and understanding the complex dynamics underlying EV adoption and AFV market diffusion. Nonetheless, to the best of the authors' knowledge, no previous research has applied system dynamics modeling to assess EV adoption in Portugal or to explicitly evaluate the justice implications related to EV adoption, which are discussed in the next section.

7.2.2 Justice issues in transport electrification

Low-carbon technologies are not inherently sustainable or just as already discussed in the literature concerning EVs (e.g., (Dall-Orsoletta, Ferreira, et al., 2022)). As mentioned earlier, the energy justice framework appears as a means to identify and understand potential injustices of energy transitions. Energy justice is mainly concerned with "*what are the unjust impacts associated with energy systems*", "*where they are located*", "*who is most affected*", and "*how these injustices become embedded in procedures and mechanisms*" (Jenkins et al., 2016). Nevertheless, different approaches and frameworks

have been proposed in the literature, such as Hancock and Ralph's (2021) energy security-justice framework employed to assess fossil fuel retrofit hydrogen exports.

Among works that have addressed EVs and energy justice, (Sovacool, 2021; Sovacool, Hook, et al., 2019; Sovacool et al., 2020; Sovacool, Lipson, et al., 2019; Sovacool, Martiskainen, et al., 2019) have touched upon the "*decarbonization divide*" and the injustices of the Nordic EV transition, such as the technology elitism. The same aspect was also showcased by (Boucher & Mérida, 2022) which correlated EV ownership with average income and education levels in Washington, underscoring a "clean tech privilege". Canepa et al. (2019) performed spatial and statistical analysis to assess EV adoption in disadvantaged communities in California, which were defined as census tracts that suffer from a combination of economic barriers and environmental burdens. Likewise, Hennessy and Syal (2023) operationalized distributive, recognition-based, and restorative injustices as they evaluated EV adoption rates across different ethnic groups and the distribution of state incentives, including in historically redlined areas, in California. Their research identified racial disparities in EV rebate allocation and adoption and between formerly redlined neighborhoods. Despite the existing literature, further research is needed "*to deepen our understanding of how EVs will impact broader transportation and energy justice concerns*" (Vega-Perkins et al., 2023).

Accordingly, much of the research focused on EV-associated injustices comprises qualitative works or statistical analysis providing evidence of their occurrence (see **Chapter 4**). Other quantitative approaches include dynamic modeling and optimization models focusing on the best locations for EVCS (e.g., (Loni & Asadi, 2023; Rabinowitz et al., 2023)). Loni & Asadi (2023) proposed a data-driven approach to place and size EV charging stations in San Francisco, prioritizing regions with lower equity access and maximizing EV demand coverage while considering site development costs. Within this body of literature, which is only touched upon here, a population is often split into advantaged and disadvantaged groups. These groups can be socioeconomic and spatially privileged or unprivileged, respectively. Concerning EVs, an advantaged group would not struggle financially to purchase an EV or pay electricity/fuel bills (socioeconomic) and have the ability to have a home or residential charger (spatial). On the other hand, a disadvantaged group would not have the financial means to bear EV upfront costs or easy access to charging.

Extending the "*triumvirate of tenets*" (D McCauley et al., 2013), Dall-Orsoletta, Dranka and Ferreira (2022) explored the literature to find information on problematics related to EV lifecycle stages and the energy justice tenets (i.e., distributive, recognition-based, procedural, cosmopolitan, restorative, and

flexibility justice). While acknowledging the intrinsic context-dependency of justice, the authors underscore that "*action must be taken to reduce inequalities and unintended negative impacts*" of EV adoption. In a subsequent study, the authors have systematically reviewed the literature to understand how energy justice tenets could be operationalized in EV research (**Chapter 4**). This research builds upon the previously built knowledge to operationalize energy justice into a system dynamics model concerned with EV adoption. To the extent of the authors' knowledge, the work of Gladkykh et al. (2021) represents the only attempt to integrate energy justice concepts into a system dynamics model, with a particular focus on the evaluation of energy access in Sub-Saharan Africa but using a simplified system dynamics model.

7.2.3 Research gap

By leveraging the literature presented, this study highlights a critical research gap that it aims to address, namely, the absence of any previous investigation into the energy injustices associated with EVs using a system dynamics model. Most of the literature on injustices associated with EVs focus on a qualitative identification of injustices (e.g., (Sovacool, Kester, et al., 2019)) or on providing quantitative evidence for such injustices (e.g., (Boucher & Mérida, 2022)), as discussed in **Chapter 4**. Additionally, within the literature that employed SD modeling to evaluate EV aspects, system dynamics models tend to focus on EV market diffusion and factors influencing its adoption (e.g., (Gnann & Plötz, 2015), (Keith et al., 2020)).

The present study aims to develop a system dynamics model able to incorporate indicators of justice related to EV adoption. In this regard, it addresses a research gap in the focus of system dynamics models applied to transport electrification from an energy justice perspective. It does so by differentiating consumer groups, their motivation to buy EVs, and their access to public EVCS. It also addresses requests for further methodological diversification in the energy justice literature (Carlton & Sultana, 2023) and advances quantitative analysis in the field. This research also builds upon previous research that assessed the ability of system dynamics models to integrate social aspects of the energy transition (Dall-Orsoletta, Uriona-Maldonado, et al., 2022).

Finally, the system dynamics model is parametrized and calibrated for the case of Portugal, which is being taken as a case study regarding EV adoption and energy justice for the first time in the literature. The case of Portugal is relevant for being a small country, member of the EU and therefore abiding to its vehicle fleet and market regulations (European Parliament, 2022), owner of one of the oldest vehicle fleets in Europe and a high importer of second-hand vehicles (IMT & INE, 2022), and currently part of the EU just transition mechanism through the just transition fund (European Commission, 2022b).

7.3 Methods

This study employs system dynamics modeling to simulate the vehicle ownership preferences of urban and rural consumers in Portugal, as well as their interactions with EV adoption, the development of new charging infrastructure, and the overall vehicle fleet composition. The analysis focuses exclusively on passenger cars. Additionally, ICEVs and EVs are the only technologies considered in the analysis, which can be purchased new or used, with the latter computed as imports. EVs represent passenger cars that can be powered 100% by electricity (i.e., BEVs), whereas ICEVs aggregate petrol, liquefied petroleum gas (LPG), and diesel cars.

7.3.1 Indicators and justice operationalization

Following recommendations on normative clarifications and the revisited energy justice framework presented by Van Uffelen et al. (2024), this section aims to define justice in relation to the object of study. Distributive justice is mainly concerned with the fair distribution of benefits and burdens that arise from a particular decision (Sovacool, Kester, et al., 2019). Based on operationalization statement structure from Hennessy & Syal (2023), the proposed model aims to quantify the disparity in EV adoption and charging accessibility between urban and rural groups. The proposed indicators are given by the difference in EV ownership and EVCS density per inhabitant and per square kilometer.

Recognition-based justice implies recognizing people affected by energy transition decisions and their interests, needs, and expectations (Sovacool, Kester, et al., 2019). Therefore, this study also attempts to address recognition-based justice by differentiating between advantaged and disadvantaged groups. Nonetheless, it stems from the knowledge-based assumption that disadvantaged groups would like to purchase EVs but are refrained to do so because of socioeconomic and spatial (i.e., infrastructure) barriers. The geographical scope of analysis is Portugal, assuming a differentiation between urban and rural areas. Consequently, it must be taken into consideration that the present study has an aggregated (i.e., regional/national) perspective that may conceal micro or local perspectives. The time scale of analysis ranges from 2010 to 2050, according to the simulation timeframe. Limitations of this approach are further acknowledged in **Section 7.6.1**.

7.3.2 System conceptualization

The process of building a system dynamics model is iterative, from gathering and synthesizing input data to developing the model structure and analyzing scenario results. **Figure 7-1** shows a simplified diagram that visually represents the system dynamics modelling process and the interactions between the main sub-models. Main feedback loops include the development of charging infrastructure as a response to an increasing number of EVs, which in turn increases EV relative utility and their adoption (reinforcing feedback loop – R1). Conversely, the adoption of EVs skews the ICEV distribution to older vehicles, decreasing the cost of second-hand ICEVs, which increases their relative utility (i.e., ICEV relative utility) and favors further adoption (balancing feedback loop – B1). Other factors influencing technologies' choice probability through the multinomial logit model (MNLM) are operational costs, range parity, status and familiarity aspects.

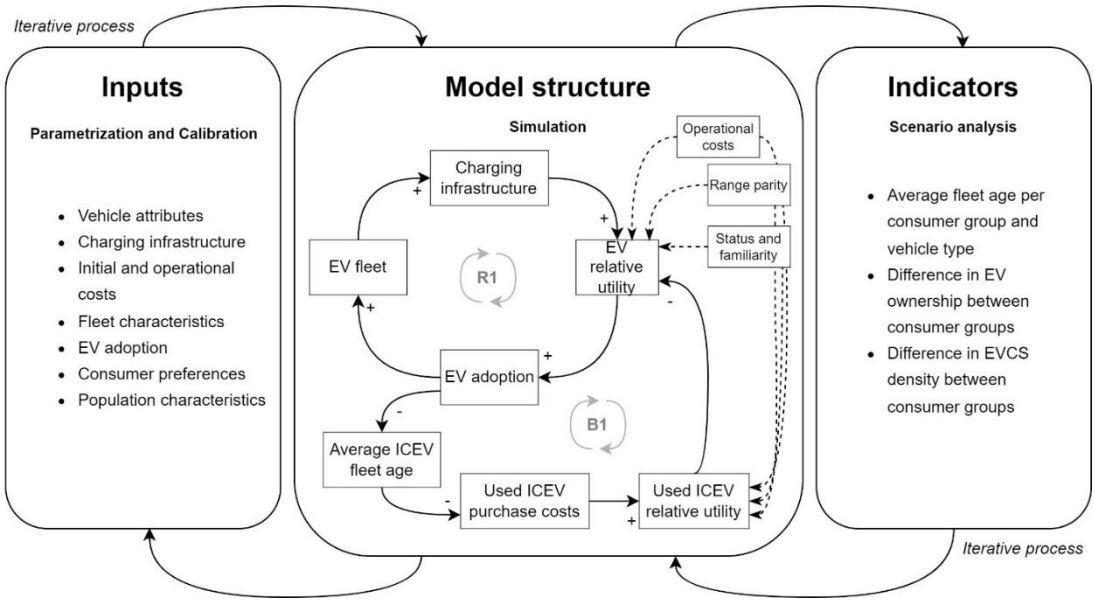


Figure 7-1. Simplified model representation.

7.3.3 Model formulation

This section presents the mathematical relationships between major variables and sub-models. The system dynamics model consists of four main sub-models: the vehicle fleet, the charging infrastructure, technology familiarization, and the MNLM. The charging infrastructure and the interaction between the

MNLM and the technology familiarization sub-models followed the system dynamics model structure presented in (Valencia et al., 2023).

The vehicle fleet is represented by an ageing chain with five stock categories based on vehicle age, as defined by Eurostat (Eurostat, 2024): less than two years, two to five years, five to ten years, ten to twenty years, and more than twenty years old. Vehicles can be of two technology types (i): EVs and ICEVs. New vehicles are added to the first stock, whereas used imported vehicles are added to the third and fourth stocks based on the average age of vehicle imports in Portugal (ACAP, 2024). The purchase of new vehicles (VP_i) and used vehicle imports (VI_i) increase the vehicle fleet (V_i), while scrapping (VS_i) decreases it (**Equation 7-1**). Scrapping is considered for vehicles older than five years for EVs, considering battery life limitations, and ten years for ICEVs. The vehicle fleet sub-model was calibrated using data from Eurostat, ACAP and INE from 2010 to 2022.

$$\frac{dV_i}{dt} = VP_i + VI_i - VS_i \qquad \textbf{(Equation 7-1)}$$

The price of used ICEVs $(C_{UsedICEV})$ is determined by an aging stock-based weighted average price and assumed depreciation rates (d_a) for each age category stock a, as shown in **Equation 7-2**, where $C_{NewICEV}$ refers to the average purchase cost of a new ICEV, and $V_{a,ICEV}, ICEV$ refers to the number of ICEVs per age category stock.

$$C_{UsedICEV} = \left({}^{C_{NewICEV}}/_{V_{ICEV}}\right) \cdot \sum_a (1 - d_a) \cdot V_{a,ICEV} \qquad \textbf{(Equation 7-2)}$$

The input of vehicles into the current fleet is given by an adjusted vehicle demand (AVD) that considers the car ownership rate (CO) calculated as the sum of new registrations $(VP + VI)$ and the current vehicle fleet (V), divided the population in each urban or rural region j, from 2013 to 2022. From 2022 onwards, a demand growth projection is available based on the logistic growth curve with the carrying capacity value defined by a percentage growth (α) from the initial ownership rate for region j at time t_0 $(COj, t0)$ (**Equation 7-3**).

$$CO_{j,t} = \alpha \cdot CO_{j,t_0} / \left[1 + exp^{-k \cdot (t - t_0)}\right] \qquad \textbf{(Equation 7-3)}$$

Where k represents the logistic growth rate, t is time, and t0 the initial time point.

The charging infrastructure model assumes a gap-closing structure in which the new demand for charging (CD_j) is given by the EV stock, the average yearly mileage (VDT_j), the utilization of public charging (UPC_j), the operational charging time of a station (OPT), the share of fast charging (FC_j), and average slow and fast charging times (SCT and FCT, respectively) (**Equation 7-4**).

$$CD_j = \frac{\left[\left(1 - FC_j\right) \cdot SCT + FCT \cdot FC_j\right] \cdot \left[V_{EV,j} \cdot \left(VDT_j / RG_{EV}\right) \cdot UPC_j\right]}{OPT} \qquad \textbf{(Equation 7-4)}$$

To account for the time lag between changes in demand and the construction of new infrastructure, a time delay was incorporated into the model, following the approach of (Valencia et al., 2023). Calibration was conducted using the total number of recharging points from 2020 to 2024 provided by the European Alternative Fuels Observatory (EAFO) (EAFO, 2024) and Mobi.E data (Mobi.E, 2024).

The technology familiarization sub-model is grounded in the Bass diffusion framework for technology adoption (Bass et al., 1994). **Equation 7-5** quantifies the annual increase of people that become familiarized with EV technology $(PFR_{EV,j})$, which is given by the imitation $(p_{EV,j})$ and innovation $(q_{EV,j})$ coefficients, the potential market to EV technology $(PM_{EV,j})$, and the number of people that are already familiarized with EVs $(PF_{EV,j})$ across consumer groups j.

$$PFR_{EV,j} = p_{EV,j} \cdot PM_{EV,j} + \left(q_{EV,j} - p_{EV,j}\right) \cdot PF_{EV,j} - \frac{q_{EV,j}}{PM_{EV,j}} \cdot {PF_{EV,j}}^2 \qquad \textbf{(Equation 7-5)}$$

Calibration of the imitation and innovation coefficients was performed based on historical EV stock data. A familiarity adjusting factor (F_{adj}) multiplied by the share of people familiar with the technology $(SPF_{EV,j} = PF_{EV,j}/PM_{EV,j})$ and constraints the choice probability $(CP_{i,k,j})$ given by the MNLM. This adjustment reflects the notion that consumers are unlikely to purchase a technology they are unfamiliar with, as shown in **Equation 7-6**. Familiarity with ICEVs is assumed to be 1.

$${CP_{i,j}}^{adj} = min(CP_{i,j}, F_{adj} \cdot SPF_{EV,j}) \qquad \textbf{(Equation 7-6)}$$

The MNLM ascertains a $CP_{i,k,j}$ for each vehicle technology option i and type k: used and new. Each consumer group j will select the vehicle i,k that maximizes its utility ($U_{i,k,j}$). The choice probability is given by **Equation 7-7**, in which the utility is normalized against the maximum utility to avoid numerical overflow.

$$CP_{i,k,j} = \frac{exp^{(U_{i,k,j} - \max(U_{i,k,j}))}}{\sum exp^{(U_{i,k,j} - \max(U_{i,k,j}))}} \quad \textbf{(Equation 7-7)}$$

Where $U_{i,k,j} = \sum \beta_j \cdot X_{i,k}$ is the consumer group's expected utility, which depends on a series of selected technological attributes ($X_{i,k}$) and their estimated coefficients (β_j). It was assumed that the perceived utility of each alternative increases with the driving range, the new charging infrastructure, and the status; while it decreases with operational and initial costs. Reasons for these choice of attributes are based on the case study context and are further explained in **Section 7.4.1**. It was also assumed there was heterogeneity in consumer groups and their decisions were independent from one another (**Section 7.6.1.**). Please refer to the **Appendix III** (**Tables 10-2., 10-3, and 10-4**) for the complete model documentation.

7.3.4 Model validation and calibration

System dynamics model validation requires structure and behavior validity testing (Barlas, 1996). Within the former category, the model validation process entails structure- and parameter-confirmation tests based on the empirical and theoretical knowledge about the system. Dimensional consistency tests were also performed (Forrester & Senge, 1980). Behavior validity testing involve simulations and comparing "*model-generated to the observed (or anticipated) behavior of the real system*" (Barlas, 1996).

Parameters that had to be calibrated include the β_j, the status parameter, the coefficients of the Bass diffusion model, the scrapping rates, additional infrastructure building, and imports availability. The calibration process included an extensive manual search of parameters, followed by Vensim built-in Powell optimization. The optimization process aimed at minimizing the payoff defined as the mean absolute error divided by the mean of the historical data for the following variables: EV stock, EV sales, car imports, total EV and ICEV stock, 20-year-old-plus vehicle stock, and total car sales. Stochastic behavior was also introduced on the average price of fossil fuels and electricity cost. The average price of fossil fuels was based on the weekly average retail selling price of diesel (or "*gasóleo rodoviário/simples*" in Portuguese)

from 2015 to 2022 (DGEG, 2024). To introduce stochasticity, a normal distribution was used, with the standard deviation derived from the same historical dataset. Public slow and fast charging prices were allowed to vary ±0.1EUR/kWh, reflecting potential fluctuations in market prices, whereas average and standard deviation for private electricity prices were obtained from biannual domestic electricity prices (Eurostat reference consumption range - "Banda DB", monthly annual consumption between 2,500 and 5,000kWh) from 2016 to 2023 (DGEG, 2024).

The validation step also entailed behavior sensitivity test using the "Sensitivity2All" feature of Vensim simulation software. Sensitivity2All consists of assessing the impact of exogenous parameters on selected model variables by varying their value (+/- 10% runs). This impact is provided numerically (e.g., mean absolute deviation, difference in variance, sum of squares errors, payoff function) and visually (i.e., comparative graphs). **Figure 7-2** illustrates six of the comparative charts for the total simulated EV stock generated by Vensim, where the base run is represented by the black line, and the red and blue lines indicate a reduction and an increase of 10% in each constant, respectively. By verifying that similar behaviors result from parameter variations, the model structure can be considered robust.

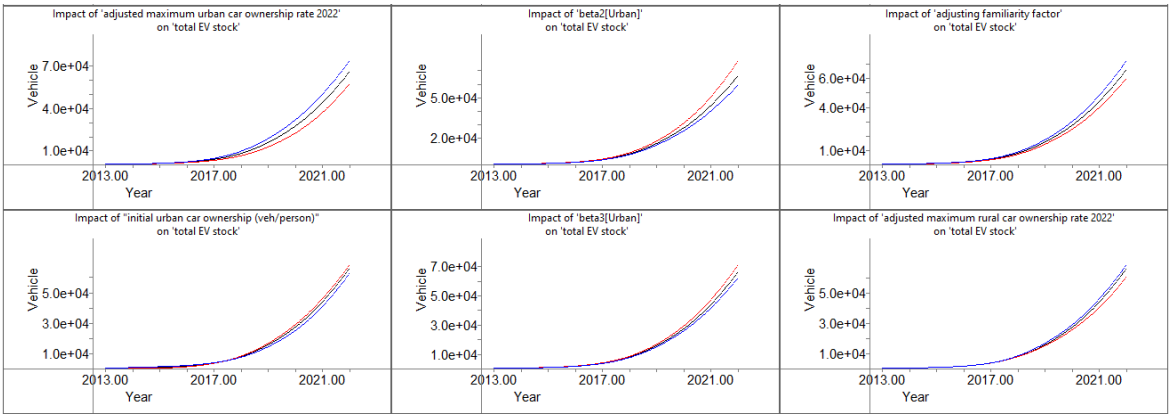


Figure 7-2. Example of sensitivity testing performed with VENSIM Sensitivity2All.

Accordingly, several model revisions were performed, refining the model structure and comparing simulation results with historical data. **Table 7-1** presents the mean absolute error (MAE), the mean absolute percentage error (MAPE), the mean squared error (MSE), and the root mean squared error (RMSE) computed when calibrating aggregated EV sales and EV stock, as well as imports, sales, and total vehicle stock across age categories. Nonetheless, it is argued that the relevance of point-by-point agreement is less important in system dynamics models than behavior consistency (Barlas, 1996). In

this regard, **Figure 7-3** indicates agreement between historical data and simulation results for the EV stock and sales.

Table 7-1. MAE, MAPE, and RMSE for selected model variables.

Variable	MAE	MAPE	RMSE
EV stock	1,418.41	8.43%	2,267.17
EV sales	982.16	20.89%	1,640.12
Imports	15,792.04	44.96%	21,335.98
Total new vehicle purchase	52,037.83	32.81%	58,915.84
Total vehicle stock (>20 years old)	157,948.04	15.98%	185,360.60

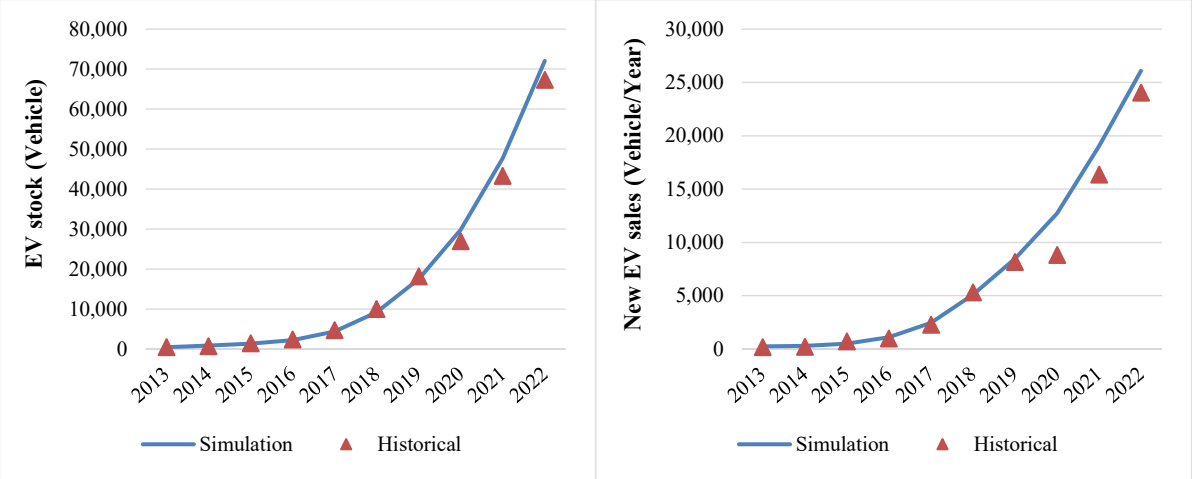


Figure 7-3. Historical data and simulation results: EV stock (left) and sales (right).

7.3.5 Scenario-based analysis

Different scenarios were tested to identify their effect on the car fleet composition, and disparities in EV adoption and charging accessibility. **Table 7-2** summarizes the simulated scenarios and their description. All scenarios were run assuming that (a) urban and rural car ownership rates would remain at 2022 levels until the end of the simulation and (b) urban and rural car ownership rates would increase by 24.0% by 2050 from 2013 levels, according to projections for OECD Europe countries, resulting from the International Energy Agency (IEA) and World Business Council for Sustainable Development (WBCSD)

Sustainable Mobility Project (SMP) Transportation Model 2004 (EEA, 2024). A similar car ownership growth rate was assumed for both rural and urban populations given the lack of group-specific projections.

Table 7-2. Scenario names and description.

Scenario name	Code	Description
Baseline	BAS	Simulation running until 2050 employing model parameters calibrated to historical data from 2013 to 2022.
Policy 1. ICEV Ban	POL1	Baseline scenario parameters plus a ban on new ICEV sales from 2035 onwards, as proposed by the EU (European Parliament, 2022).
Policy 2. EV purchase cost subsidy	POL2	Baseline scenario parameters plus a EUR5,000 reduction in the purchase cost of new EVs. This value was based on existing public incentives (e.g.., Incentive for the introduction of zero-emission vehicles (VEN 2023) (Fundo Ambiental, 2024)).
Policy 3. Scrapping scheme	POL3	Baseline scenario parameters plus an increase in the scrapping rate of vehicles older than 20 years, from 7.0 to 20.0% per year.
Policy 4. Increasing fossil fuel prices	POL4	Baseline scenario parameters plus a 5.0% annual increase in the average fossil fuel price from 2025 to 2035.
Mix of policies	MIX1	Baseline scenario parameters plus a combination of policies 1, 2, 3, and 4.

7.4 Results

7.4.1 Case study: EV adoption in Portugal

EVs are gaining significant traction in Portugal, driven by the country's and European investment and its commitment to sustainability (**Figure 7-4**). According to the 2021-2022 EIB Climate Survey, 84% of Portuguese car buyers are planning to acquire a hybrid or electric car in their next purchase, which is 17 points higher than the European average (EIB, 2023). The Portuguese government has implemented several incentives, including financial incentives and tax breaks for EV purchases for both consumers and businesses. Consumers, in particular, receive price reductions up to EUR 4,000 in new cars, tax reductions in vehicles (*Imposto Sobre Veículos* - ISV) and value-added taxes (VAT), plus monetary support for charging and home chargers (Barros & Novo, 2023). Additionally, the country has made significant investments in EV infrastructure, and Mainland Portugal now has 3,954 stations and 8,536 charging points across the country (Mobi.E, 2024). Portugal's support for EVs aligns with its 2050 carbon neutrality goal, given that the country's electricity matrix has a low emission factor of approximately 0.202 CO2e kg/kWh (AIB, 2021; Scopes Data, 2024).

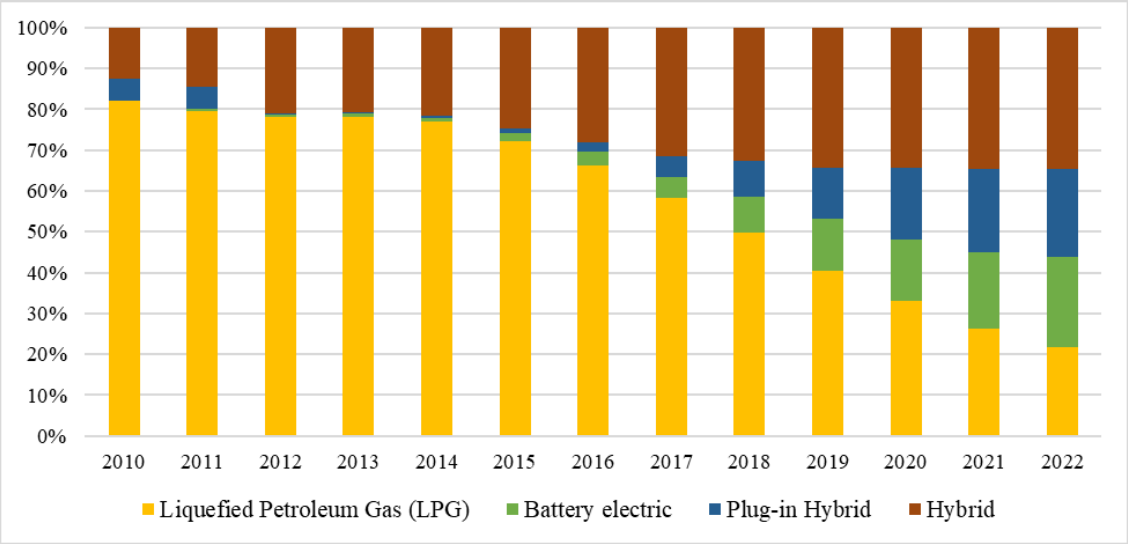


Figure 7-4. Share of alternative propulsion technologies in the light passenger vehicles fleet in Portugal (excluding gasoline and diesel vehicles). Source: Adapted from (EAFO, 2024).

In Portugal, consumers' preferences for EVs are mainly centered on monetary considerations, even outweighing privileges related to parking and lanes (Oliveira et al., 2015). In other words, consumers are more likely to adopt EVs if the purchase price decreases or if gasoline and diesel prices rise significantly (Miranda & Delgado, 2020; Oliveira et al., 2015). Charging stations' convenience and battery lifetime were also identified as factors being pondered in EV purchase decisions in the country, with no statistical evidence supporting pro-environmental attitudes (Miranda & Delgado, 2020). That is why emissions were not included as a technology attribute influencing the choice probability in the MLNM. A more recent study by Campino et al. (2023) examined why Portuguese consumers choose eco-friendly vehicles. It was found that the most preferred choice was hybrid vehicles (no plug-in) and that the energy generation-factor played a less significant role in purchase decisions regarding the acquisition of eco-friendly vehicles. Interestingly, only Campino et al. (2023) analyzed purchase preferences based on socioeconomic conditions, namely monthly gross income, although no correlation was attempted to be established between income and adoption rates. Additionally, none of the studies considered spatial factors, such as participants living in urban or rural locations.

Preferences aside, it is important to note that Portugal has a relatively old vehicle fleet: 64% of all light passenger vehicles in Portugal are older than 10 years, with an average age of 19.4 years (IMT & INE, 2022). **Figure 7-5** shows the age distribution of passenger cars from 2014 to 2022. Portugal's high

share of older vehicles indicates that the fleet renovation process will take longer than in other European countries (Barros & Novo, 2023), also due to a large second-hand market of ICEVs. Accordingly, two-thirds of all new car registrations in the country in 2022 were imported second-hand vehicles (Lusa, 2023). The aging fleet and strong second-hand ICEV market bring interesting dynamics to the case study.

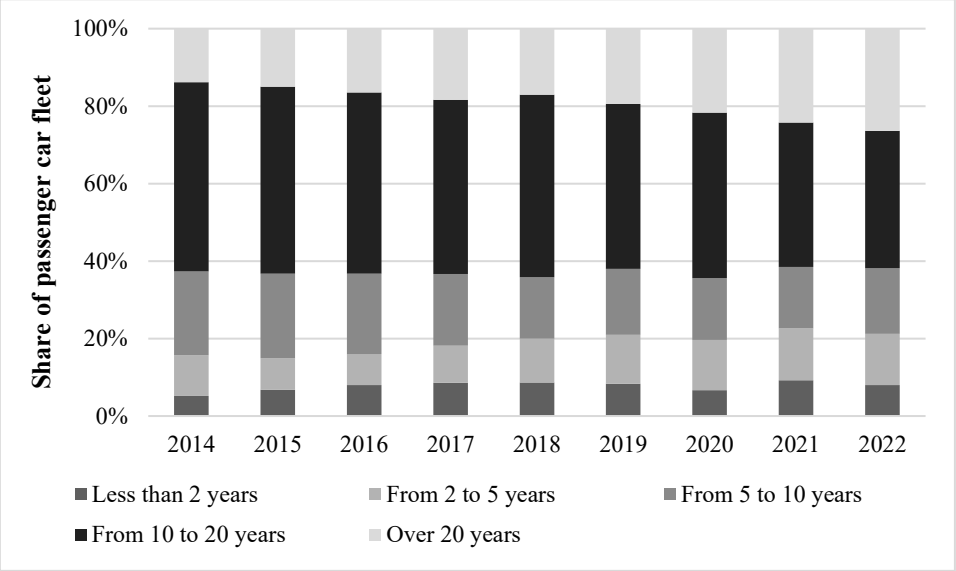


Figure 7-5. Age distribution of passenger cars in Portugal from 2014 to 2022. Source: Adapted from (Eurostat, 2024).

Although only aggregated data for EV ownership is available from open sources, disparities in technology adoption between urban and rural populations have been already reported. In a working paper published in 2022 by the International Council on Clean Transportation (ICCT) (Morrison & Wappelhorst, 2022), the authors compared the share of BEVs amongst 2020 new passenger car registrations at regional and national levels in Europe, differentiating regions in urban, intermediate, and rural regions. Rural regions in Portugal had a much lower BEV adoption rate (closer to 0%) compared to the national and intermediate and urban regions' average (approximately 12.5% and 5.0%, respectively) (Morrison & Wappelhorst, 2022). Ala et al. (2021) has also demonstrated how AFV adoption is higher in more populated and urban areas, more specifically the districts of Porto, Lisbon, and Aveiro. Rural regions in Portugal are also subject to lower average gross income and higher at-risk-of-poverty rates. In 2012, the average income in rural regions was three quarters of the average income in urban areas (EUR1,152.1 vs. 860.5) (INE, 2024a). Furthermore, the proportion of resident population at-risk-of poverty or social exclusion by degree of

urbanization shows a difference of 7.7 p.p. between thinly and densely populated areas (24.4 vs. 17.1%, respectively) (INE, 2024b).

Concerning EVCS, Ala et al. (2021) presented charging infrastructure information for several European countries and regions in Portugal, sourced from Ayvens (former LeasePlan). Nonetheless, the referred data source is no longer available. Therefore, open data from MOBI.e on charging stations, points, and outlets was collected at the municipality level (Mobi.E, 2024). This data was cross-analyzed against population, population density, area, and urban typologies from INE. Given challenges in urban typologies identification (Henriques et al. , 2020), two categorizations are provided in Table 3. The first one is based on population density categories derived from the Sturges formula (low population density [0.5-237.2 people/km^2], medium (232.2-473.9], high (473.9-710.6]), whereas the second categorization employs INE "Tipologia de Áreas Urbanas" (TIPAU) that categorizes areas into predominantly urban (APU), predominantly rural (APR), and medium urban areas (AMU). Nonetheless, the TIPAU classification may have limitations when applied at the municipal level, as it was originally designed for parish-level analysis. Yet, **Table 7-3** is relevant as it compares the charging infrastructure density using a purely mathematical division based on the population density and a classification that considers morphological and planning criteria (Henriques et al., 2020). It also shows how both categorization methods present disparities in charging accessibility between urban and rural or low and high density areas, which is more apparent when comparing the number of EVCS per 1,000 km^2.

Table 7-3. Comparison of EVCS density between urban and rural areas in Portugal in 2024.

Urban typology classification (TIPAU)							
Label	**Municipalities (No.)**	**Population**	**Area (km^2)**	**Avg. population density (people/km^2)**	**EVCS (No.)**	**EVCS per 100,000 people**	**EVCS per 1,000 km^2**
APR	57	2,857,587	696,009.01	4.11	3,225	45.98	1.89
AMU	27	1,015,807	50,771.31	20.01	380	37.41	7.48
APU	194	5,896,170	144,108.33	40.91	1,314	54.70	22.38
Population density classification							
Label	**Municipalities (No.)**	**Population**	**Area (km^2)**	**Avg. population density (people/km^2)**	**EVCS (No.)**	**EVCS per 100,000 people**	**EVCS per 1,000 km^2**

Low	270	8,146,829	887,259.07	9.18	3,672	45.07	4.14
Medium	4	525,912	1,864.53	282.06	330	62.75	176.99
High	4	1,096,823	1,765.05	621.41	917	83.61	519.53

7.4.2 Simulation results

Simulation results are presented according to the composition of the passenger car fleet (**Section 7.4.2.1**), disparities in EV ownership (**Section 7.4.2.2**) and charging density per inhabitant and square kilometer (**Section 7.4.2.3**).

7.4.2.1 Fleet composition

Figures 7-6 and 7-7 show the age distribution of vehicles (<2 years, 2-5 years, 5-10 years, and >20 years) in Portugal and the total share of EVs in the passenger car fleet from 2013 to 2050 across six scenarios described in **Table 7-2**. **Figure 7-6** presents these scenarios considering no growth in the car ownership rate. Conversely, **Figure 7-7** presents the simulation results assuming a 24-percent increase in urban and rural car ownership rates by 2050 from 2013 levels (EEA, 2024). Each scenario shows a progressive increase in EV share over time, following an S-curve pattern that aligns with typical technology adoption trends.

Under the Baseline scenario, the EV market share gradually increases to 25.51% by 2050 without considering any growth in car ownership (BAS). When an increase in vehicle demand is introduced (BASb), the EV share rises to 51.76%. Scenarios POL1, POL2, and POL4 show higher EV market shares by 2050 compared to BAS, surpassing forty- and thirty-percent, respectively. Likewise, the EV market share in POL1b, POL2b, and POL4b comprises almost sixty-percent of the fleet by 2050. However, in all these scenarios, newer vehicles (<2 years) remain a relatively small portion of the fleet (less than 10.00%), suggesting limited fleet turnover.

With policies incentivizing the scraping of older vehicles, POL3 shows a significant reduction in the number of vehicles older than 20 years and a faster growth in EV adoption (57.17% of the fleet in 2050). In POL3b, the EV share reaches 79.53% by 2050. Consequently, this scenario shows a more balanced distribution across vehicle age groups, indicating improved fleet turnover. Results from MIX1, which combines various policies (scrapping scheme, EV subsidy, fossil fuel cost increase, and ICEV ban), highlight the synergistic effect of these measures in accelerating EV adoption and fleet renewal compared to individual policies.

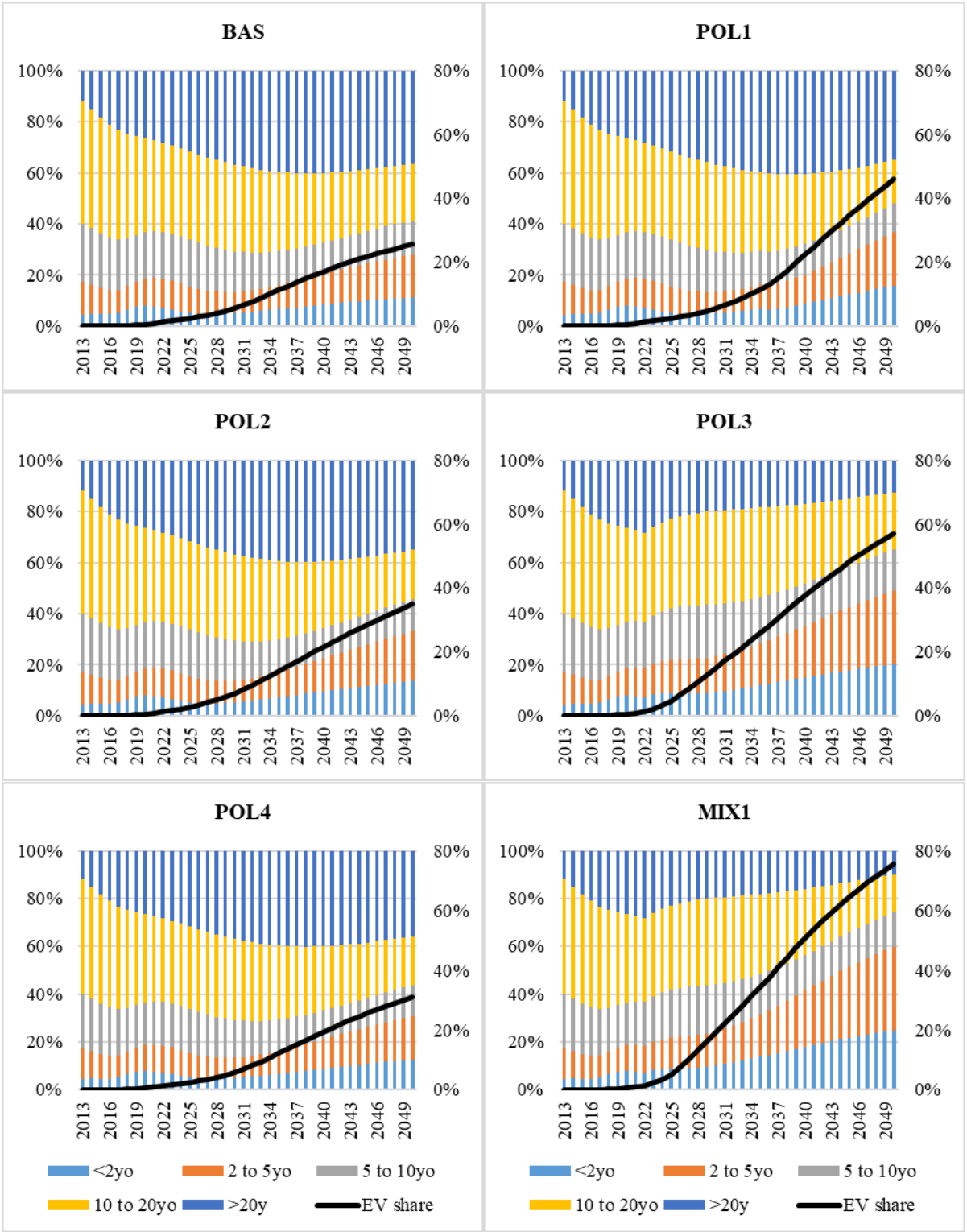


Figure 7-6. Total fleet composition: Age distribution (left axis) and EV share (right axis) across scenarios assuming no growth in car ownership from 2022 levels.

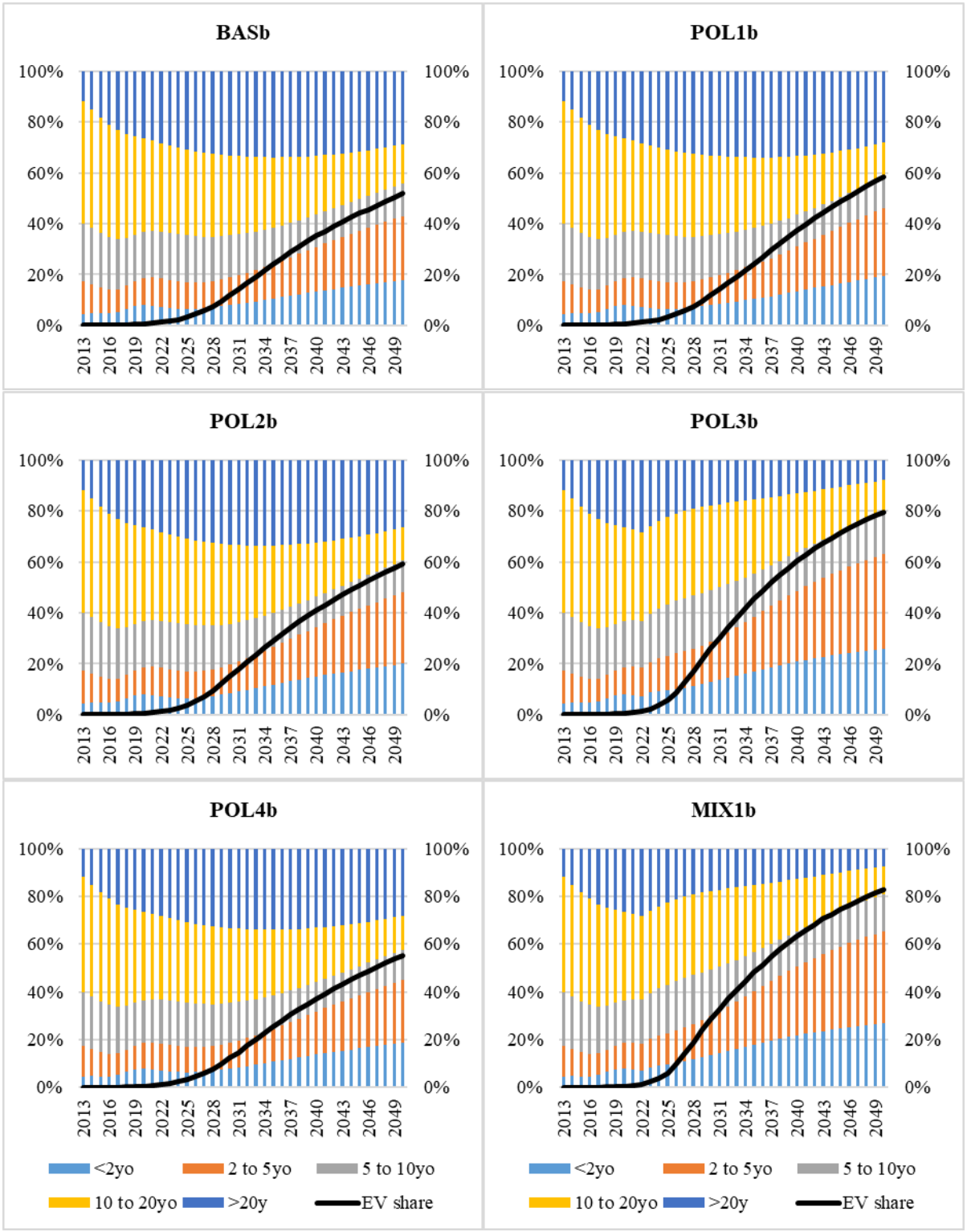


Figure 7-7. Total fleet composition: Age distribution (left axis) and EV share (right axis) across scenarios assuming a 24-percent increase in car ownership rate by 2050 from 2013 levels.

7.4.2.2 Disparities in EV adoption

Figure 7-8 displays the relationship between the year of EV ownership parity between urban and rural populations and the EV share at parity for all scenarios (**Table 7-2**). Parity in this context refers to the point at which EV ownership in rural areas reaches a level comparable to urban areas. Scenarios BAS, POL1, and POL4 reach parity relatively early, around 2029, but with a low EV share (approx. 5%). In POL2, parity is slightly delayed by approximately one year at an EV share of 6.74%. Comparatively, POL3 causes parity to be achieved earlier but with a higher share (approx. 13%). Finally, MIX1 suggests that combining policies increases EV ownership, albeit with a delayed timeline for parity.

Figure 7-8 also contrasts the differences between considering or not growth in vehicle demand. Scenarios with higher vehicle demand (Figure 7-8, bottom) imply a longer time to reach parity. BASb and POL1b reach parity at around 2033 at 20% EV share. POL4b slightly delays parity while increasing the EV share. Nonetheless, in POL2b, parity is significantly delayed, occurring around 2045 at approximately 50% EV share. In POL3b and MIX1, although the year of parity is indicated in 2050, these scenarios would take even longer to reach parity, albeit at higher EV shares of approximately 80 and 83%, respectively.

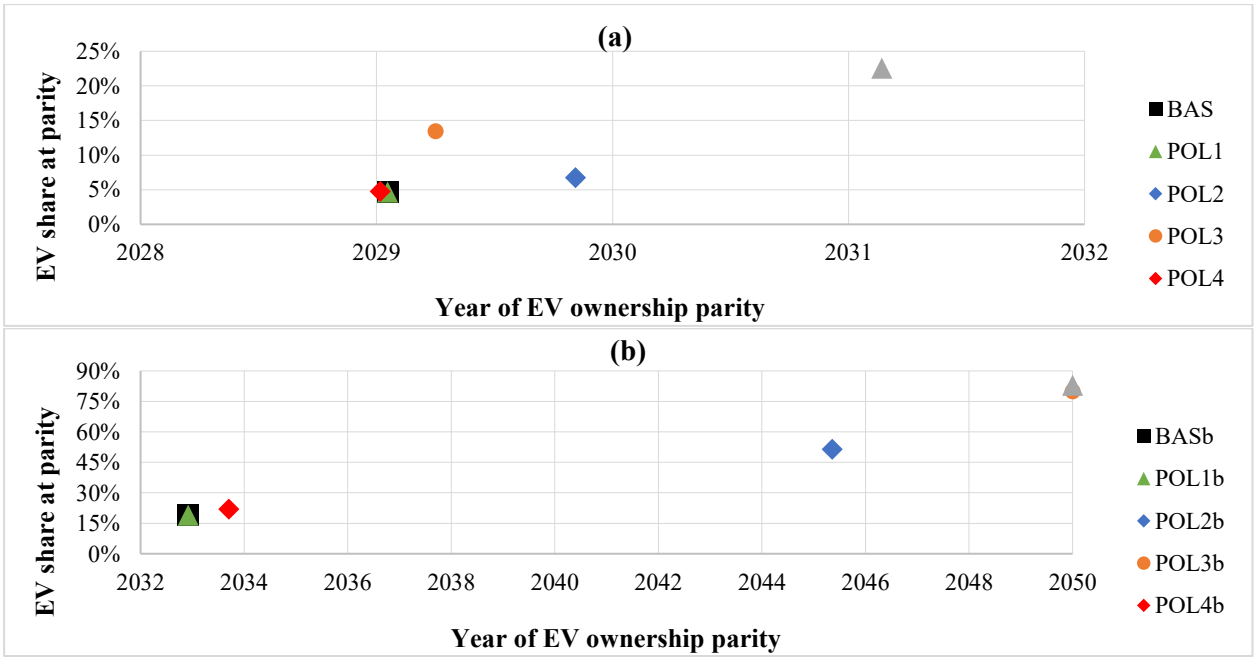


Figure 7-8. Scenario comparison: Year of EV ownership parity between urban and rural populations and EV share at parity. No growth in vehicle demand (a) and a 24-percent increase in car ownership rate by 2050 from 2013 levels (b).

7.4.2.3 Charging infrastructure accessibility

Figures 7-9 and 7-10 contrast scenarios with no growth in car ownership rates (left) and those assuming an increase in vehicle demand (right chart). **Figures 7-9** compares policy scenarios according to the ratio of EVCS per 1,000km^2 between urban and rural populations. As it can be seen in **Figure 7-9**, while a significant disparity exists in 2030, this gap narrows from 2030 to 2050 in all scenarios, although starting from a position of significant disparity in 2030. However, it increases from 2040 to 2050 in scenarios POL1, POL3, and MIX1 when assuming no growth in car ownership rates, and in scenario POL1b when assuming a 24% increase in car ownership rates by 2050 from 2013 levels. The baseline scenario (BAS) exhibits the lowest urban-to-rural EVCS ratio by 2050 (approximately 2 EVCS/1,000km^2). Conversely, a combination of policies, MIX1 and MIX1b, leads to the highest ratio of approximately 7 and 8 EVCS/1,000km^2 by 2050, respectively.

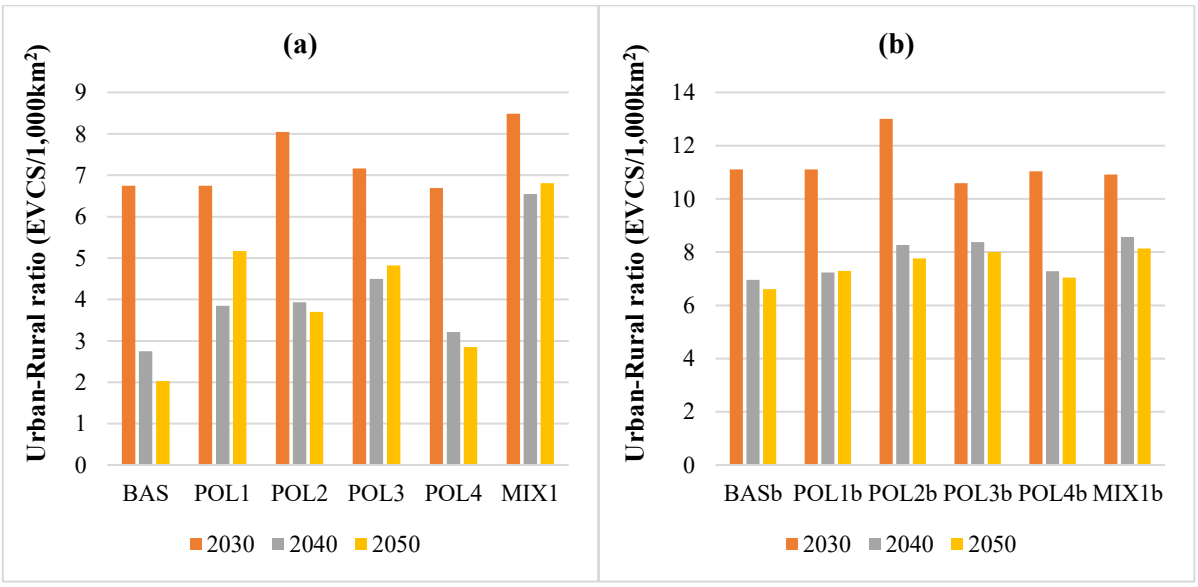


Figure 7-9. Ratio of EVCS per 1,000km^2 between urban and rural populations. No growth in vehicle demand (a) and a 24-percent increase in car ownership rate by 2050 from 2013 levels (b).

Figure 7-10 compares scenarios using the urban-rural ratio of EVCS per 100,000 people. Accordingly, the population-based ratio follows a similar pattern over time than the area-based ratio (**Figure 7-9**). Nonetheless, the disparity between populations is less in the scenarios that consider a growth in car ownership rate since the ratio is closer to one by 2050 (**Figure 7-10**, right). Likewise, this ratio shows less discrepancy when comparing EVCS per 100,000 people than EVCS per area (1,000 km^2).

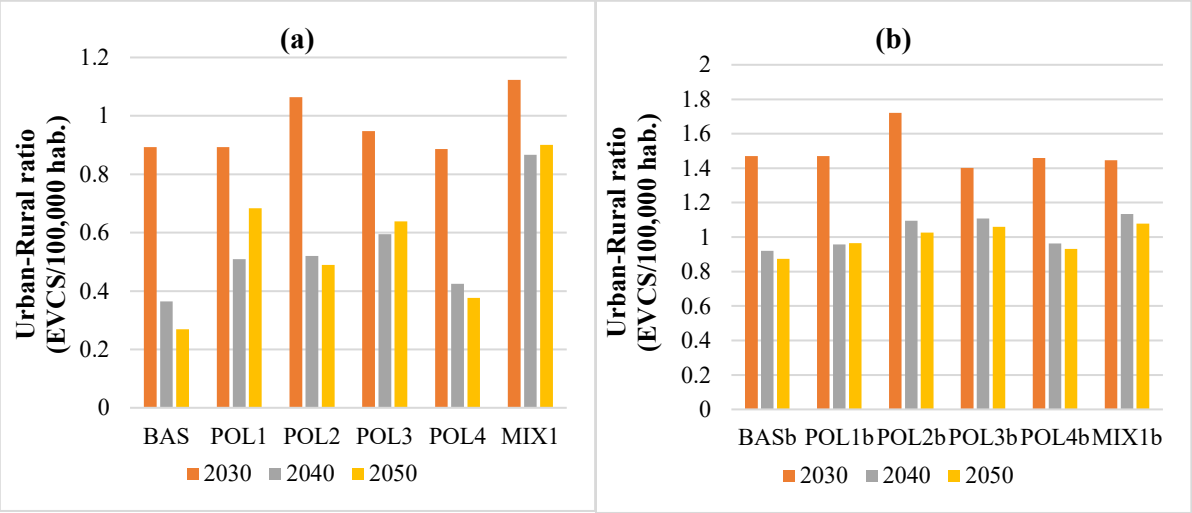


Figure 7-10. Ratio of EVCS per 100,000 people between urban and rural populations. No growth in vehicle demand (a) and a 24-percent increase in car ownership rate by 2050 from 2013 levels (b).

7.5 Discussion

The simulation results shed light on how different policies impact EV adoption and their effect on the disparity of EV ownership and EVCS density in Portugal. The analysis of EV shares across different scenarios reveals an S-curve growth pattern that peaks at different levels based on the policy, with higher EV share observed when an increase in car ownership rates is factored ('b' scenarios) (**Figures 7-6 and 7-7**). Notably, scenarios MIX1 and POL3 outperform the others in terms of achieving a higher final EV share, while BAS lags. The share of EVs in 2050 ranges from 25.51% in the BAS scenario to 82.87% in the MIX1b scenario. However, these results should be interpreted with caution, as the potential market growth of other technologies was not considered in the model. Given the comparable stock of BEVs and PHEVs in Portugal in 2022 (65,769 vs. 67,347 vehicles), PHEVs may pose a significant competitive challenge to EVs (IMT & INE, 2022).

For vehicles older than twenty years (>20 years), a significant reduction in their share to approximately 10% of the fleet occurs only in POL3 and MIX1 scenarios, compared to 30-40% in other scenarios from 2022 onward. This reduction is due to an increase in their scrapping rate, which promotes fleet renewal. Scenarios like MIX1, which combine multiple policy measures, demonstrate that multi-faceted approaches are more effective at both reducing the age of the fleet and increasing EV adoption. In

contrast, policies focused solely on EV adoption (e.g., subsidies) may lead to increased ownership but still leave a significant portion of older vehicles in use.

Regarding parity in EV ownership (**Figure 7-8**), an increase in the vehicle demand, as observed in the 'b' scenarios, causes a delay in the year when ownership parity is reached. Nonetheless, the EV share when parity is achieved also increases correspondingly. For example, in POL3b and MIX1b, parity is attained after 2050, at an EV share of approximately 80 and 83%, respectively. Interestingly, POL2, which introduces EV subsidies, further delays the year of parity in both scenario groups (with and without an increased car ownership rates). This suggests that the urban population benefit more from subsidies than the rural population, raising questions about the effectiveness of subsidies in promoting equitable distribution and accessibility. These implications, however, should be further explored using appropriate methods, such as statistical analysis of the profiles of EV subsidy recipients in Portugal (e.g., (Hennessy & Syal, 2023; Williams, 2023)). Nonetheless, the results suggest that parity in EV adoption between urban and rural populations can be achieved as the technology evolves to address range anxiety and the charging infrastructure becomes more widely available amongst both groups. Yet, the projected year of parity should be interpreted carefully, as it is sensitive to beta parameter values, which are highly uncertain.

Regarding charging infrastructure, the modeling results indicate an uneven area-based distribution of charging stations across all scenarios (**Figure 7-9**), ranging from an urban-to-rural ratio of approximately 2 in the BAS scenario by 2050 to a factor of 13 in the POL2b by 2030. By 2050, the urban-rural gap decreases in all scenarios compared to 2030. However, disparities still persist, especially under higher vehicle demand scenarios, such as mixed policies (MIX1 and MIX1b) and scrappage-focused policies (POL3 and POL3b). A similar time-pattern is observed for the population-based distribution of charging stations (**Figure 7-10**). However, due to the lower population density in rural areas compared to urban ones, the ratio was sometimes skewed in favor of rural areas. This raises concerns about the appropriateness of such indicators in evaluating the fair distribution of EVCS across different populations, highlighting the need for a more targeted approach. Specifically, the location of charging stations relative to users may be more relevant from a justice perspective than their sheer number. Therefore, an alternative method to the one employed in this study is recommended for future evaluations (e.g., (Khan et al., 2022; Li et al., 2022)).

7.6 Conclusion

This study highlights the critical role of integrating justice considerations into the adoption of low-carbon technologies, specifically EVs, within decision-making tools and quantitative models. This study represents the first attempt in the literature to integrate an energy justice metric into a quantitative simulation and system dynamics model for EV adoption. The model incorporates EV ownership parity and the density of EVCS per unit of area and population, as proxies for energy justice. Taking the case of Portugal, these groups were represented by urban and rural populations. Simulation results show that encouraging the scrappage of older vehicles (POL3, MIX1) is crucial for a faster transition to a younger, less-emitting vehicle fleet. These scenarios show the most rapid reduction of older vehicles and higher adoption of EVs. Regarding ownership parity, results indicate that while certain policies may delay the time when ownership parity is achieved, they also result in higher overall adoption rates. Scenarios like BAS and POL1 achieve parity earlier (around 2029), but with lower overall EV shares. In contrast, MIX1b delay parity until after 2050 but achieve a significantly higher EV share (approx. 83%). Interestingly, EV subsidies (POL2 and POL2b) delay parity without increasing the share of EVs significantly compared to BAS and POL1 scenarios.

EVCS charging ratios show significant urban-rural disparities in 2030 across all scenarios. Comparatively, the urban-rural gap decreases in all scenarios by 2050, but disparities still persist, especially under a combination of policies in a per-area basis. Differences between the density of EVCS per area and population suggest that alternative methods are considered, particularly those that point to the location of public charging infrastructure over their sheer number. The findings underscore the importance of addressing disparities in EV ownership and charging infrastructure, particularly between urban and rural populations, and emphasize the need for more nuanced representations of socioeconomic and spatial groups to better reflect real-world inequities.

7.6.1 Limitations

The first limitation of this study refers to the epistemological assumption behind the identification of distributional justice-related issues. It is assumed that rural groups would like to or have the right to have the same access to EVs and their infrastructure as urban groups, since ICEV sales are to be banned from 2035 onward in the EU and EVs are the current low-carbon alternative for private mobility. Secondly, the differentiation between urban and rural groups as representatives of advantaged and disadvantaged populations is a simplistic manner of representing the socioeconomic diversity that exists within these

two groups. Nevertheless, the lack of data on consumer group preferences and vehicle ownership by region and socioeconomic conditions has refrained the authors from adding another component of uncertainty into the model. In case data becomes available, it is recommended to segregate urban and rural into sub-groups (e.g., socioeconomically advantaged and disadvantaged) as a means to fully capture socioeconomic and spatial disparities. Thirdly, further discussion is needed regarding how simulation timeframes may reflect the principle of temporality.

Regarding the modelling approach, data availability constraints and different consumer dynamics for HEVs and PHEVs caused these alternatives to be excluded from the analysis, more specifically the establishment of beta parameters in the MNLM. Considering the weight of PHEVs in the current vehicle registrations in Portugal, their non-inclusion is likely to be a significant limitation of the present study that should be addressed in the future when data becomes available. Additionally, the number of assumptions that were required to parametrize the model in face of lacking consumer-based information is a limitation to be acknowledged. Likewise, the consideration of consumer heterogeneity and choice independence in the MNLM is a strong assumption that can significantly alter the model's mathematical formulation and, consequently, results.

Although the model underwent a lengthy validation process, "*even 'perfect' structures may not yield accurate point prediction*" (Barlas, 1996). Consequently, simulations results must be treated with caution. However, considering this study's purpose of advancing the integration of energy justice issues into quantitative modelling, the presented limitations do not undermine its contribution to literature. Rather, it reinforces that the developed system dynamics model should not be seen as a final version of itself, or an optimal way of assessing justice within low-carbon technological adoption, but a changing entity that can be improved as further data becomes available and more knowledge is assimilated into its structure. Therefore, the proposed model should be viewed as an evolving tool that can be refined with additional data and insights.

7.6.2 Potential research lines

Given the presented methodological limitations, this study would greatly benefit from further empirical data collection on the perception of justice in EV ownership and charging accessibility across different socioeconomic and urban typologies. With such data, populations could be represented in a more nuanced manner (e.g., socioeconomically advantaged and disadvantaged, income quintiles, etc.) rather than the simplified representation used in this study (i.e., urban vs. rural).

Additionally, more comprehensive data on consumer preferences and mobility choices would enable the inclusion of other technologies, such as PHEVs, as well as alternative modes of transportation. This deeper understanding could also allow for the incorporation of more subjective feedback loops, such as how perceptions of disparity or injustice in government policies or technological adoption impact the uptake of new technologies among less privileged groups. Exploring these dynamics could open new and compelling research avenues. Lastly, with additional data, the mathematical formulation of the model could also be further refined.

Future research could also focus on household-level aggregation to identify how certain technological options are excluded on the basis of unaffordability. In this case, the percentage of household income spent on vehicle ownership would become a key factor in the decision to own a car, given the available mobility options. When integrating justice issues into decision-making tools and quantitative models, caution is essential. As this line of research evolves, the subjectivity and context-dependency of social and ethical concerns must not be overlooked. While this study advances this line of research, it emphasizes the need for further debate on how (and whether) justice can be operationalized without compromising its core principles. For instance, one limitation of the simulation is the timeframe, which may not fully capture the long-term, context-dependent nature of energy justice issues. The concern is that trying to measure or simulate justice using fixed or oversimplified timelines might not capture the complexity and fluidity of justice-related matters, potentially distorting or oversimplifying the concept. Therefore, the presented model and findings should not be viewed as a definitive method for assessing justice in adoption of low-carbon technology, but rather as part of an evolving research agenda aimed at shifting the focus from a purely technology, techno-centric view to a more systemic and balanced approach. Additionally, future research could leverage the insights from this study to incorporate energy justice considerations into optimization or multi-criteria models.

In this regard, it becomes clear that the complex nature of justice necessitates a combination of diverse methods in order to be integrated into modeling and decision-making tools. These methods range from understanding the concept of justice within each particular case, identifying justice issues through qualitative and quantitative approaches, and representing these issues via proxies for monitoring and assessment over time. As echoed in other works (Van Uffelen et al., 2024), this study calls for careful consideration of these aspects to avoid overusing terms such as "*justice*", "*fairness*", and "*equity*", therefore, compromising justice's intrinsic values in research and policy development.

While this research advances the understanding of justice issues in EV adoption in Portugal and its operationalization in quantitative modelling, it also calls for caution in the understanding and representation of justice. It is necessary to ensure that the utilization of the concept is contextually and normatively grounded. Future work should focus on the development of more robust data sets to capture the complexities of justice, including the characterization of consumer groups, the effect of justice itself on technological adoption, and the improvement of the modeling approach. Ultimately, this study serves as a steppingstone toward a more systemic and balanced approach to technological adoption modeling that is sensitive to social and ethical dimensions.

8 Conclusions

This Chapter concludes this PhD thesis by summarizing its main findings (**Section 8.1**) and limitations (**Section 8.2**) and proposing a future research agenda (**Section 8.3**).

8.1 Summary of key findings

This thesis makes a pioneering contribution by being among the first to embed energy justice indicators into system dynamics models in the context of EV adoption. The overarching research questions of this thesis revolve around (**RQ1, Section 1.2**) understanding the social, economic, and environmental issues associated with EV adoption from an energy justice, whole-systems perspective, and (**RQ2, Section 1,2**) exploring how justice considerations in the EV transition can be operationalized and integrated into system dynamics modeling.

RQ1 was addressed through a comprehensive exploration of the justice implications of EV adoption. In **Chapter 2**, potential injustices across the EV lifecycle, ranging from raw material extraction to end-of-life disposal, were identified and mapped. The identification process employed the energy justice tenet-based framework in combination with a whole-systems approach. This was performed through an exploratory analysis of peer-reviewed and grey literature, which pointed to issues such as the risk of reinforcing inequalities between and within countries via extractive supply chains and geopolitical asymmetries and policies favoring the wealthier, respectively; and the unequal distribution of environmental externalities across the supply chain.

Taking the case of Portugal, in **Chapters 5, 6, and 7**, the research identified that the key justice-related impacts of the EV transition refer to lithium mining for EV batteries and asymmetries in EV adoption and access to charging infrastructure. This identification followed a robust documentary analysis covering governmental and industry reports, online news, statistical data, and peer-reviewed literature.

In sum, This thesis provides empirical and methodological evidence that, while EVs offer clear decarbonization benefits, their adoption presents a complex matrix of justice implications. A whole-systems energy justice perspective is essential to ensure that these technologies contribute to a JET rather than exacerbate existing inequalities by emphasizing the complexity and controversies of low-carbon transitions.

Next, this thesis addresses **RQ2** by developing and applying a methodological pathway for integrating justice considerations into system dynamics modeling. It does so by moving from conceptual foundations established in **Chapters 2, 3 and 4,** to empirical application in **Chapters 5, 6, and 7**, demonstrating how system dynamics can be structured to build knowledge regarding energy justice concerns related to EV transitions.

Chapter 2 outlines the diverse energy justice issues across the EV lifecycle, identifying normative tenets and setting the stage for their translation into quantitative proxies. **Chapter 3** systematically reviews how justice-related issues have been operationalized quantitatively in the literature. This review identifies relevant indicators and metrics (e.g., income levels, EV accessibility, air pollution exposure) that can be included in quantitative modeling. Next, **Chapter 4** bridges the conceptual with the methodological by evaluating how social and justice dimensions have been incorporated into existing system dynamics models of energy transitions. It highlights strengths, such as the ability to model heterogeneity and feedback over time, and challenges, such as the inconsistent representation of social aspects, especially when evaluating in socio-political dynamics.

In **Chapter 5**, besides presenting the case study context, system dynamics is justified as a modeling paradigm that is not only technically robust but epistemologically aligned with energy justice goals, particularly when addressing long-term transitions, feedback-rich environments, and the need for inclusive, participatory modeling processes. Particularly, in **Section 5.3**, it is argued that system dynamics, as a modeling tool, is useful for justice-related assessments for the following reasons:

(i) recognize different actors of the transition (income level, urban vs. rural, educational level, political influence, etc.) as they can be incorporated into models that differentiate between stakeholder groups;

(ii) capture feedback loops and delays, which can reflect factors that relate to cumulative advantage or systemic delay (e.g., feedback between EV adoption, charging infrastructure investment, and affordability);

(iii) policy levers and scenario testing, by which justice-based interventions (e.g., subsidies for EV adoption, procedural fairness mechanisms in mining approval) can be tested in the models to assess their impact over time, helping explore the implications of justice-sensitive policy design;

(iv) convey specific abstraction levels (i.e., the degree of detail and scale used to represent real-world phenomena in a model) required to address the spatial and contextual specificity (e.g., focusing on the Barroso mining project or rural communities in Portugal) of justice issues.

Finally, **RQ2** is also addressed in **Chapters 6 and 7**, where system dynamics is applied to the two critical justice-related issues identified in the EV transition in Portugal: lithium mining and urban-rural asymmetries in EV adoption, respectively. **Chapter 6** applies system dynamics modeling to the issue of social acceptance in lithium mining, emphasizing procedural and recognition-based justice. The model includes variables for trust, alignment of interests, and government responsiveness, which influence the SLO and, by extension, resource availability for EV battery production. This application shows how actor perceptions and power asymmetries can be dynamically modeled, although in a stylized manner, and how these influence material supply and transition risks.

Chapter 7 focuses on distributional justice in EV adoption by modeling disparities in EV ownership and charging infrastructure between urban and rural areas in Portugal. The model incorporates equity indicators (e.g., infrastructure availability and urban-rural EV ownership rates) and simulates their evolution under different policy scenarios. This demonstrates how system dynamics modeling can be used to explore the justice-related implications of policies for the energy transition.

Conclusively, this thesis provides evidence that system dynamics modeling can serve as a powerful tool for operationalizing energy justice in the EV transition, provided it is deliberately structured to reflect justice-related concerns. By incorporating actor heterogeneity, dynamic feedback loops, context specificity, and policy sensitivity, system dynamics models can move beyond technical optimization to act as a learning tool able to simulate the socio-environmental trade-offs and equity outcomes of EV adoption. Nevertheless, there is plenty of space for reflections and limitations, which must also compound the answer to **RQ2**, as underscored in **Section 8.2**.

8.2 Limitations and reflections

This thesis has aimed "to explore systemic socio-environmental asymmetries associated with EV adoption through an energy justice and whole-systems lens, integrating energy justice considerations into system dynamics modeling as a means to identify pathways for a JET" (**General objective, Section 1.2**).

However, several limitations must be acknowledged regarding the conceptual framework's application, the case studies analyzed, and the modeling approach adopted. These limitations, while partly methodological, also underscore the deeper tensions involved in representing normative and complex social phenomena within computational models (McDowall & Geels, 2017).

A first major limitation of both quantitative models (presented in **Chapters 6 and 7**) stems from the reliance on secondary data and the large number of assumptions, which substituted primary data collection and greater stakeholder engagement due to time and resource constraints. In both case studies, the lack of direct engagement with affected communities represents a significant shortcoming. For instance, the model developed in **Chapter 6** to assess the Barroso lithium mine (Dall-Orsoletta, Verrier et al., 2025) was based on expert input and literature review, without validation through direct engagement with local residents and the responsible company, which constrains the model's ability to reflect the situated understandings of justice and socio-environmental risk. As noted in prior literature, stakeholder participation can provide critical insights, reveal divergent values, and strengthen model legitimacy (McDowall & Geels, 2017). The absence of such engagement here reduces the model's role to that of a **learning tool for the modeler rather than a robust learning and decision support mechanism**.

Additionally, representing complex justice dimensions through simplified metrics within a quantitative model risks (epistemic and methodological) **reductionism**[1] due to the reduction of rich, multi-dimensional concepts (e.g., trust, social acceptance, procedural justice) to simpler, measurable constructs in order to study and evaluate them. While such abstraction is often necessary in quantitative modeling, it may obscure the nuanced and context-dependent nature of social and cultural phenomena[2]. In the Barroso case, for instance, procedural justice was reduced to a single dimension in the developed model despite being deeply entangled with historical grievances, regulatory processes, and local governance dynamics. Although efforts were made to build context and situate the research in its broader historical and regulatory environment of the project, it is acknowledged that a much richer discussion

[1] A reductionist approach to science involves explaining complex phenomena by breaking them down into their simpler, constituent parts (Andersen, 2001; Pigliucci, 2014). It is often approached as opposed to holism, although they can be in fact complementary, as argued by (Fang & Casadevall, 2011) when discussing molecular biology and systems biology. A holistic approach emphasizes understanding systems as integrated wholes rather than merely analyzing their individual components (Andersen, 2001; Pigliucci, 2014). In a complementary approach, reductionism would be useful to generate hypothesis (e.g., causal relationships), while holism would help contextualize findings, encouraging cross-disciplinary insights. In other words, an operationalization of justice without broader, in-depth contextualization, would risk epistemic losses in the understanding of this complex phenomena and, consequently, methodological reductionism.

[2] This argument is often present in interdisciplinary studies that attempt to somehow quantify cultural- and social-related aspects, such as critics to social impact assessment through the social return on investment (Maier et al., 2015) and limited integration of social sciences into quantitative modeling (Trutnevyte et al., 2019).

stemming from social and political sciences could be developed around the understanding of justice within the particular context of the Barroso Mine and its neighboring communities, and, for instance, the clash of values with the mining company.

In the second model (Dall-Orsoletta, Oosthuizen, et al., 2025) presented in **Chapter 7**, which analyzed equity in EV ownership and infrastructure access, similar limitations emerged. The model did not incorporate empirical consultation with rural and urban populations, raising concerns about the validity of its assumptions. Specifically, the presumption that lower EV uptake in rural areas reflects injustice may be misleading if residents do not perceive EV ownership as a relevant issue. Justice, in this context, may instead lie in the absence of affordable and alternative mobility options compared to that of private cars. The risk here is of **imposing an externalized notion of equity (centered on EV access) rather than responding to locally articulated needs**. This highlights the risk of epistemic injustice and also a broader tension between modeling at national or international levels and the local, individualized realities that often frame perceptions of fairness and priority. This is directly linked to discussions surrounding "thick" and "thin" morality, notions presented by Walzer (1995). Walzer calls "thick morality" the values which people are more thickly connected to, i.e., close community, including family, school, neighbors, and religious beliefs (*apud* Galvin, 2019). Conversely, in "thin morality", our moral values are stretched towards settings far from where they were developed. This was masterfully discussed in the context of energy justice by Galvin (2019, p. 182):

> *"We cannot demand, for example, that a politician in London whose moral compass is almost entirely 'thick'– focused on local hardships and needs – suddenly becomes an advocate for the rights of, say, rural people in Peru who are being displaced by the building of a hydroelectric dam. Our intellectual argument may be spotless in its own terms, but it may not connect with the meaning of life for those we are trying to convince, and may simply come across as irritating."*

This diversity and differences in "thick" moral values pertaining to the countless communities that exist around the world, underscore how **discussions around what is "just" or "fair" cannot be generalized from one context to another.** Likewise, it cannot be neglected that the moral compass of researchers themselves may have an influence on how justice-related research is conducted. This is to say that, even though the energy justice framework provides guidance on how to identify injustices, this identification will remain subject to the researcher's own biases and moral values; thereby the

importance of further normative and **epistemic clarification** (i.e., what is meant by justice and by whom). As emphasized by Van Uffelen et al. (2024), **different cultural, legal, and philosophical traditions inform diverse interpretations of what constitutes a JET**. This plurality was only partially acknowledged in the modeling framework, which largely drew upon established Western conceptions of distributive, procedural, and recognition justice. A more reflexive approach would have involved critical questioning of whose perspectives are represented in the model and how justice is framed.

A further conceptual limitation of this thesis involves the **risk of conflating empirical evidence of structural effects with consequences of the low-carbon transitio**n. For instance, that wealthier individuals are more likely to own EVs is a reflection of wider socioeconomic inequality (structural effect), not necessarily a direct manifestation of injustice due to EVs (consequence of the low-carbon transition). However, if electrification policies restrict access to affordable transport without addressing systemic inequalities, they may indeed produce unjust outcomes. **Models must therefore carefully distinguish between patterns of disparity and structural injustices, lest they lead to reductive or misplaced policy recommendations.**

From a methodological standpoint, several limitations stem from the use of **system dynamics modeling** itself. While this approach is valuable for exploring feedback loops and unintended consequences, as mentioned in **Chapters 5, 6 and 7** and summarized in **Section 8.1**, it is inherently heuristic and shaped by the biases of the modeler. **The structural assumptions embedded in the models, particularly regarding system boundaries and aggregation levels, may obscure as much as they reveal.** For instance, decisions about spatial scale (i.e., whether to model justice concerns at a local, national, or regional level) affect the visibility of certain injustices while potentially erasing others (e.g., Barroso Mine perspective vs. social conflicts in the Lithium Triangle in South America). Similarly, the choice of time horizon influences which justice concerns (e.g., short-term affordability vs. long-term sustainability) are prioritized.

Nevertheless, **this broader epistemological constraint lies in the nature of all modeling as a practice of abstraction**[3]. Consequently, even if model complexity or scope are increased through more

[3] Because models are always simplifications of reality, they inevitably exclude some aspects of the systems they represent. As coined by George Box and Norman Draper: "All models are wrong, but some are useful" (cited by (Mitchell, 2009) *apud* (Priesmann et al., 2019)). As a consequence, the knowledge models produce is partial, selective, and shaped by the modeler's perspective.

data, variables, or disaggregated actors, it does not necessarily enhance accuracy or insight[4]. Particularly **in the context of justice, the application of models or their expanded versions may generate an illusion of "precision".** As computational models become more sophisticated and widely used, there is a tendency to overestimate their capacity to resolve certain dilemmas (e.g., including justice- or cultural-related). Yet, it is important to remember that the ability to simulate does not imply methodological superiority or appropriateness. Often, qualitative or historical approaches may be better suited to uncovering hidden injustices of energy transitions. **Over-reliance on modeling may contribute to the depoliticization of justice concerns**, where contestable value judgments are embedded within seemingly objective tools, and the continuation of technocratic approaches.

Finally, a practical and methodological limitation must be acknowledged regarding the **power of models in shaping decision-making**. Despite the large number of quantitative models that have been created in the context of the energy transition, **one could wonder how many of these models, and to what extent, have had an influence on regional and national transition policies**. This raises questions regarding the largely used term "decision-making aiding tool" in scholarly research presenting quantitative models; term which was also employed in this thesis. Nevertheless, **a tool is only a tool when it is used to perform a function**. In this sense, most of the models developed in research (the ones developed within this thesis included) are experiments for learning, unfortunately often limited to the modelers, rather than decision-making tools. In this regard, while it has been argued that participatory modeling approaches can enhance procedural justice and foster shared understanding (McGookin et al., 2021), improving model-based learning and impact opportunities, it is also true that it introduces practical challenges related to interdisciplinarity, resource constraints, and the challenge of managing conflicting values among stakeholders. Moreover, **participatory processes do not guarantee substantively just outcomes**; they can just as easily reinforce existing power asymmetries if not carefully designed and facilitated (Sundaram et al., 2024). This reflection calls for further consideration on the future of modeling and its broader implications.

[4] Although not formally recognized, my own practice in the field has led to the recognition of different "schools of thoughts" within system dynamics. One of them stems from the origins of the field in operations research with Jay Forrester in the 70s. This school is mainly concerned with understanding and representing a particular problem, testing potential solutions and system levelers. Secondly, with the growth of IAMs and internationally-recognized system dynamics models En-ROADS and EUROGREEN, there has been a tendency to increase model size by endogenizing more and more variables, enlarging the number of questions that can be answered by one specific model. I would say there is even a third school of system dynamics that has applying its software as a more visual accounting method, substituting spreadsheets by system dynamics models and their visual causal relationships. Nevertheless, this discussion is not the focus of this thesis and deserves further exploration.

In conclusion, this thesis has demonstrated the potential for integrating energy transition asymmetries into modeling frameworks, but it has also exposed the limitations and risks of doing so. Therefore, complementing the answer to **RQ2** provided in **Section 8.1**: **Justice cannot be fully captured in a model, it must also be narrated, debated, and situated. Models should be seen not as conclusive "answer machines" but as platforms for critical inquiry, reflective dialogue and learning among multiple stakeholders.**

8.3 Future research agenda

In addition to the specific research agendas referring to methodological refinement and research gaps that can be found in **Chapters 2, 3, 4, 6, and 7**, this thesis offers broader recommendations for future research that stem from three interrelated areas: (1) philosophy and reflexivity, (2) computational modeling, and (3) methodological approaches.

Future research is encouraged to take a philosophical "step back" when engaging with the concepts of "energy transition" and, in particular, the JET as scientific objects. This step back involves critically examining the materiality of the energy transition, questioning whether it is a current, past, or prospective phenomenon that can be empirically investigated, or rather an aspiration shaped by scientific and political discourse. Recent developments in the oil and gas sector and growing geopolitical tensions compel us to reconsider whether research in energy systems and net-zero policy scenarios risks becoming detached from reality, closer to comforting narratives rather than actionable insights. This calls for deep reflexivity in the use of terms such as "energy transition," "just energy transition," and "sustainable energy systems."

Building on the reflections and limitations discussed in **Section 8.2**, future research should further interrogate the role, purpose, and audience of computational models in the energy domain. Researchers should critically assess whether their models genuinely serve as decision-support tools, or whether their utility ends with publication and citation. Given the epistemic limitations of models, regardless of how many variables or relationships are included, they should be seen as exploratory tools, not definitive predictors. Models are, by nature, reductive, and framing them as holistic solutions risks reinforcing a reductionist paradigm under the guise of complexity.

In light of this, researchers should be even more cautious in integrating complex normative concepts such as justice into quantitative modeling. While quantitative approaches (e.g., system dynamics) can offer valuable insights into specific justice-related aspects (assuming these are clearly defined and operationalized into measurable indicators), their scope and limitations must be transparently acknowledged. Concepts like justice are inherently abstract, context-dependent, and grounded in "thick" moral values. When integrated into already complex sociotechnical processes (e.g., energy transitions) modeling, these terms must be clearly defined, critically scoped, and complemented by other social science research methods. Without such care, there is a significant risk of epistemic bias and injustice, as vague or uncritical use may obscure rather than illuminate the power dynamics and social implications involved. In the field of complex socio-technical systems and modeling targeting the inclusion of social and cultural aspects, future research could contribute by refining model boundaries, expanding interdisciplinary research, and reducing normative ambiguity.

As framed in the introduction of this thesis, energy transitions are inherently sociotechnical in nature, comprising complex interactions among technological, social, political, and economic subsystems. Therefore, addressing such complexity requires collaboration not only among diverse academic disciplines (e.g., engineering, law, economics, political science), but also with stakeholders affected by or involved in energy decisions. Yet, ensuring meaningful participation and substantively fair outcomes is not straightforward even in participatory modeling approaches. Therefore, as a last future research line, it is recommended to focus on establishing and testing methodological frameworks that facilitate this engagement and enable more robust, inclusive, and reflective knowledge production.

9 References

ACAP. (2024). *Balanço Anual do Mmercado Automóvel Nacional*. Associação Automóvel de Portugal (ACAP). Retrieved from https://acap.pt/pt/estatisticas/dados

ACEA. (2023). *Tax benefits and purchase incentives: Electric passenger cars* (pp. 1–8). pp. 1–8. ACEA. Retrieved from https://www.acea.auto/files/Electric_cars-Tax_benefits__purchase_incentives_2023.pdf

Ademulegun, O. O., Flynn, D., & Hewitt, N. J. (2025). Designing tariff for charging electric vehicles at home with equity in mind – The tripartite tariff. *Sustainable Cities and Society*, *118*(November 2024), 106018. https://doi.org/10.1016/j.scs.2024.106018

Agusdinata, D. B., Liu, W., Eakin, H., & Romero, H. (2018). Socio-environmental impacts of lithium mineral extraction: Towards a research agenda. *Environmental Research Letters*, *13*(12). https://doi.org/10.1088/1748-9326/aae9b1

AIB. (2021). *European Residual Mix*. Association of Issuing Bodies (AIB). Retrieved from https://www.aib-net.org/facts/european-residual-mix/2021

Akhtar, Mohammad K., Wibe, J., Simonovic, S. P., & MacGee, J. (2013). Integrated assessment model of society-biosphere-climate-economy-energy system. *Environmental Modelling & Software*, *49*, 1–21. https://doi.org/10.1016/j.envsoft.2013.07.006

Akhtar, Mohammad Khaled, Simonovic, S. P., Wibe, J., & MacGee, J. (2019). Future realities of climate change impacts: An integrated assessment study of Canada. *International Journal of Global Warming*, *17*(1), 59–88. https://doi.org/10.1504/IJGW.2019.096761

Ala, G., Colak, I., Di Filippo, G., Miceli, R., Romano, P., Silva, C., … Viola, F. (2021). Electric mobility in portugal: Current situation and forecasts for fuel cell vehicles. *Energies*, *14*(23). https://doi.org/10.3390/en14237945

Alozie, A. C. (2019). *Sustainable management of Mineral Resource Active Regions : A Participatory Framework for the Application of Systems Thinking Alaoma Chidirim Alozie*.

Alshahapy, H., Bozeman, J. F., Carley, S., Nock, D., & Matisoff, D. (2025). Modern challenges facing electric vehicle adoption: a review of barriers to adoption, supply chain challenges, and equity. *Environmental Research Letters* , *20*(2). https://doi.org/10.1088/1748-9326/ada6de

Ambrose, H., & O'Dea, J. (2021). Electric vehicle batteries. *Union of Concerned Scientists*, pp. 1–9. https://doi.org/10.1149/2.f05961if

Andersen, H. (2001). The history of reductionism versus holistic approaches to scientific research.

Endeavour, *25*(4), 153–156. https://doi.org/10.1016/S0160-9327(00)01387-9

André, M., Pasquier, A., & Carteret, M. (2018). Experimental determination of the geographical variations in vehicle fleet composition and consequences for assessing low-emission zones. *Transportation Research Part D: Transport and Environment*, *65*(October), 750–760. https://doi.org/10.1016/j.trd.2018.10.005

Annandale, M., Meadows, J., & Erskine, P. (2021). Indigenous forest livelihoods and bauxite mining: A case-study from northern Australia. *Journal of Environmental Management*, *294*(May), 113014. https://doi.org/10.1016/j.jenvman.2021.113014

APA. (2023). *Título Único Ambiental - TUA e Declaração de Impacte Ambiental*. República Portuguesa.

Araújo, E., Bento, S., & Silva, M. (2022). Politicizing the future: on lithium exploration in Portugal. *European Journal of Futures Research*, *10*(1). https://doi.org/10.1186/s40309-022-00209-3

Araújo, K. (2014). The emerging field of energy transitions: Progress, challenges, and opportunities. *Energy Research and Social Science*, *1*, 112–121. https://doi.org/10.1016/j.erss.2014.03.002

Armand, M., Axmann, P., Bresser, D., Copley, M., Edström, K., Ekberg, C., … Zhang, H. (2020). Lithium-ion batteries – Current state of the art and anticipated developments. *Journal of Power Sources*, *479*(July). https://doi.org/10.1016/j.jpowsour.2020.228708

Aslani, A., Akbari, S., & Tabasi, S. (2018). The Robustness of Natural Gas Energy Supply: System Dynamics Modelling. *International Journal of System Dynamics Applications*, *7*(3), 57–71. https://doi.org/10.4018/IJSDA.2018070103

Aslani, A., Helo, P., & Naaranoja, M. (2013). Evaluation of renewable energy development in power generation in Finland. *Journal of Renewable and Sustainable Energy*, *5*(6), 063132. https://doi.org/10.1063/1.4855095

ATIC. (2018). The Lithium-Ion Battery Value Chain – New Economy Opportunities for Australia. In *Australian Trade and Investment Commission*.

Automotive from Ultima Media. (2021). Electric vehicle and hybrid vehicle plant database. Retrieved August 17, 2021, from https://www.automotivelogistics.media/electric-vehicles/electric-vehicle-and-hybrid-vehicle-plant-database/41931.article

Ayetor, G. K., Mbonigaba, I., Sackey, M. N., & Andoh, P. Y. (2021). Vehicle regulations in Africa: Impact on used vehicle import and new vehicle sales. *Transportation Research Interdisciplinary Perspectives*, *10*(July 2020), 100384. https://doi.org/10.1016/j.trip.2021.100384

Bai, B., Wang, Y., Xiong, S., & Ma, X. (2021). Electric vehicle-attributed environmental injustice: Pollutant transfer into regions with poor traffic accessibility. *Science of the Total Environment*, *756*, 143853.

https://doi.org/10.1016/j.scitotenv.2020.143853

Baker, S., DeVar, S., & Prakash, S. (2019). *The Energy Justice Workbook* (pp. 1–76). pp. 1–76. Initiative for energy justice. Retrieved from https://iejusa.org/workbook/

Bale, C. S. E., Varga, L., & Foxon, T. J. (2015). Energy and complexity: New ways forward. *Applied Energy*, *138*, 150–159. https://doi.org/10.1016/j.apenergy.2014.10.057

Barakos, G., & Mischo, H. (2021). Insertion of the social license to operate into the early evaluation of technical and economic aspects of mining projects: Experiences from the Norra Kärr and Bokan Dotson rare earth element projects. *Extractive Industries and Society*, *8*(2), 100814. https://doi.org/10.1016/j.exis.2020.09.008

Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics. *System Dynamics Review*, *12*(3), 183–210. https://doi.org/10.1002/(sici)1099-1727(199623)12:3<183::aid-sdr103>3.3.co;2-w

Barros, G. O. de, & Novo, G. (2023). *Veículos Elétricos em Portugal - Oportunidades e Desafios Económicos e Ambientais*. Retrieved from https://www.gee.gov.pt/pt/estudos-e-seminarios/estudos-de-temas-economicos-category/34-temas-economicos/33127-te-119-veiculos-eletricos-em-portugal-oportunidades-e-desafios-economicos-e-ambientais

Bartiaux, F., Vandeschrick, C., Moezzi, M., & Frogneux, N. (2018). Energy justice, unequal access to affordable warmth, and capability deprivation: A quantitative analysis for Belgium. *Applied Energy*, *225*(June), 1219–1233. https://doi.org/10.1016/j.apenergy.2018.04.113

Barton, J., Davies, L., Dooley, B., Foxon, T. J., Galloway, S., Hammond, G. P., … Thomson, M. (2018). Transition pathways for a UK low-carbon electricity system: Comparing scenarios and technology implications. *Renewable and Sustainable Energy Reviews*, *82*(October 2017), 2779–2790. https://doi.org/10.1016/j.rser.2017.10.007

Bass, F. M., Krishnan, T. V, & Jain, D. C. (1994). Why the Bass model fits without decision variables. *Marketing Science*, *13*(3), 203–223.

Bažbauers, G., Bariss, U., Timma, L., Lauka, D., Blumberga, A., & Blumberga, D. (2015). Electricity saving in households due to the market liberalization and change in the consumer behaviour. *Energetika*, *61*(3–4), 108–118. https://doi.org/10.6001/energetika.v61i3-4.3251

Benchmark Source. (2024). Spodumene prices soften to three year low amid weak lithium chemical prices. Retrieved December 6, 2024, from https://source.benchmarkminerals.com/article/spodumene-prices-soften-to-three-year-low-amid-weak-lithium-chemical-prices?mc_cid=833859d141&mc_eid=c6b32f56a5

Berzi, L., Delichristov, D., Favilli, T., Pierini, M., Ponchant, M., Qehajaj, A., & Pugi, L. (2020). Smart Energy Management of Auxiliary Load for Electric Vehicles. *Proceedings - 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe, EEEIC / I and CPS Europe 2020*. https://doi.org/10.1109/EEEIC/ICPSEurope49358.2020.9160762

Besley, J. C. (2010). Public Engagement and the Impact of Fairness Perceptions on Decision Favorability and Acceptance. *Science Communication*, *32*(2), 256–280. https://doi.org/10.1177/1075547009358624

Bevir, M. (2009). Systems Theory. In *Key Concepts in Governance* (p. 205). London: SAGE Publications Ltd. https://doi.org/10.4135/9781446214817.n49

Beyazit, M. A., Erenoglu, A. K., & Tascikaraoglu, A. (2024). Fairness and Equity in Electric Vehicle Charging with Mobile Charging Stations. *IEEE Transactions on Industry Applications*, *61*(2), 1280–1291. https://doi.org/10.1109/TIA.2024.3477426

Bharati, A. K., Singhal, A., Jinsiwale, R., Kazimierczuk, K., Yoshimura, J., & Tarekegne, B. (2023). Advancing Energy Equity Considerations in Distribution Systems Planning. *2023 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 1–5. IEEE. https://doi.org/10.1109/ISGT51731.2023.10066350

Bhattacharyya, S. C., & Timilsina, G. R. (2010). A review of energy system models. *International Journal of Energy Sector Management*, *4*(4), 494–518. https://doi.org/10.1108/17506221011092742

Bishoge, O. K., Kombe, G. G., & Mvile, B. N. (2021). Energy consumption efficiency knowledge, attitudes and behaviour among the community. *International Journal of Sustainable Energy Planning and Management*, *31*, 175–188. https://doi.org/10.5278/ijsepm.6153

Blanco, H., Vilchez, J. J. G., Nijs, W., Thiel, C., & Faaij, A. (2019). Soft-linking of a behavioral model for transport with energy system cost optimization applied to hydrogen in EU. *Renewable and Sustainable Energy Reviews*, *115*, 109349. https://doi.org/10.1016/j.rser.2019.109349

Blumberga, A., Cilinskis, E., Gravelsins, A., Svarckopfa, A., & Blumberga, D. (2018). Analysis of regulatory instruments promoting building energy efficiency. *Energy Procedia*, *147*, 258–267. https://doi.org/https://doi.org/10.1016/j.egypro.2018.07.090

Blumberga, A., Gravelsins, A., & Blumberga, D. (2022). Deliberation platform for energy transition policies: How to make complex things simple. *Energies*, *15*(1). https://doi.org/10.3390/en15010090

Blumberga, A., Lauka, D., Barisa, A., & Blumberga, D. (2016). Modelling the Baltic power system till

2050. *Energy Conversion and Management*, *107*(SI), 67–75. https://doi.org/10.1016/j.enconman.2015.09.005

Boldy, R., Santini, T., Annandale, M., Erskine, P. D., & Sonter, L. J. (2021). Understanding the impacts of mining on ecosystem services through a systematic review. *Extractive Industries and Society*, *8*(1), 457–466. https://doi.org/10.1016/j.exis.2020.12.005

Bolger, M., Marin, D., Tofighi-Niaki, A., & Seelmann, L. (2021). "Green mining" is a mith: The case for cutting EU resource consumption. *EEB and Friends of the Earth Europe*. EEB. Retrieved from https://eeb.org/library/green-mining-is-a-myth/

Bolwig, S., Bazbauers, G., Klitkou, A., Lund, P. D., Blumberga, A., Gravelsins, A., & Blumberga, D. (2019). Review of modelling energy transitions pathways with application to energy system flexibility. *Renewable and Sustainable Energy Reviews*, *101*(June 2018), 440–452. https://doi.org/10.1016/j.rser.2018.11.019

Bonsu, N. O. (2020). Towards a circular and low-carbon economy: Insights from the transitioning to electric vehicles and net zero economy. *Journal of Cleaner Production*, *256*, 120659. https://doi.org/10.1016/j.jclepro.2020.120659

Bos, V., Marie, F., & Gunzburger, Y. (2024). Lithium-based energy transition through Chilean and Australian miningscapes. *Extractive Industries and Society*, *17*(November 2023), 101384. https://doi.org/10.1016/j.exis.2023.101384

Boucher, J. L., & Mérida, W. (2022). Inflated lives and a clean tech privilege in Washington State: Policy amidst spatialized affluence. *Energy Research & Social Science*, *85*(July 2021), 102418. https://doi.org/10.1016/j.erss.2021.102418

Bridge, G. (2004). Contested terrain: Mining and the environment. *Annual Review of Environment and Resources*, *29*, 205 – 259. https://doi.org/10.1146/annurev.energy.28.011503.163434

Brueckner, M., & Eabrasu, M. (2018). Pinning down the social license to operate (SLO): The problem of normative complexity. *Resources Policy*, *59*(June), 217–226. https://doi.org/10.1016/j.resourpol.2018.07.004

Bruno, M., & Fiore, S. (2024). Review of lithium-ion batteries' supply-chain in Europe: Material flow analysis and environmental assessment. *Journal of Environmental Management*, *358*(April), 120758. https://doi.org/10.1016/j.jenvman.2024.120758

Butu, A. I., & Strachan, P. (2022). Navigating Pathways for Community Renewable Electricity in Rural Areas: Stakeholders' Perspectives on the Shape Community Project, Nigeria. *International Journal of Sustainable Energy Planning and Management*, *33*, 19–34.

https://doi.org/10.5278/ijsepm.6813

Caesar, L., Sakschewski, B., Andersen, L. S., Beringer, T., Braun, J., Dennis, D., ... Rockstrom, J. (2024). *Planetary Health Check: A Scientific Assessment of the State of the Planet*. Postdam, Germany.

Cai, Y., Zhang, J., Gu, Q., & Wang, C. (2024). An Analytical Framework for Assessing Equity of Access to Public Electric Vehicle Charging Stations: The Case of Shanghai. In *Sustainability (Switzerland)* (Vol. 16). https://doi.org/10.3390/su16146196

Calzadilla, P. V., & Mauger, R. (2018). The UN's new sustainable development agenda and renewable energy: the challenge to reach SDG7 while achieving energy justice. *Journal of Energy and Natural Resources Law*, *36*(2), 233–254. https://doi.org/10.1080/02646811.2017.1377951

Campino, J., Mendes, F. P., & Rosa, Á. (2023). The race of ecological vehicles: consumer behavior and generation impact in the Portuguese market. *SN Business & Economics*, *3*(8), 1–30. https://doi.org/10.1007/s43546-023-00524-2

Canelas, J., & Carvalho, A. (2023). The dark side of the energy transition: Extractivist violence, energy (In) justice and lithium mining in Portugal. *Energy Research and Social Science*, *100*(May). https://doi.org/10.1016/j.erss.2023.103096

Canepa, K., Hardman, S., & Tal, G. (2019). An early look at plug-in electric vehicle adoption in disadvantaged communities in California. *Transport Policy*, *78*(April 2018), 19–30. https://doi.org/https://doi.org/10.1016/j.tranpol.2019.03.009

Cappellaro, F., Chiarini, R., Meloni, C., & Snels, C. (2019). Smart community co-creation: The case of centocelle project. *International Journal of Sustainable Energy Planning and Management*, *24*, 155–162. https://doi.org/10.5278/ijsepm.3339

Carballo-Cruz, F., & Cerejeira, J. (2020). *O Projeto da Mina do Barroso: Impactos Económicos e Desenvolvimento*.

Carlton, G. J., & Sultana, S. (2022). Electric vehicle charging station accessibility and land use clustering: A case study of the Chicago region. *Journal of Urban Mobility*, *2*(April), 100019. https://doi.org/10.1016/j.urbmob.2022.100019

Carlton, G. J., & Sultana, S. (2024). Electric vehicle charging equity and accessibility: A comprehensive United States policy analysis. *Transportation Research Part D: Transport and Environment*, *129*(October 2023), 104123. https://doi.org/10.1016/j.trd.2024.104123

Carlton, G., & Sultana, S. (2023). Transport equity considerations in electric vehicle charging research: a scoping review. *TRANSPORT REVIEWS*, *43*(3), 330–355. https://doi.org/https://doi.org/10.1080/01441647.2022.2109775

Caulfield, B., Furszyfer, D., Stefaniec, A., & Foley, A. (2022). Measuring the equity impacts of government subsidies for electric vehicles. *Energy*, *248*, 123588. https://doi.org/10.1016/j.energy.2022.123588

CEPII. (2021). BACI database.

Cesar, S., & Jhony, O. (2021). Making or breaking social license to operate in the mining industry: Factors of the main drivers of social conflict. *Journal of Cleaner Production*, *278*, 123640. https://doi.org/10.1016/j.jclepro.2020.123640

Chang, M., Thellufsen, J. Z., Zakeri, B., Pickering, B., Pfenninger, S., Lund, H., & Østergaard, P. A. (2021). Trends in tools and approaches for modelling the energy transition. *Applied Energy*, *290*, 116731. https://doi.org/10.1016/j.apenergy.2021.116731

Chang, S. Y., Huang, J., Chaveste, M. R. R., Lurmann, F. W. W., Eisinger, D. S. S., Mukherjee, A. D. D., … Knipping, E. (2023). Electric vehicle fleet penetration helps address inequalities in air quality and improves environmental justice. *Communications Earth and Environment*, *4*(1). https://doi.org/10.1038/s43247-023-00799-1

Chaves, C., Pereira, E., Ferreira, P., & Guerner Dias, A. (2021). Concerns about lithium extraction: A review and application for Portugal☆. *The Extractive Industries and Society*, *8*(3), 100928. https://doi.org/10.1016/j.exis.2021.100928

Chen, W. A., Chen, C. F., & Tomasik, S. (2024). Investigating intentions and barriers in adopting decentralized home energy management systems: A justice dimension of demand flexibility. *Energy and Buildings*, *318*(February), 114458. https://doi.org/10.1016/j.enbuild.2024.114458

Chen, W. A., Chen, C. F., Tomasik, S., Pournaras, E., & Liu, M. (2024). Flexibility justice: Exploring the relationship between electrical vehicle charging behaviors, demand flexibility and psychological factors. *Energy Research and Social Science*, *118*(March), 103753. https://doi.org/10.1016/j.erss.2024.103753

Choi, S. J., Jiao, J., & Mendez, T. (2024). Who owns Electric Vehicles (EVs)? The relationship between EV adoption and socio-demographic characteristics across different price segments and brands in the Texas triangle. *Research in Transportation Business and Management*, *57*(January), 101225. https://doi.org/10.1016/j.rtbm.2024.101225

Choopojcharoen, T., & Magzari, A. (2012). *Mathematics behind System Dynamics* (Worcester Polytechnic Institute). Worcester Polytechnic Institute. Retrieved from http://m.wpi.edu/Pubs/E-project/Available/E-project-052812-144829/unrestricted/MathematicsBehindSystemDynamics.pdf

Chung, D., Elgqvist, E., & Santhanagopalan, S. (2016). Automotive Lithium-ion Cell Manufacturing: Regional Cost Structures and Supply Chain Considerations. In *Clean Energy Manufacturing Analysis Center (CEMAC)*. Retrieved from http:/www.osti.gov/scitech

CIC energiGUNE. (2021). World Map of Gigafactories. Retrieved October 11, 2021, from https://cicenergigune.com/en/blog/world-map-gigafactories

Ciftci, M. M., & Lemaire, X. (2023). Deciphering the impacts of `green' energy transition on socio-environmental lithium conflicts: Evidence from Argentina and Chile. *EXTRACTIVE INDUSTRIES AND SOCIETY*, *16*(December 2022), 101373. https://doi.org/10.1016/j.exis.2023.101373

Clora, F., & Yu, W. (2022). GHG emissions, trade balance, and carbon leakage: Insights from modeling thirty-one European decarbonization pathways towards 2050. *Energy Economics*, *113*(September 2021), 106240. https://doi.org/10.1016/j.eneco.2022.106240

Conde, M., & Le Billon, P. (2017). Why do some communities resist mining projects while others do not? *Extractive Industries and Society*, *4*(3), 681–697. https://doi.org/10.1016/j.exis.2017.04.009

Connolly, D., Lund, H., Mathiesen, B. V., & Leahy, M. (2010). A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy*, *87*(4), 1059–1082. https://doi.org/10.1016/j.apenergy.2009.09.026

Connor, P., & Wise, P. (2021). *An Analysis of Lithium-ion Battery Fires in Waste Management and Recycling*.

Creswell, J. W. (2014). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches* (Fourth). SAGE Publications Inc.

Crootof, A., Shrestha, R., Albrecht, T., Ptak, T., & Scott, C. A. (2021). Sacrificing the local to support the national: Politics, sustainability, and governance in Nepal's hydropower paradox. *Energy Research & Social Science*, *80*, 102206. https://doi.org/10.1016/j.erss.2021.102206

Cross, J., & Murray, D. (2018). The afterlives of solar power: Waste and repair off the grid in Kenya. *Energy Research and Social Science*, *44*(April), 100–109. https://doi.org/10.1016/j.erss.2018.04.034

Cruz, T. L., Matlaba, V. J., Mota, J. A., & Filipe dos Santos, J. (2021). Measuring the social license to operate of the mining industry in an Amazonian town: A case study of Canaã dos Carajás, Brazil. *Resources Policy*, *74*(October 2020). https://doi.org/10.1016/j.resourpol.2020.101892

CST. (2020). *A Systems Approach to Delivering Net Zero: Recommendations from the Prime Minister's Council for Science and Technology*.

Dale, M., Krumdieck, S., & Bodger, P. (2012). Global energy modelling — A biophysical approach

(GEMBA) part 1: An overview of biophysical economics. *Ecological Economics*, *73*, 152–157. https://doi.org/10.1016/j.ecolecon.2011.10.014

Dall-Orsoletta, A., Ferreira, P., & Gilson Dranka, G. (2022). Low-carbon technologies and just energy transition: Prospects for electric vehicles. *Energy Conversion and Management: X*, *16*(December 2021), 100271. https://doi.org/10.1016/j.ecmx.2022.100271

Dall-Orsoletta, A., Oosthuizen, R., Dranka, G. G., & Ferreira, P. (2025). A quantitative modeling approach to energy justice in electric vehicle adoption. *Energy*, *322*, 135676. https://doi.org/10.1016/j.energy.2025.135676

Dall-Orsoletta, A., Uriona-Maldonado, M., Dranka, G., & Ferreira, P. (2022). A review of social aspects integration in system dynamics energy systems models. *International Journal of Sustainable Energy Planning and Management*, *36*, 33–52. https://doi.org/10.54337/ijsepm.7478

Dall-Orsoletta, A., Verrier, B., Uriona-Maldonado, M., Dranka, G. G., & Ferreira, P. (2025). How does social acceptance affect transition minerals production in Europe? A system dynamics approach and case study in Portugal. *Extractive Industries and Society*, *22*(May 2024). https://doi.org/10.1016/j.exis.2025.101625

Damonte, G., Godfrid, J., & López, A. P. (2021). Mining and urbanization:Ways of generating water insecurity in Andean territories. *Extractive Industries and Society*, *8*(3). https://doi.org/10.1016/j.exis.2021.100954

Daneshzand, F., Amin-Naseri, M. R., Asali, M., Elkamel, A., & Fowler, M. (2019). A system dynamics model for optimal allocation of natural gas to various demand sectors. *Computers and Chemical Engineering*, *128*, 88–105. https://doi.org/10.1016/j.compchemeng.2019.05.040

Daneshzand, F., Asali, M., Al-Sobhi, S. A., Diabat, A., & Elkamel, A. (2022). A simulation-based optimization scheme for phase-out of natural gas subsidies considering welfare and economic measures. *Energy*, *259*(March 2021), 124879. https://doi.org/10.1016/j.energy.2022.124879

Dangerman, A. T. C. J., & Schellnhuber, H. J. (2013). Energy systems transformation. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(7), 549–558. https://doi.org/10.1073/pnas.1219791110

Dartford, K., & AFP. (2021). Locals and environment groups in David and Goliath battle over Tesla's Berlin "Gigafactory." Retrieved August 17, 2021, from https://www.euronews.com/2021/04/18/locals-and-environment-groups-in-battle-over-tesla-berlin-gigafactory

de Gooyert, V., Rouwette, E., van Kranenburg, H., Freeman, E., & van Breen, H. (2016). Sustainability

transition dynamics: Towards overcoming policy resistance. *Technological Forecasting and Social Change*, *111*, 135–145. https://doi.org/10.1016/j.techfore.2016.06.019

De Stercke, S., Mijic, A., Buytaert, W., & Chaturvedi, V. (2018). Modelling the dynamic interactions between London's water and energy systems from an end-use perspective. *Applied Energy*, *230*(September), 615–626. https://doi.org/10.1016/j.apenergy.2018.08.094

Declaration on Mining and the Energy Transition for COP26. (2021). Retrieved October 11, 2021, from Human Rights Watch website: https://www.hrw.org/news/2021/10/28/declaration-mining-and-energy-transition-cop26#

Del Pero, F., Berzi, L., Antonacci, A., & Delogu, M. (2020). Automotive lightweight design: Simulation modeling of mass-related consumption for electric vehicles. *Machines*, *8*(3). https://doi.org/10.3390/machines8030051

Delbosc, A., & Currie, G. (2011). The spatial context of transport disadvantage, social exclusion and well-being. *Journal of Transport Geography*, *19*(6), 1130–1137. https://doi.org/10.1016/j.jtrangeo.2011.04.005

Deloitte. (2020). *Caracterização do Cluster da Indústria Automóvel em Portugal*. Compete 2020 and Mobinov.

Deonandan, K., Schoenfeld, J., Salim, A., & Bourassa, M. (2024). Social License to Operate (SLO): Private governance and barriers to community engagement. *Extractive Industries and Society*, *17*(August 2023), 101404. https://doi.org/10.1016/j.exis.2024.101404

DGEG, & Grupo de Trabalho. (2017). *Relatório do Grupo de Trabalho "Lítio."* Lisboa.

Di Felice, L. J., Renner, A., & Giampietro, M. (2021). Why should the EU implement electric vehicles? Viewing the relationship between evidence and dominant policy solutions through the lens of complexity. *Environmental Science and Policy*, *123*(May), 1–10. https://doi.org/10.1016/j.envsci.2021.05.002

Dibattista, I., Camara, A. R., Molderez, I., Benassai, E. M., & Palozza, F. (2023). Socio-environmental impact of mining activities in Guinea: The case of bauxite extraction in the region of Boké. *Journal of Cleaner Production*, *387*(December 2022), 135720. https://doi.org/10.1016/j.jclepro.2022.135720

Dillman, K. J., Árnadóttir, Á., Heinonen, J., Czepkiewicz, M., & Davíðsdóttir, B. (2020). Review and meta-analysis of EVs: Embodied emissions and environmental breakeven. *Sustainability (Switzerland)*, *12*(22), 1–32. https://doi.org/10.3390/su12229390

Dillman, K. J., Czepkiewicz, M., Heinonen, J., & Davíðsdóttir, B. (2021). A safe and just space for urban

mobility: A framework for sector-based sustainable consumption corridor development. *Global Sustainability*, *4*(December). https://doi.org/10.1017/sus.2021.28

Ding, S., & Wu, L. (2025). Disparities in electric vehicle charging infrastructure distribution: A socio-spatial clustering study in King County, Washington. *Sustainable Cities and Society*, *121*(October 2024), 106193. https://doi.org/10.1016/j.scs.2025.106193

Direção-Geral de Energia e Geologia. (2019). *Plano Nacional Energia e Clima 2021-2030*.

Direção-Geral de Energia e Geologia. (2024). *Estrutura dos Preços Médios e Taxas (à 2ª feira) do Gasóleo Rodoviário e Gasolina 95, em Portugal Continental*. Direção de Serviços de Planeamento Energético e Estatística.

Dobele, A. R., Westberg, K., Steel, M., & Flowers, K. (2014). An Examination of Corporate Social Responsibility Implementation and Stakeholder Engagement: A Case Study in the Australian Mining Industry. *Business Strategy and the Environment*, *23*(3), 145–159. https://doi.org/10.1002/bse.1775

Dolganova, I., Rödl, A., Bach, V., Kaltschmitt, M., & Finkbeiner, M. (2020). A review of life cycle assessment studies of electric vehicles with a focus on resource use. *Resources*, *9*(3), 1–26. https://doi.org/10.3390/resources9030032

Domingues, N. (2022). Lithium Prospection in Portugal for E-Mobility and Solar PV Expansion. *Commodities*, *1*(2), 98–114. https://doi.org/10.3390/commodities1020007

Doumbia, M., Toure, N. E., Silue, S., Yoboue, V., Diedhiou, A., & Hauhouot, C. (2018). Emissions from the road traffic of West African cities: Assessment of vehicle fleet and fuel consumption. *Energies*, *11*(9), 1–16. https://doi.org/10.3390/en11092300

Dranka, G. G., & Ferreira, P. (2020). Electric Vehicles and Biofuels Synergies in the Brazilian Energy System. *Energies*, *13*(17), 4423. https://doi.org/10.3390/en13174423

Dunlap, A., & Riquito, M. (2023). Social warfare for lithium extraction? Open-pit lithium mining, counterinsurgency tactics and enforcing green extractivism in northern Portugal. *Energy Research and Social Science*, *95*(August 2022). https://doi.org/10.1016/j.erss.2022.102912

Durán, A. P., Rauch, J., & Gaston, K. J. (2013). Global spatial coincidence between protected areas and metal mining activities. *Biological Conservation*, *160*, 272–278. https://doi.org/10.1016/j.biocon.2013.02.003

DW. (2024, August 11). Serbia: Protests over vast Rio Tinto lithium mining project. Retrieved December 4, 2024, from DW Politics website: https://www.dw.com/en/serbia-protests-over-vast-rio-tinto-lithium-mining-project/a-69910000

EAFO. (2024). *European Alternative Fuels Observatory: Portugal*. Directorate-General for Mobility and Transport. Retrieved from https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/portugal/infrastructure

Ebbrecht, G., & Chen, J. (2023). Enhancing equitable resilience of urban energy systems via strategic planning of EV charging infrastructure. *The Electricity Journal*, *36*(5), 107275. https://doi.org/https://doi.org/10.1016/j.tej.2023.107275

EEA. (2024). *Car ownership rates projections*. European Environmental Agency (EEA, 2024). Retrieved from http://www.wbcsd.org/plugins/DocSearch/details.asp?type=DocDet&ObjectId=MTE0Njc

Eftekhari Shahabad, M., Mostafaeipour, A., Hosseini Nasab, H., Sadegheih, A., & Ao Xuan, H. (2022). A new model to investigate effects of subsidies for home solar power systems using system dynamics approach: A case study. *Sustainable Energy Technologies and Assessments*, *49*(October 2021), 101706. https://doi.org/10.1016/j.seta.2021.101706

Egbue, O. (2012). Assessment of social impacts of lithium for electric vehicle batteries. *62nd IIE Annual Conference and Expo 2012*, 1314–1320.

EIB. (2023). *2021-2022 EIB Climate Survey*. European Investment Bank. Retrieved from https://www.eib.org/en/surveys/climate-survey/4th-climate-survey/index.htm

Eker, S., & van Daalen, E. (2015). A model-based analysis of biomethane production in the Netherlands and the effectiveness of the subsidization policy under uncertainty. *ENERGY POLICY*, *82*(1), 178–196. https://doi.org/10.1016/j.enpol.2015.03.019

Eker, S., Zimmermann, N., Carnohan, S., & Davies, M. (2018). Participatory system dynamics modelling for housing, energy and wellbeing interactions. *Building Research and Information*, *46*(7), 738–754. https://doi.org/10.1080/09613218.2017.1362919

EPA. (2013). *Application of Life- Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles*. Retrieved from https://archive.epa.gov/epa/sites/production/files/2014-01/documents/lithium_batteries_lca.pdf

Esmaili, A., Oshanreh, M. M., Naderian, S., MacKenzie, D., & Chen, C. (2024). Assessing the spatial distributions of public electric vehicle charging stations with emphasis on equity considerations in King County, Washington. *Sustainable Cities and Society*, *107*(March), 105409. https://doi.org/10.1016/j.scs.2024.105409

European Commission. (2012). *Energy roadmap 2050*. Publications Office of the European Union.

European Commission. (2019). Directive (EU) 2019/1161 of the European Council and of the European Parliament of 20 June 2019, amending Directive 2009/33/EC on the promotion of clean and

energy-efficient road transport vehicles. *Offical Journal of the European Union*, Vol. 2019, pp. 1–15. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L1161&from=EN

European Commission. (2020a). Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability. In *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS*. Brussels.

European Commission. (2020b). Regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020. In *European Commission*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798

European Commission. (2022a). Critical Raw Materials Act. Retrieved November 16, 2023, from https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en

European Commission. (2022b). EU Cohesion Policy: €223.8 million for a just climate transition in Portugal. Retrieved September 16, 2024, from European Commission website: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7718

European Commission. (2024). *The European Green Deal*. Retrieved from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/story-von-der-leyen-commission/european-green-deal_en

European Parliament. (2022). EU ban on the sale of new petrol and diesel cars from 2035 explained. Retrieved September 13, 2024, from https://www.europarl.europa.eu/topics/en/article/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained

Eurostat. (2021). Share of people living in households owning or renting their home, 2021 (in %). Retrieved April 1, 2025, from EUROSTAT website: https://ec.europa.eu/eurostat/cache/digpub/housing/vis/01_01_01/index.html

Eurostat. (2024). *Passenger cars by age*. Eurostat. Retrieved from https://ec.europa.eu/eurostat/databrowser/product/page/road_eqs_carage

Fang, F. C., & Casadevall, A. (2011). Reductionistic and Holistic Science. *Infection and Immunity*, *79*(4), 1401–1404. https://doi.org/10.1128/IAI.01343-10

Farjana, S. H., Huda, N., & Mahmud, M. A. P. (2019). Life cycle assessment of cobalt extraction process.

Journal of Sustainable Mining, *18*(3), 150–161. https://doi.org/10.1016/j.jsm.2019.03.002

Fattahi, A., Sijm, J., & Faaij, A. (2020). A systemic approach to analyze integrated energy system modeling tools: A review of national models. *Renewable and Sustainable Energy Reviews*, *133*(August), 110195. https://doi.org/10.1016/j.rser.2020.110195

Fernandes, S. (2024). "Just" Means "Just" Everywhere: How Extractivism Stands in the Way of an Internationalist Paradigm for Just Transitions. *International Journal of Politics, Culture and Society*, (0123456789). https://doi.org/10.1007/s10767-024-09475-4

Ferreira, M., & Gabriel, P. (2024). Exploração de lítio na Serra da Argemela pode não avançar devido a...morcegos. Retrieved December 4, 2024, from SIC Notícias website: https://sicnoticias.pt/pais/2024-01-25-Exploracao-de-litio-na-Serra-da-Argemela-pode-nao-avancar-devido-a.morcegos-ac96cc1b

Fiddaman, T. S. (1997). Feedback Complexity in Integrated Climate-Economy Models. Massachusetts Institute of Technology.

Findlay, A. (2020). Dark side of low carbon. *Nature Climate Change*, *10*(3), 184–184. https://doi.org/10.1038/s41558-020-0724-1

Flexer, V., Baspineiro, C. F., & Galli, C. I. (2018). Lithium recovery from brines: A vital raw material for green energies with a potential environmental impact in its mining and processing. *Science of the Total Environment*, *639*, 1188–1204. https://doi.org/10.1016/j.scitotenv.2018.05.223

Fodstad, M., Crespo del Granado, P., Hellemo, L., Knudsen, B. R., Pisciella, P., Silvast, A., ... Straus, J. (2022). Next frontiers in energy system modelling: A review on challenges and the state of the art. *Renewable and Sustainable Energy Reviews*, *160*(February), 112246. https://doi.org/10.1016/j.rser.2022.112246

Ford, A. (1999). *Modeling the Environment: An Introduction to System Dynamics Models of Environmental Systems*.

Fornillo, B., & Lampis, A. (2023). From the Lithium Triangle to the Latin American quarry: The shifting geographies of de-fossilisation. *Extractive Industries and Society*, *15*(February), 101326. https://doi.org/10.1016/j.exis.2023.101326

Forrester, J.W, & Senge, P. . (1980). Tests for building confidence in systems dynamics models. *TIMS Studies in the Management Science*, (14), 209–228.

Forrester, Jay W. (1971). *World Dynamics*.

Fox, N. J. (2023). Green capitalism, climate change and the technological fix: A more-than-human assessment. *The Sociological Review*, *71*(5), 1115–1134.

https://doi.org/10.1177/00380261221121232

Fragkos, P., Laura van Soest, H., Schaeffer, R., Reedman, L., Köberle, A. C., Macaluso, N., ... Iyer, G. (2021). Energy system transitions and low-carbon pathways in Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Republic of Korea, Russia and the United States. *Energy*, *216*. https://doi.org/10.1016/j.energy.2020.119385

Freeman, R. (2021). Modelling the socio-political feasibility of energy transition with system dynamics. *Environmental Innovation and Societal Transitions*, *40*(October), 486–500. https://doi.org/10.1016/j.eist.2021.10.005

Frynas, J. G., & Buur, L. (2020). The presource curse in Africa: Economic and political effects of anticipating natural resource revenues. *Extractive Industries and Society*, *7*(4), 1257–1270. https://doi.org/10.1016/j.exis.2020.05.014

Fundo Ambiental. (2024). Incentivo pela Introdução no Consumo de Veículos de Emissões Nulas (VEN 2023). Retrieved September 13, 2024, from https://www.fundoambiental.pt/apoios-2023/mitigacao-de-alteracoes-climaticas/incentivo-pela-introducao-no-consumo-de-veiculos-de-emissoes-nulas-ven-2023.aspx

Galende-Sánchez, E., & Sorman, A. H. (2021). From consultation toward co-production in science and policy: A critical systematic review of participatory climate and energy initiatives. *Energy Research and Social Science*, *73*(January), 94–99. https://doi.org/10.1016/j.erss.2020.101907

Galvin, R. (2019). What does it mean to make a moral claim? A Wittgensteinian approach to energy justice. *Energy Research and Social Science*, *54*(December 2018), 176–184. https://doi.org/10.1016/j.erss.2019.04.018

Gao, J., Zuo, F., Yang, D., Tang, Y., Ozbay, K., & Seeley, M. (2025). Toward Equitable Progress: A Review of Equity Assessment and Perspectives in Emerging Technologies and Mobility Innovations in Transportation. *Journal of Transportation Engineering, Part A: Systems*, *151*(1). https://doi.org/10.1061/JTEPBS.TEENG-8675

García-García, P., Carpintero, Ó., & Buendía, L. (2020). Just energy transitions to low carbon economies: A review of the concept and its effects on labour and income. *Energy Research & Social Science*, *70*(January), 101664. https://doi.org/10.1016/j.erss.2020.101664

Gazmeh, H., Guo, Y., & Qian, X. (2024). Understanding the opportunity-centric accessibility for public charging infrastructure. *Transportation Research Part D: Transport and Environment*, *131*(February), 104222. https://doi.org/10.1016/j.trd.2024.104222

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: A multi-level

perspective and a case-study. *Research Policy*, *31*(8–9), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Geels, F. W. (2010). Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective. *Research Policy*, *39*(4), 495–510. https://doi.org/10.1016/j.respol.2010.01.022

Gesevičius, K., Catalão-Lopes, M., & Carvalho, P. M. S. S. (2021). The impact of electric vehicles' market expansion on wholesale electricity price – The case of Lithuania. *Case Studies on Transport Policy*, *9*(2), 477–487. https://doi.org/10.1016/j.cstp.2021.02.003

Ghosh, A. (2020). Possibilities and challenges for the inclusion of the electric vehicle (EV) to reduce the carbon footprint in the transport sector: A review. *Energies*, *13*(10). https://doi.org/10.3390/en13102602

Gladkykh, G., Davíðsdóttir, B., & Diemer, A. (2021). When justice narratives meet energy system models: Exploring energy sufficiency, sustainability, and universal access in Sub-Saharan Africa. *Energy Research and Social Science*, *79*, 102075. https://doi.org/10.1016/j.erss.2021.102075

Gnann, T., & Plötz, P. (2015). A review of combined models for market diffusion of alternative fuel vehicles and their refueling infrastructure. *Renewable and Sustainable Energy Reviews*, *47*, 783–793. https://doi.org/https://doi.org/10.1016/j.rser.2015.03.022

Gobierno de Chile. (2020). *Chile's Nationally Determined Contribution*.

Gómez Vilchez, J. J., & Jochem, P. (2019). Simulating vehicle fleet composition: A review of system dynamics models. *Renewable and Sustainable Energy Reviews*, *115*(September). https://doi.org/10.1016/j.rser.2019.109367

Gómez Vilchez, J. J., & Jochem, P. (2020). Powertrain technologies and their impact on greenhouse gas emissions in key car markets. *Transportation Research Part D: Transport and Environment*, *80*(January), 102214. https://doi.org/10.1016/j.trd.2019.102214

Gottesfeld, P. (2019). Commentary health risks from climate fix: The downside of energy storage batteries. *Environmental Research*, *178*(August), 108677. https://doi.org/10.1016/j.envres.2019.108677

Gozluklu, B., & Sterman, J. (2023). System dynamics to understand and improve the performance of complex projects. *Research Handbook on Complex Project Organizing*, (February), 70–77. https://doi.org/10.4337/9781800880283.00017

Gulley, A. L., McCullough, E. A., & Shedd, K. B. (2019). China's domestic and foreign influence in the global cobalt supply chain. *Resources Policy*, *62*(June 2018), 317–323. https://doi.org/10.1016/j.resourpol.2019.03.015

Günther, H. O., Kannegiesser, M., & Autenrieb, N. (2015). The role of electric vehicles for supply chain sustainability in the automotive industry. *Journal of Cleaner Production*, *90*(2015), 220–233. https://doi.org/10.1016/j.jclepro.2014.11.058

Guo, S., & Kontou, E. (2021). Disparities and equity issues in electric vehicles rebate allocation. *ENERGY POLICY*, *154*(August 2020), 112291. https://doi.org/10.1016/j.enpol.2021.112291

Haag, S., Tunn, J., Kalt, T., Muller, F., & Simon, J. (2024). Who profits from the green energy rush? Retrieved December 6, 2024, from Transnational Institute website: https://www.tni.org/en/article/who-profits-from-the-green-energy-rush

Haarstad, H., Sareen, S., Kandt, J., Coenen, L., & Cook, M. (2022). Beyond automobility? Lock-in of past failures in low-carbon urban mobility innovations. *Energy Policy*, *166*(May), 113002. https://doi.org/10.1016/j.enpol.2022.113002

Haas, T. (2022). The political economy of mobility justice. Experiences from Germany. *Mobilities*, *17*(6), 899–913. https://doi.org/https://doi.org/10.1080/17450101.2021.1987153

Hafner, S., Jones, A., & Anger-Kraavi, A. (2021). Economic impacts of achieving a net-zero emissions target in the power sector. *Journal of Cleaner Production*, *312*(July 2020), 127610. https://doi.org/10.1016/j.jclepro.2021.127610

Halimi, Z., SafariTaherkhani, M., & Cui, Q. (2025). A Generalized Framework for Assessing Equity in Ground Transportation Infrastructure : Exploratory Study. *Journal of Management in Engineering*, *41*(2). https://doi.org/10.1061/JMENEA.MEENG-6336

Hamann, R. (2014). Patient dialogue between mining companies and communities is tougher and scarcer than imagined: A response to Hodge. *Journal of Cleaner Production*, *84*(1), 35–36. https://doi.org/10.1016/j.jclepro.2014.08.101

Hancock, L, Ralph, N., & Ali, S. H. (2018). Bolivia's lithium frontier: Can public private partnerships deliver a minerals boom for sustainable development? *Journal of Cleaner Production*, *178*, 551–560. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.12.264

Hancock, Linda, & Ralph, N. (2021). A framework for assessing fossil fuel 'retrofit' hydrogen exports: Security-justice implications of Australia's coal-generated hydrogen exports to Japan. *Energy*, *223*, 119938. https://doi.org/10.1016/j.energy.2021.119938

Hannula, I., & Reiner, D. M. (2019). Near-Term Potential of Biofuels, Electrofuels, and Battery Electric Vehicles in Decarbonizing Road Transport. *Joule*, *3*(10), 2390–2402. https://doi.org/10.1016/j.joule.2019.08.013

Hao, H., Liu, Z., Zhao, F., Geng, Y., & Sarkis, J. (2017). Material flow analysis of lithium in China.

Resources Policy, *51*(November 2016), 100–106. https://doi.org/10.1016/j.resourpol.2016.12.005

Hao, H., Mu, Z., Jiang, S., Liu, Z., & Zhao, F. (2017). GHG Emissions from the production of lithium-ion batteries for electric vehicles in China. *Sustainability (Switzerland)*, *9*(4). https://doi.org/10.3390/su9040504

Haraldsson, H. V. S., & Sverdrup, H. U. (2021). *Systems Science and System Thinking in practice: How to develop qualitative and numerical models for evolving understandings of challenges and response*. Retrieved from https://www.naturvardsverket.se/Documents/publ-filer/6900/978-91-620-6981-0.pdf?pid=28356

Hardman, S., Jenn, A., Tal, G., Axsen, J., Beard, G., Daina, N., … Witkamp, B. (2018). A review of consumer preferences of and interactions with electric vehicle charging infrastructure. *Transportation Research Part D: Transport and Environment*, *62*, 508–523. https://doi.org/https://doi.org/10.1016/j.trd.2018.04.002

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., … Anderson, P. (2019). Recycling lithium-ion batteries from electric vehicles. *Nature*, *575*(7781), 75–86. https://doi.org/10.1038/s41586-019-1682-5

Harrison, D., & Ludwig, C. (2021). *Electric Vehicle Battery Supply Analysis: How Battery Demand and Production Are Reshaping the Automotive Industry*. Retrieved from https://www.automotivelogistics.media/electric-vehicles/electric-vehicle-battery-supply-chain-analysis-2021-how-lithium-ion-battery-demand-and-production-are-reshaping-the-automotive-industry/41924.article

Harrison, G., Thiel, C., & Jones, L. (2016). Powertrain Technology Transition Market Agent Model (PTTMAM). In *JRC Technical Reports*. Publications Office. https://doi.org/doi/10.2790/719385

Hassani, A., & Maleki, A. (2021). Projection of passenger cars' fuel demand and greenhouse gas emissions in Iran by 2050. *Energy Conversion and Management: X*, *12*, 100126. https://doi.org/10.1016/j.ecmx.2021.100126

Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Strømman, A. H. (2013). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology*, *17*(1), 53–64. https://doi.org/10.1111/j.1530-9290.2012.00532.x

Healy, N., & Barry, J. (2017). Politicizing energy justice and energy system transitions: Fossil fuel divestment and a "just transition." *Energy Policy*, *108*(May), 451–459. https://doi.org/10.1016/j.enpol.2017.06.014

Hearn, A. X., Sohre, A., & Burger, P. (2021). Innovative but unjust? Analysing the opportunities and justice issues within positive energy districts in Europe. *Energy Research and Social Science*, *78*, 102127. https://doi.org/10.1016/j.erss.2021.102127

Heffron, R., Halbrügge, S., Körner, M., Obeng-Darko, N., Sumarno, T., Wagner, J., & Weibelzahl, M. (2021). Justice in solar energy development. *Solar Energy*, *218*(March), 68–75. https://doi.org/10.1016/j.solener.2021.01.072

Heffron, R. J. (2020). The role of justice in developing critical minerals. *Extractive Industries and Society*, *7*(3), 855–863. https://doi.org/10.1016/j.exis.2020.06.018

Heffron, R., & McCauley, D. (2017). The concept of energy justice across the disciplines. *Energy Policy*, *105*(November 2016), 658–667. https://doi.org/10.1016/j.enpol.2017.03.018

Heffron, Raphael, Körner, M., Wagner, J., Weibelzahl, M., & Fridgen, G. (2020). Industrial demand-side flexibility: A key element of a just energy transition and industrial development. *Applied Energy*, *269*(April), 115026. https://doi.org/10.1016/j.apenergy.2020.115026

Heffron, Raphael, McCauley, D., & Sovacool, B. (2015). Resolving society's energy trilemma through the Energy Justice Metric. *Energy Policy*, *87*, 168–176. https://doi.org/10.1016/j.enpol.2015.08.033

Henderson, J. (2020). EVs Are Not the Answer: A Mobility Justice Critique of Electric Vehicle Transitions. *Annals of the American Association of Geographers*, *110*(6), 1993 – 2010. https://doi.org/10.1080/24694452.2020.1744422

Hennessy, E. M., & Syal, S. M. (2023). Assessing justice in California's transition to electric vehicles. *IScience*, *26*(7), 106856. https://doi.org/10.1016/j.isci.2023.106856

Henriques, C., Domingues, A., & Pereira, M. (2020). What is urban after all? A critical review of measuring and mapping urban typologies in Portugal. *ISPRS International Journal of Geo-Information*, *9*(11). https://doi.org/10.3390/ijgi9110630

Heymann, F., Miranda, V., Soares, F. J., Duenas, P., Perez Arriaga, I., & Prata, R. (2019). Orchestrating incentive designs to reduce adverse system-level effects of large-scale EV/PV adoption – The case of Portugal. *Applied Energy*, *256*(March), 113931. https://doi.org/10.1016/j.apenergy.2019.113931

Hitch, M., & Barakos, G. (2021). Virtuous natural resource development: The evolution and adaptation of social licence in the mining sector. *Extractive Industries and Society*, *8*(2), 100902. https://doi.org/10.1016/j.exis.2021.100902

Hodge, R. A. (2014). Mining company performance and community conflict: Moving beyond a seeming paradox. *Journal of Cleaner Production*, *84*(1), 27–33.

https://doi.org/10.1016/j.jclepro.2014.09.007

Humfrey, H., Sun, H., & Jiang, J. (2019). Dynamic charging of electric vehicles integrating renewable energy: A multiobjectiveoptimisation problem. *IET Smart Grid*, *2*(2), 250 – 259. https://doi.org/10.1049/iet-stg.2018.0066

IAPMEI. (2022). *Análise setorial*. Retrieved from https://www.iapmei.pt/

Ibis World. (2024). *Motor vehicle fuel retailing in Portugal - Market Size, Industry Analysis, Trends, and Forecasts (2024-2029)*. Retrieved from https://www.ibisworld.com/portugal/industry/motor-vehicle-fuel-retailing/200234/#IndustryStatisticsAndTrends

IEA. (2020a). Electric car stock by region and technology. Retrieved July 17, 2021, from IEA website: https://www.iea.org/data-and-statistics/charts/electric-car-stock-by-region-and-technology-2013-2019

IEA. (2020b). Global EV Outlook 2020: Entering the decade of electric drive? In *International Energy Agency*. Retrieved from https://www.iea.org/reports/global-ev-outlook-2020

IEA. (2021a). Global EV Outlook 2021: Accelerating ambitions despite the pandemic. In *International Energy Agency*. Retrieved from https://www.iea.org/reports/global-ev-outlook-2021

IEA. (2021b). *Net Zero by 2050: A Roadmap for the Global Energy Sector*.

IEA. (2021c). *World Energy Outlook 2021*. Retrieved from www.iea.org/weo

IEA. (2023). Global EV Outlook 2023: Catching up with climate ambitions. In *International Energy Agency*. Retrieved from https://www.iea.org/reports/global-ev-outlook-2023

IEA. (2024a). Global Critical Minerals Outlook 2024. *IEA*, p. 282. IEA. Retrieved from https://www.iea.org/reports/global-critical-minerals-outlook-2024?utm_content=buffer3599f&utm_medium=social&utm_source=linkedin.com&utm_campaign=buffer

IEA. (2024b). *Global EV Outlook 2024: Moving towards increased a*. Retrieved from https://www.iea.org/reports/global-ev-outlook-2024

IEA. (2024c). *Recycling of Critical Minerals*. Paris: IEA. Retrieved from https://www.iea.org/reports/recycling-of-critical-minerals

IMT, & INE. (2022). *Parque de veículos rodoviários motorizados de passageiros presumivelmente em circulação, por escalões de idade, segundo o tipo de veículo*. INE. Retrieved from imt-ip.pt

INE. (2022). *Contas Nacionais e Regionais* (pp. 1–15). pp. 1–15. Instituto Nacional de Estatística.

INE. (2024a). *Ganho médio mensal (€) por Localização geográfica (NUTS - 2002), Sexo e Tipologia de áreas urbanas; Anual*. Instituto Nacional de Estatística. Retrieved from http://www.ine.pt

INE. (2024b). *Proportion of resident population at-risk-of poverty or social exclusion (Europe 2020) (%)*. Instituto Nacional de Estatística. Retrieved from http://www.ine.pt

INE. (2024c). Sistema Nacional de Contas Integradas de Empresas. Retrieved from Instituto Nacional de Estatística website: https://www.ine.pt

Instituto do Ambiente e Desenvolvimento. (2022). *Programa de Prospeção e Pesquisa de Lítio de 8 áreas potenciais para lançamento de procedimento concursal para atribuição de direitos de prospeção e pesquisa de Lítio*.

Insuasty-Reina, J. G., Osorio-Gómez, J. C., & Manotas-Duque, D. F. (2022). A System Dynamics Model for the Analysis of CO2 Emissions Derived from the Inclusion of Hydrogen Obtained from Coal in the Energy Matrix in Colombia. *International Journal of Energy Economics and Policy*, *12*(2), 72–82. https://doi.org/10.32479/ijeep.12538

International Institute for Sustainable Development. (2019). *Sustainability and Second Life: The case for cobalt and lithium recycling*. (March), 1–68.

IPCC, I. P. O. C. C. (2008). *Working Group III Report:"Mitigation of Climate Change."*

Israel, F., Ettema, D., & van Lierop, D. (2023). Mechanisms with equity implications for the (non-) adoption of electric mobility in the early stage of the energy transition. *Transport Reviews*, *44*(3), 659–683. https://doi.org/10.1080/01441647.2023.2283497

Iwińska, K., Lis, A., & Mączka, K. (2021). From framework to boundary object? Reviewing gaps and critical trends in global energy justice research. *Energy Research and Social Science*, *79*(July). https://doi.org/10.1016/j.erss.2021.102191

Jafarpour, A., & Khatami, S. (2021). Analysis of Environmental Costs' Effect in Green Mining Strategy Using a System Dynamics Approach: A Case Study. *Mathematical Problems in Engineering*, *2021*. https://doi.org/10.1155/2021/4893776

Janipour, Z., de Gooyert, V., Huijbregts, M., & de Coninck, H. (2022). Industrial clustering as a barrier and an enabler for deep emission reduction: a case study of a Dutch chemical cluster. *Climate Policy*, *22*(3), 320–338. https://doi.org/10.1080/14693062.2022.2025755

Jartti, T., Litmanen, T., Lacey, J., & Moffat, K. (2020). National level paths to the mining industry's Social Licence to Operate (SLO) in Northern Europe: The case of Finland. *Extractive Industries and Society*, *7*(1), 97–109. https://doi.org/10.1016/j.exis.2020.01.006

Jayapalan, C., Hariharan, T. S., & Ganesh, L. S. (2022). Power supply to electric vehicle charging stations in India:Justification of a framework for a dynamic and adaptive electricity tariff policy. *The Electricity Journal*, *35*(10), 107219. https://doi.org/https://doi.org/10.1016/j.tej.2022.107219

Jenkins, K., McCauley, D., & Forman, A. (2017). Energy justice: A policy approach. *Energy Policy*, *105*(February), 631–634. https://doi.org/10.1016/j.enpol.2017.01.052

Jenkins, K., Mccauley, D., Heffron, R., & Stephan, H. (2014). Energy Justice, a Whole Systems Approach. *Queens Political Review*, *2*(2), 74–87. Retrieved from http://hdl.handle.net/1765/125765

Jenkins, K., McCauley, D., Heffron, R., Stephan, H., & Rehner, R. (2016). Energy justice: A conceptual review. *Energy Research and Social Science*, *11*, 174–182. https://doi.org/10.1016/j.erss.2015.10.004

Jenkins, K., Sovacool, B. K., Mouter, N., Hacking, N., Burns, M. K., & McCauley, D. (2021). The methodologies, geographies, and technologies of energy justice: A systematic and comprehensive review. *Environmental Research Letters*, *16*(4). https://doi.org/10.1088/1748-9326/abd78c

Jha, S., Pani, A., Puppala, H., Varghese, V., & Unnikrishnan, A. (2025). An equity-based approach for addressing inequality in electric vehicle charging infrastructure: Leaving no one behind in transport electrification. *Energy for Sustainable Development*, *85*, 101643. https://doi.org/10.1016/j.esd.2024.101643

Ji, S., Cherry, C. R., Zhou, W., Sawhney, R., Wu, Y., Cai, S., ... Marshall, J. D. (2015). Environmental Justice Aspects of Exposure to $PM_{2.5}$ Emissions from Electric Vehicle Use in China. *Environmental Science and Technology*, *49*(24), 13912–13920. https://doi.org/10.1021/acs.est.5b04927

Jiao, J., Choi, S. J., & Nguyen, C. (2024). Toward an equitable transportation electrification plan: Measuring public electric vehicle charging station access disparities in Austin, Texas. *PLoS ONE*, *19*(9 September), 1–28. https://doi.org/10.1371/journal.pone.0309302

Jin, E., Mendis, G. P., & Sutherland, J. W. (2019). Integrated sustainability assessment for a bioenergy system: A system dynamics model of switchgrass for cellulosic ethanol production in the U.S. midwest. *Journal of Cleaner Production*, *234*, 503–520. https://doi.org/10.1016/j.jclepro.2019.06.205

Jodoin, L. (2021). Let capabilities ring: Operationalizing energy justice in Guinea. *Energy Research and Social Science*, *72*(January), 101894. https://doi.org/10.1016/j.erss.2020.101894

Johnson, C. A., Clavijo, A., Lorca, M., & Andrade, M. O. (2024). Bringing the state back in the lithium triangle: An institutional analysis of resource nationalism in Chile, Argentina, and Bolivia. *Extractive Industries and Society*, *20*(May), 101534. https://doi.org/10.1016/j.exis.2024.101534

Jordão, M., & Fernandes, F. (2022). *A INDÚSTRIA AUTOMÓVEL EM PORTUGAL* (p. 22). p. 22. Direção-Geral das Atividades Económicas.

Joyce, S., & Thomson, I. (2000). Earning a social licence to operate: Social acceptability and resource

development in Latin America. *CIM Bulletin*, *93*(1037), 49 – 53. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-0033627008&partnerID=40&md5=69ed7c43430df533babb44f944004817

Kallitsis, E., Korre, A., Kelsall, G., Kupfersberger, M., & Nie, Z. (2020). Environmental life cycle assessment of the production in China of lithium-ion batteries with nickel-cobalt-manganese cathodes utilising novel electrode chemistries. *Journal of Cleaner Production*, *254*, 120067. https://doi.org/10.1016/j.jclepro.2020.120067

Karunathilake, H., Hewage, K., Prabatha, T., Ruparathna, R., & Sadiq, R. (2020). Project deployment strategies for community renewable energy: A dynamic multi-period planning approach. *Renewable Energy*, *152*, 237–258. https://doi.org/10.1016/j.renene.2020.01.045

Kaunda, R. B. (2020). Potential environmental impacts of lithium mining. *Journal of Energy and Natural Resources Law*, *38*(3), 237–244. https://doi.org/10.1080/02646811.2020.1754596

Kehler, S., & Birchall, S. J. (2021). Social vulnerability and climate change adaptation: The critical importance of moving beyond technocratic policy approaches. *Environmental Science and Policy*, *124*(June), 471–477. https://doi.org/10.1016/j.envsci.2021.07.025

Keith, D. R., Struben, J. J. R., & Naumov, S. (2020). The Diffusion of Alternative Fuel Vehicles: A Generalised Model and Future Research Agenda. *Journal of Simulation*, *14*(4), 260–277. https://doi.org/10.1080/17477778.2019.1708219

Keyhanpour, M. J., Musavi Jahromi, S. H., & Ebrahimi, H. (2021). System dynamics model of sustainable water resources management using the Nexus Water-Food-Energy approach. *Ain Shams Engineering Journal*, *12*(2), 1267–1281. https://doi.org/10.1016/j.asej.2020.07.029

Khan, H. A. U., Price, S., Avraam, C., & Dvorkin, Y. (2022). Inequitable access to EV charging infrastructure. *The Electricity Journal*, *35*(3), 107096. https://doi.org/https://doi.org/10.1016/j.tej.2022.107096

Kifle, D., Sverdrup, H., Koca, D., & Wibetoe, G. (2012). A Simple Assessment of the Global Long Term Supply of the Rare Earth Elements by Using a System Dynamics Model. *Environment and Natural Resources Research*, *3*(1). https://doi.org/10.5539/enrr.v3n1p77

Kim, D. H. (2000). System Archetypes I: Diagnosing Systemic Issues and Designing High-Leverage Interventions. In K. W. O'Reilly, G. Wiley, & L. K. Johnson (Eds.), *Toolbox Reprint Series*. Walthan, MA: Pegasus Communications.

Koirala, B. P., Araghi, Y., Kroesen, M., Ghorbani, A., Hakvoort, R. A., & Herder, P. M. (2018). Trust, awareness, and independence: Insights from a socio-psychological factor analysis of citizen

knowledge and participation in community energy systems. *Energy Research and Social Science*, *38*(January), 33–40. https://doi.org/10.1016/j.erss.2018.01.009

Kolie, B., Elshkaki, A., Sunahara, G., Diakite, M. L., & Sangare, M. (2024). Energy and water infrastructures management under energy transition pressure in mineral extraction urban and rural areas: A case study of the Republic of Guinea. *Extractive Industries and Society*, *17*(August 2023), 101433. https://doi.org/10.1016/j.exis.2024.101433

Komnitsas, K. (2020). Social license to operate in mining: Present views and future trends. *Resources*, *9*(6). https://doi.org/10.3390/resources9060079

Kotak, Y., Fernández, C. M., Casals, L. C., Kotak, B. S., Koch, D., Geisbauer, C., ... Schweiger, H. G. (2021). End of electric vehicle batteries: Reuse vs. recycle. *Energies*, *14*(8), 1–15. https://doi.org/10.3390/en14082217

Kotzur, L., Nolting, L., Hoffmann, M., Groß, T., Smolenko, A., Priesmann, J., ... Robinius, M. (2021). A modeler's guide to handle complexity in energy systems optimization. *Advances in Applied Energy*, *4*(August), 100063. https://doi.org/10.1016/j.adapen.2021.100063

Krause, J., Thiel, C., Tsokolis, D., Samaras, Z., Rota, C., Ward, A., ... Verhoeve, W. (2020). EU road vehicle energy consumption and CO2 emissions by 2050 – Expert-based scenarios. *Energy Policy*, *138*(February), 111224. https://doi.org/10.1016/j.enpol.2019.111224

Krumm, A., Süsser, D., & Blechinger, P. (2022). Modelling social aspects of the energy transition: What is the current representation of social factors in energy models? *Energy*, *239*, 121706. https://doi.org/10.1016/j.energy.2021.121706

Ku, A., Kammen, D. M., & Castellanos, S. (2021). A quantitative, equitable framework for urban transportation electrification: Oakland, California as a mobility model of climate justice. *Sustainable Cities and Society*, *74*. https://doi.org/10.1016/j.scs.2021.103179

Kubli, M., & Ulli-Beer, S. (2016). Decentralisation dynamics in energy systems: A generic simulation of network effects. *Energy Research and Social Science*, *13*, 71–83. https://doi.org/10.1016/j.erss.2015.12.015

Labanca, N., Pereira, A. G., Watson, M., Krieger, K., Padovan, D., Watts, L., ... Mehta, L. (2020). Transforming innovation for decarbonisation? Insights from combining complex systems and social practice perspectives. *Energy Research & Social Science*, *65*(February), 101452. https://doi.org/10.1016/j.erss.2020.101452

Lacey-Barnacle, M., Robison, R., & Foulds, C. (2020). Energy justice in the developing world: a review of theoretical frameworks, key research themes and policy implications. *Energy for Sustainable*

Development, *55*, 122–138. https://doi.org/10.1016/j.esd.2020.01.010

Laimon, M., Mai, T., Goh, S., & Yusaf, T. (2019). Energy Sector Development: System Dynamics Analysis. *Applied Sciences*, *10*(1), 134. https://doi.org/10.3390/app10010134

Laimon, M., Mai, T., Goh, S., & Yusaf, T. (2022). System dynamics modelling to assess the impact of renewable energy systems and energy efficiency on the performance of the energy sector. *Renewable Energy*, *193*, 1041–1048. https://doi.org/10.1016/j.renene.2022.05.041

Lamas, I. A. (2023). Governance gap? Vale's corporate action and socioenvironmental conflicts in an international perspective. *Extractive Industries and Society*, *13*(February 2022), 101172. https://doi.org/10.1016/j.exis.2022.101172

Lapeyronie, H., & Szedlacsek, E. (2025). Mining in Africa: Are local communities paying the price of the global energy transition? *Extractive Industries and Society*, *21*(November 2024), 101565. https://doi.org/10.1016/j.exis.2024.101565

Leaver, J. D., Gillingham, K., & Baglino, A. (2012). *System Dynamics Modelling of Pathways to a Hydrogen Economy in New Zealand: Final Report*.

Lebedeva, N., Persio, D. F., & Boon-Brett, L. (2017). Lithium ion battery value chain and related opportunities for Europe. In *Science for Policy report by the Joint Research Centre (JRC)*. https://doi.org/10.2760/6060

Lee, D.-Y. Y., McDermott, M. H., Sovacool, B. K., & Isaac, R. (2024). Toward just and equitable mobility: Socioeconomic and perceptual barriers for electric vehicles and charging infrastructure in the United States. *Energy and Climate Change*, *5*(July), 100146. https://doi.org/10.1016/j.egycc.2024.100146

Lee, D. Y., Wilson, A., McDermott, M. H., Sovacool, B. K., Kaufmann, R., Isaac, R., … Ward, J. (2025). Does electric mobility display racial or income disparities? Quantifying inequality in the distribution of electric vehicle adoption and charging infrastructure in the United States. *Applied Energy*, *378*(PA), 124795. https://doi.org/10.1016/j.apenergy.2024.124795

Lee, R., & Brown, S. (2021). Social & locational impacts on electric vehicle ownership and charging profiles. *ENERGY REPORTS*, *7*(2, SI), 42–48. https://doi.org/https://doi.org/10.1016/j.egyr.2021.02.057

Lelieveld, J., Klingmüller, K., Pozzer, A., Burnett, R. T., Haines, A., & Ramanathan, V. (2019). Effects of fossil fuel and total anthropogenic emission removal on public health and climate. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(15), 7192–7197. https://doi.org/10.1073/pnas.1819989116

Leopold, A. (2016). Energy related system dynamic models: a literature review. *Central European Journal of Operations Research*, *24*(1), 231–261. https://doi.org/10.1007/s10100-015-0417-4

Lesser, P., Gugerell, K., Poelzer, G., Hitch, M., & Tost, M. (2021). European mining and the social license to operate. *The Extractive Industries and Society*, *8*(May 2020), 100787.

Li, F. G. N., Trutnevyte, E., & Strachan, N. (2015). A review of socio-technical energy transition (STET) models. *Technological Forecasting and Social Change*, *100*(December 2017), 290–305. https://doi.org/10.1016/j.techfore.2015.07.017

Li, G., Luo, T., & Song, Y. (2022). Spatial equity analysis of urban public services for electric vehicle charging—Implications of Chinese cities. *Sustainable Cities and Society*, *76*(October 2021), 103519. https://doi.org/10.1016/j.scs.2021.103519

Li, Z., Smith-Colin, J., & Wang, J. (2025). A unified multi-criteria equity metric for data-driven decision-making: Application to tract-level electric vehicle charging station planning. *Engineering Applications of Artificial Intelligence*, *144*(December 2024), 110070. https://doi.org/10.1016/j.engappai.2025.110070

Litmanen, T., Jartti, T., & Rantala, E. (2016). Refining the preconditions of a social licence to operate (SLO): reflections on citizens' attitudes towards mining in two Finnish regions. *Extractive Industries and Society*, *3*(3), 782–792. https://doi.org/10.1016/j.exis.2016.04.003

Liu, H., Dai, Z., Rodgers, M. O., & Guensler, R. (2022). Equity issues associated with US plug-in electric vehicle income tax credits. *TRANSPORTATION RESEARCH PART D-TRANSPORT AND ENVIRONMENT*, *102*(December 2021), 103159. https://doi.org/10.1016/j.trd.2021.103159

Liu, X., Mao, G., Ren, J., Li, R. Y. M., Guo, J., & Zhang, L. (2015). How might China achieve its 2020 emissions target? A scenario analysis of energy consumption and CO2 emissions using the system dynamics model. *Journal of Cleaner Production*, *103*(2015), 401–410. https://doi.org/https://doi.org/10.1016/j.jclepro.2014.12.080

Liu, Z., Song, J., Kubal, J., Susarla, N., Knehr, K. W., Islam, E., … Ahmed, S. (2021). Comparing total cost of ownership of battery electric vehicles and internal combustion engine vehicles. *Energy Policy*, *158*(August), 112564. https://doi.org/10.1016/j.enpol.2021.112564

Llamosas, C., & Sovacool, B. K. (2021). Transboundary hydropower in contested contexts: Energy security, capabilities, and justice in comparative perspective. *Energy Strategy Reviews*, *37*, 100698. https://doi.org/10.1016/j.esr.2021.100698

Loni, A., & Asadi, S. (2023). Data-driven equitable placement for electric vehicle charging stations: Case study San Francisco. *Energy*, *282*, 128796. https://doi.org/10.1016/j.energy.2023.128796

Lopez-Arboleda, E., Sarmiento, A. T., & Cardenas, L. M. (2023). Policy assessment for electromobility promotion in Colombia: A system dynamics approach. *Transportation Research Part D: Transport and Environment*, *121*(June), 103799. https://doi.org/10.1016/j.trd.2023.103799

Lopion, P., Markewitz, P., Robinius, M., & Stolten, D. (2018). A review of current challenges and trends in energy systems modeling. *Renewable and Sustainable Energy Reviews*, *96*(July), 156–166. https://doi.org/10.1016/j.rser.2018.07.045

Lowans, C., Furszyfer Del Rio, D., Sovacool, B. K., Rooney, D., & Foley, A. M. (2021). What is the state of the art in energy and transport poverty metrics? A critical and comprehensive review. *Energy Economics*, *101*(June), 105360. https://doi.org/10.1016/j.eneco.2021.105360

Lund, H., Arler, F., Østergaard, P. A., Hvelplund, F., Connolly, D., Mathiesen, B. V., & Karnøe, P. (2017). Simulation versus optimisation: Theoretical positions in energy system modelling. *Energies*, *10*(7), 1–17. https://doi.org/10.3390/en10070840

Lund, H., & Hvelplund, F. (2012). The economic crisis and sustainable development: The design of job creation strategies by use of concrete institutional economics. *Energy*, *43*(1), 192–200. https://doi.org/10.1016/j.energy.2012.02.075

Lund, H., Thellufsen, J. Z., Sorknæs, P., Mathiesen, B. V., Chang, M., Madsen, P. T., … Skov, I. R. (2022). Smart energy Denmark. A consistent and detailed strategy for a fully decarbonized society. *Renewable and Sustainable Energy Reviews*, *168*(July). https://doi.org/10.1016/j.rser.2022.112777

Lundstøl, O. (2022). Taxing the extractives: Revenue sharing between the state and mining companies in Tanzania and Zambia. *Extractive Industries and Society*, *11*(July). https://doi.org/10.1016/j.exis.2022.101126

Lusa. (2023). Dois terços das novas matrículas de 2022 são de carros usados comprados lá fora. *Público Comunicação Social*.

Lusa. (2024a). Autarca de Montalegre preocupada com projectos de lítio, fotovoltaicos e eólicos. Retrieved December 4, 2024, from Público website: https://www.publico.pt/2024/10/22/azul/noticia/autarca-montalegre-preocupada-projectos-litio-fotovoltaicos-eolicos-2108951

Lusa. (2024b). Galp desiste de refinaria de lítio em Setúbal após abandono da Northvolt. Retrieved December 4, 2024, from Público website: https://www.publico.pt/2024/11/26/economia/noticia/galp-desiste-refinaria-litio-setubal-apos-abandono-northvolt-2113466

Maddox, R., & Ninomiya, M. E. M. (2025). Indigenous sovereignty in research and epistemic justice: Truth telling through research. *Global Public Health*, *20*(1). https://doi.org/10.1080/17441692.2024.2436436

Madruga, P., Rodrigues, H., & Ferreira, R. (2023). *Diagnóstico Prospetivo da Indústria de Componentes Automóvel em Portugal*. Retrieved from https://www.ey.com/pt_pt/strategy/diagnostico-prospetivo-da-industria-de-componentes-automovel-em-portugal

Maier, F., Schober, C., Simsa, R., & Millner, R. (2015). SROI as a Method for Evaluation Research: Understanding Merits and Limitations. *VOLUNTAS: International Journal of Voluntary and Nonprofit Organizations*, *26*(5), 1805–1830. https://doi.org/10.1007/s11266-014-9490-x

Malode, S. J., Prabhu, K. K., Mascarenhas, R. J., Shetti, N. P., & Aminabhavi, T. M. (2021). Recent advances and viability in biofuel production. *Energy Conversion and Management: X*, *10*(September 2020), 100070. https://doi.org/10.1016/j.ecmx.2020.100070

Mandolakani, F. S., & Singleton, P. A. (2024). Electric vehicle charging infrastructure deployment: A discussion of equity and justice theories and accessibility measurement. *Transportation Research Interdisciplinary Perspectives*, *24*(March), 101072. https://doi.org/10.1016/j.trip.2024.101072

Marczinkowski, H. M. (2022). Rethinking Islands and their Models in Sustainable Energy Planning: How Inclusive Local Perspectives Improve Energy Planning Globally. *International Journal of Sustainable Energy Planning and Management*, *33*, 7–18. https://doi.org/10.5278/ijsepm.6970

Marin, D. (2024). Economic Transition: Resource Justice and Raw Materials. Retrieved December 3, 2024, from European Environmental Bureau (EEB) website: https://eeb.org/work-areas/economic-transition/resource-justice-and-raw-materials/

Marshall, J. (2023). Vale in Mozambique: Creator and destroyer of jobs, livelihoods and communities. *Extractive Industries and Society*, *13*(March 2022), 101190. https://doi.org/10.1016/j.exis.2022.101190

Martens, K. (2016). *Transport Justice*. Routledge. https://doi.org/10.4324/9781315746852

Martin, N., Madrid-López, C., Talens-Peiró, L., Süsser, D., Gaschnig, H., & Lilliestam, J. (2020). *Observed trends and modelling paradigms on the social and environmental aspects of the energy transition. Deliverable 2.1. Sustainable Energy Transitions Laboratory (SENTINEL) project (1.0)*. (837089). Retrieved from https://dx.doi.org/10.5281/zenodo.4917183

McCauley, D, Heffron, R., Stephan, H., & Jenkins, K. (2013). Advancing energy justice: the triumvirate of tenets. *Int. Energy Law Rev.*, *32*(3), 9–25. Retrieved from http://hdl.handle.net/1765/125727

McCauley, Darren, Ramasar, V., Heffron, R. J., Sovacool, B. K., Mebratu, D., & Mundaca, L. (2019).

Energy justice in the transition to low carbon energy systems: Exploring key themes in interdisciplinary research. *Applied Energy*, *233–234*, 916–921. https://doi.org/10.1016/j.apenergy.2018.10.005

McDowall, W., & Geels, F. W. (2017). Ten challenges for computer models in transitions research: Commentary on Holtz et al. *Environmental Innovation and Societal Transitions*, *22*, 41–49. https://doi.org/10.1016/j.eist.2016.07.001

McGookin, C., Ó Gallachóir, B., & Byrne, E. (2021). Participatory methods in energy system modelling and planning – A review. *Renewable and Sustainable Energy Reviews*, *151*(November 2020). https://doi.org/10.1016/j.rser.2021.111504

Meadows, D. H. (2008). *Thinking in Systems* (Vol. 69). Earthscan Publications Ltd.

Meadows, D. H., Meadows, D. L., Randers, J., & Behrends, W. W. (1972). *The limits to growth*. New York: Universe Books. https://doi.org/10.1016/B978-0-444-63768-0.00630-2

Mejía-Duwan, J., Hino, M., & Mach, K. J. (2023). Emissions redistribution and environmental justice implications of California's clean vehicle rebate project. *PLOS Climate*, *2*(5), e0000183. https://doi.org/10.1371/journal.pclm.0000183

Mejía-Montero, A., Lane, M., van Der Horst, D., & Jenkins, K. (2021). Grounding the energy justice lifecycle framework: An exploration of utility-scale wind power in Oaxaca, Mexico. *Energy Research and Social Science*, *75*(February 2020), 102017. https://doi.org/10.1016/j.erss.2021.102017

Meng, F., McNeice, J., Zadeh, S. S., & Ghahreman, A. (2021). Review of Lithium Production and Recovery from Minerals, Brines, and Lithium-Ion Batteries. *Mineral Processing and Extractive Metallurgy Review*, *42*(2), 123–141. https://doi.org/10.1080/08827508.2019.1668387

Menges, R., & Beyer, G. (2014). Underground cables versus overhead lines: Do cables increase social acceptance of grid development? results of a contingent valuation survey in Germany. *International Journal of Sustainable Energy Planning and Management*, *3*, 33–48. https://doi.org/10.5278/ijsepm.2014.3.4

Mercer-Mapstone, L., Rifkin, W., Louis, W. R., & Moffat, K. (2018). Company-community dialogue builds relationships, fairness, and trust leading to social acceptance of Australian mining developments. *Journal of Cleaner Production*, *184*, 671–677. https://doi.org/10.1016/j.jclepro.2018.02.291

Miao, Y., Hynan, P., Von Jouanne, A., & Yokochi, A. (2019). Current li-ion battery technologies in electric vehicles and opportunities for advancements. *Energies*, *12*(6), 1–20. https://doi.org/10.3390/en12061074

Miller, D. (2025). Justice. In E. Zalta & U. Nodelman (Eds.), *The Stanford Encyclopedia of Philosophy*

(Spring 202). The Metaphysics Research Lab, Stanford University. Retrieved from https://plato.stanford.edu/archives/spr2025/entries/justice/

Min, Y., & Lee, H. W. (2020). Social Equity of Clean Energy Policies in Electric-Vehicle Charging Infrastructure Systems. In M. ElAsmar, P. Tang, & D. Grau (Eds.), *CONSTRUCTION RESEARCH CONGRESS 2020: INFRASTRUCTURE SYSTEMS AND SUSTAINABILITY* (pp. 221–229).

Min, Y., Lee, H. W., & Hurvitz, P. M. (2023). Clean energy justice: Different adoption characteristics of underserved communities in rooftop solar and electric vehicle chargers in Seattle. *Energy Research and Social Science*, *96*, 102931. https://doi.org/10.1016/j.erss.2022.102931

Min, Y., & Mayfield, E. (2023). Rooftop solar, electric vehicle, and heat pump adoption in rural areas in the United States. *Energy Research and Social Science*, *105*(September), 103292. https://doi.org/10.1016/j.erss.2023.103292

Miranda, J. L., & Delgado, C. J. M. (2020). Determinants of electric car purchase intention in Portugal. *Developments in Corporate Governance and Responsibility*, *15*, 161–172. https://doi.org/10.1108/S2043-052320200000015009

Mitchell, A., & Griffin, L. (2005). The Esri Guide to GIS Analysis, Volume 2: Spatial Measurements and Statistics. In *ESRI Press* (Second edi). ESRI Press. Retrieved from https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-statistics/h-how-spatial-autocorrelation-moran-s-i-spatial-st.htm

Mitchell, M. (2009). *Complexity: A guided tour*. New York, New York, USA: Oxford University Press.

Mobaseri, M., Mousavi, S. N., & Mousavi Haghighi, M. H. (2021). Causal effects of population growth on energy utilization and environmental pollution: A system dynamics approach. *Caspian Journal of Environmental Sciences*, *19*(4), 601–618. https://doi.org/10.22124/cjes.2021.5088

Mobi.E. (2024). Find charging points. Retrieved March 19, 2024, from Mobi.E: Mobilidade Elétrica website: https://www.mobie.pt/en/mobienetwork/finding-charging-points

Moffat, K., & Zhang, A. (2014). The paths to social licence to operate: An integrative model explaining community acceptance of mining. *Resources Policy*, *39*(1), 61–70. https://doi.org/10.1016/j.resourpol.2013.11.003

Mononen, T., Kivinen, S., Kotilainen, J. M., & Leino, J. (2022). Social and environmental impacts of mining activities in the EU. In *STUDY: Requested by the PETI committee* (Vol. 2).

Mononen, Tuija, & Sairinen, R. (2021). Mining with social license: Case study of Kylylahti mine in Northern Karelia, Finland. *Extractive Industries and Society*, *8*(2), 100744. https://doi.org/10.1016/j.exis.2020.05.023

Morales-Betancourt, R., Galvis, B., Rincón-Riveros, J. M., Rincón-Caro, M. A., Rodriguez-Valencia, A., &

Sarmiento, O. L. (2019). Personal exposure to air pollutants in a Bus Rapid Transit System: Impact of fleet age and emission standard. *Atmospheric Environment*, *202*(July 2018), 117–127. https://doi.org/10.1016/j.atmosenv.2019.01.026

Moro, A., & Lonza, L. (2018). Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. *Transportation Research Part D: Transport and Environment*, *64*(April 2017), 5–14. https://doi.org/10.1016/j.trd.2017.07.012

Morrison, K., & Wappelhorst, S. (2022). *Battery electric vehicle access in Europe: A comparison of rural, intermediate, and urban regions* (No. 18). Retrieved from https://theicct.org/wp-content/uploads/2022/06/bev-access-europe-jun22.pdf

Mrozik, W., Rajaeifar, M. A., Heidrich, O., & Christensen, P. (2021). Environmental impacts, pollution sources and pathways of spent lithium-ion batteries. *Energy & Environmental Science*, *14*(12), 6099–6121. https://doi.org/10.1039/D1EE00691F

Muhirwa, F., Shen, L., Elshkaki, A., Hirwa, H., Umuziranenge, G., & Velempini, K. (2023). Linking large extractive industries to sustainable development of rural communities at mining sites in Africa: Challenges and pathways. *Resources Policy*, *81*(November 2022), 103322. https://doi.org/10.1016/j.resourpol.2023.103322

Munro, P., van der Horst, G., & Healy, S. (2017). Energy justice for all? Rethinking Sustainable Development Goal 7 through struggles over traditional energy practices in Sierra Leone. *Energy Policy*, *105*(November 2016), 635–641. https://doi.org/10.1016/j.enpol.2017.01.038

Mutingi, M., Mbohwa, C., & Kommula, V. P. (2017). System dynamics approaches to energy policy modelling and simulation. *Energy Procedia*, *141*, 532–539. https://doi.org/10.1016/j.egypro.2017.11.071

Nakata, T., Silva, D., & Rodionov, M. (2011). Application of energy system models for designing a low-carbon society. *Progress in Energy and Combustion Science*, *37*(4), 462–502. https://doi.org/10.1016/j.pecs.2010.08.001

Nijs, W., & Ruiz Castello, P. (2021). JRC-EU-TIMES Full model. Retrieved September 24, 2022, from European Commission, Joint Research Centre (JRC) website: http://data.europa.eu/89h/8141a398-41a8-42fa-81a4- 5b825a51761b

Nilsson, M., Dzebo, A., Savvidou, G., & Axelsson, K. (2020). A bridging framework for studying transition pathways – From systems models to local action in the Swedish heating domain. *Technological Forecasting and Social Change*, *151*(March 2017), 119260. https://doi.org/10.1016/j.techfore.2018.04.003

Normann, S. (2021). Green colonialism in the Nordic context: Exploring Southern Saami representations of wind energy development. *Journal of Community Psychology*, *49*(1), 77–94. https://doi.org/10.1002/jcop.22422

NRGI. (2015). The Resource Curse - The Political and Economic Challenges of Natural Resource Wealth. *NRGI Reader*.

Nunes, P., & Brito, M. C. (2017). Displacing natural gas with electric vehicles for grid stabilization. *Energy*, *141*, 87–96. https://doi.org/10.1016/j.energy.2017.09.064

Oliveira, G. D., Dias, L. M. C., & Santos, P. C. S. Dos. (2015). Modelling consumer preferences for electric vehicles in Portugal: An exploratory study. *Management of Environmental Quality: An International Journal*, *26*(6), 929–950. https://doi.org/10.1108/MEQ-03-2014-0047

Onat, Nuri C., Kucukvar, M., Tatari, O., & Egilmez, G. (2016). Integration of system dynamics approach toward deepening and broadening the life cycle sustainability assessment framework: a case for electric vehicles. *International Journal of Life Cycle Assessment*, *21*(7), 1009–1034. https://doi.org/10.1007/s11367-016-1070-4

Onat, Nuri Cihat, Kucukvar, M., & Tatari, O. (2015). Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States. *Applied Energy*, *150*, 36–49. https://doi.org/10.1016/j.apenergy.2015.04.001

Osorio-Aravena, J. C., Aghahosseini, A., Bogdanov, D., Caldera, U., Muñoz-Cerón, E., & Breyer, C. (2020). Transition toward a fully renewable-based energy system in Chile by 2050 across power, heat, transport and desalination sectors. *International Journal of Sustainable Energy Planning and Management*, *25*, 77–94. https://doi.org/10.5278/ijsepm.3385

Owen, J. R., & Kemp, D. (2013). Social licence and mining: A critical perspective. *Resources Policy*, *38*(1), 29–35. https://doi.org/https://doi.org/10.1016/j.resourpol.2012.06.016

Pakere, I., Kacare, M., Grāvelsiņš, A., Freimanis, R., & Blumberga, A. (2022). Spatial analyses of smart energy system implementation through system dynamics and GIS modelling. Wind power case study in Latvia. *Smart Energy*, *7*(June). https://doi.org/10.1016/j.segy.2022.100081

Papachristos, G. (2019). System dynamics modelling and simulation for sociotechnical transitions research. *Environmental Innovation and Societal Transitions*, *31*(September 2018), 248–261. https://doi.org/10.1016/j.eist.2018.10.001

Pedro, A., Ayuk, E. T., Bodouroglou, C., Milligan, B., Ekins, P., & Oberle, B. (2017). Towards a sustainable development licence to operate for the extractive sector. *Mineral Economics*, *30*(2), 153–165. https://doi.org/10.1007/s13563-017-0108-9

Peng, Z., Wang, M. W. H., Yang, X., Chen, A., & Zhuge, C. (2024). An analytical framework for assessing equitable access to public electric vehicle chargers. *Transportation Research Part D: Transport and Environment*, *126*(November 2023), 103990. https://doi.org/10.1016/j.trd.2023.103990

Penn, I., & Lipton, E. (2021). The Lithium Gold Rush: Inside the Race to Power Electric Vehicles. Retrieved December 3, 2021, from The New York Times website: https://www.nytimes.com/2021/05/06/business/lithium-mining-race.html

Perissi, I., Martelloni, G., Bardi, U., Natalini, D., Jones, A., Nikolaev, A., ... Solé, J. (2021). Cross-validation of the MEDEAS energy-economy- environment model with the integrated MARKAL-EFOM system (TIMES) and the long-range energy alternatives planning system (LEAP). *Sustainability (Switzerland)*, *13*(4), 1–27. https://doi.org/10.3390/su13041967

Perrone, A., Inam, A., Albano, R., Adamowski, J., & Sole, A. (2020). A participatory system dynamics modeling approach to facilitate collaborative flood risk management: A case study in the Bradano River (Italy). *Journal of Hydrology*, *580*(May 2019). https://doi.org/10.1016/j.jhydrol.2019.124354

Peshin, T., Sengupta, S., Thakrar, S. K., Singh, K., Hill, J., Apte, J. S., ... Azevedo, I. M. L. (2024). Air quality, health, and equity impacts of vehicle electrification in India. *Environmental Research Letters*, *19*(2). https://doi.org/10.1088/1748-9326/ad1c7a

Piçarra, A., Annesley, I. R., Otsuki, A., & Waard, R. De. (2021). Market assessment of cobalt : Identification and evaluation of supply risk patterns. *Resources Policy*, *73*(June), 102206. https://doi.org/10.1016/j.resourpol.2021.102206

Pigliucci, M. (2014). Between holism and reductionism: a philosophical primer on emergence. *Biological Journal of the Linnean Society*, *112*(2), 261–267. https://doi.org/10.1111/bij.12060

Pillay, N. S. (2018). *System Dynamics Simulation of Income Distribution and Electric Vehicle Diffusion for Electricity Planning in South Africa*. Stellenbosch University.

Poelzer, G., Lindahl, K. B., Segerstedt, E., Abrahamsson, L., & Karlsson, M. (2020). Licensing acceptance in a mineral-rich welfare state: Critical reflections on the social license to operate in Sweden. *Extractive Industries and Society*, *7*(3), 1096–1107. https://doi.org/10.1016/j.exis.2020.05.008

Portuguese Government. (2024a). Government approves Green Mobility Package: Measures for a more sustainable future. Retrieved March 31, 2025, from República Portuguesa website: https://www.portugal.gov.pt/en/gc24/communication/news-item?i=government-approves-green-mobility-package-measures-for-a-more-sustainable-future

Portuguese Government. (2024b). *National Energy Plan and Climate 2021-2030 (NECP 2030)*

Update/Review. Retrieved from https://commission.europa.eu/system/files/2023-07/EN_PORTUGAL DRAFT UPDATED NECP.pdf

Portuguese Government. (2025). Ministro da Economia aplaude escolha de Portugal para produzir novo carro elétrico da Volkswagen. Retrieved January 4, 2025, from Notícias website: https://www.portugal.gov.pt/pt/gc24/comunicacao/noticia?i=ministro-da-economia-aplaude-escolha-de-portugal-para-produzir-novo-carro-eletrico-da-volkswagen

Pournaras, E., Jung, S., Yadhunathan, S., Zhang, H., & Fang, X. (2019). Socio-technical smart grid optimization via decentralized charge control of electric vehicles. *Applied Soft Computing Journal*, *82*(2019), 105573. https://doi.org/10.1016/j.asoc.2019.105573

Powells, G., & Fell, M. J. (2019). Flexibility capital and flexibility justice in smart energy systems. *Energy Research and Social Science*, *54*(April), 56–59. https://doi.org/10.1016/j.erss.2019.03.015

Priesmann, J., Nolting, L., & Praktiknjo, A. (2019). Are complex energy system models more accurate? An intra-model comparison of power system optimization models. *Applied Energy*, *255*(August), 113783. https://doi.org/10.1016/j.apenergy.2019.113783

Prina, M. G., Manzolini, G., Moser, D., Nastasi, B., & Sparber, W. (2020). Classification and challenges of bottom-up energy system models - A review. *Renewable and Sustainable Energy Reviews*, *129*, 109917. https://doi.org/10.1016/j.rser.2020.109917

Prina, M. G., Moser, D., Vaccaro, R., & Sparber, W. (2020). EPLANopt optimization model based on EnergyPLAN applied at regional level: The future competition on excess electricity production from renewables. *International Journal of Sustainable Energy Planning and Management*, *27*(Special Issue), 35–50. https://doi.org/10.5278/ijsepm.3504

Prno, J. (2013). An analysis of factors leading to the establishment of a social licence to operate in the mining industry. *Resources Policy*, *38*(4), 577–590. https://doi.org/10.1016/j.resourpol.2013.09.010

Prno, J., & Slocombe, D. S. (2014). A systems-based conceptual framework for assessing the determinants of a social license to operate in the mining industry. *Environmental Management*, *53*(3), 672–689. https://doi.org/10.1007/s00267-013-0221-7

Qarnain, S. S., Sattanathan, M., & Sankaranarayanan, B. (2020). Analysis of social inequality factors in implementation of building energy conservation policies using fuzzyanalytical hierarchy process methodology. *International Journal of Sustainable Energy Planning and Management*, *29*, 153–170. https://doi.org/10.5278/ijsepm.3616

Qiao, Q., Zhao, F., Liu, Z., & Hao, H. (2019). Electric vehicle recycling in China: Economic and

environmental benefits. *Resources, Conservation and Recycling*, *140*(July 2018), 45–53. https://doi.org/10.1016/j.resconrec.2018.09.003

Qudrat-Ullah, H. (2013). Understanding the dynamics of electricity generation capacity in Canada: A system dynamics approach. *Energy*, *59*, 285–294. https://doi.org/10.1016/j.energy.2013.07.029

Qudrat-Ullah, H. (2017). How to enhance the future use of energy policy simulation models through ex post validation. *Energy*, *120*, 58–66. https://doi.org/10.1016/j.energy.2016.12.095

Rabinowitz, A. I., Smart, J. G., Coburn, T. C., & Bradley, T. H. (2023). Assessment of Factors in the Reduction of BEV Operational Inconvenience. *IEEE Access*, *11*, 30486–30497. https://doi.org/10.1109/ACCESS.2023.3255103

Raugei, M., & Winfield, P. (2019). Prospective LCA of the production and EoL recycling of a novel type of Li-ion battery for electric vehicles. *Journal of Cleaner Production*, *213*, 926–932. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.12.237

Rawls, J. (1971). *A Theory of Justice* (Original E). Harvard University Press. https://doi.org/10.2307/j.ctvjf9z6v

RCM nº 11/2018. (2018). *Estratégia Nacional para valorização do potencial de minerais de Lítio em Portugal*. República Portuguesa.

Reddi, K. R., Li, W., Wang, B., & Moon, Y. (2013). System dynamics modelling of hybrid renewable energy systems and combined heating and power generator. *International Journal of Sustainable Engineering*, *6*(1), 31–47. https://doi.org/10.1080/19397038.2012.689781

Reinhardt, R., Christodoulou, I., Gassó-Domingo, S., & Amante García, B. (2019). Towards sustainable business models for electric vehicle battery second use: A critical review. *Journal of Environmental Management*, *245*, 432–446. https://doi.org/10.1016/j.jenvman.2019.05.095

Ribeiro, T., Lima, A., & Vasconcelos, C. (2021). The need for transparent communication in mining: a case study in lithium exploitation. *International Journal of Science Education, Part B: Communication and Public Engagement*, *11*(4), 324–343. https://doi.org/10.1080/21548455.2021.1999530

Ridha, E., Nolting, L., & Praktiknjo, A. (2020). Complexity profiles: A large-scale review of energy system models in terms of complexity. *Energy Strategy Reviews*, *30*(June), 100515. https://doi.org/10.1016/j.esr.2020.100515

Ringkjøb, H. K., Haugan, P. M., & Solbrekke, I. M. (2018). A review of modelling tools for energy and electricity systems with large shares of variable renewables. *Renewable and Sustainable Energy*

Reviews, *96*(August), 440–459. https://doi.org/10.1016/j.rser.2018.08.002

Roberts, S. H., Foran, B. D., Axon, C. J., Warr, B. S., & Goddard, N. H. (2018). Consequences of selecting technology pathways on cumulative carbon dioxide emissions for the United Kingdom. *Applied Energy*, *228*, 409–425. https://doi.org/10.1016/j.apenergy.2018.06.078

Robson, C. (2002). *Real world research* (Second). Blackwell Publishing.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S. I., Lambin, E., ... Foley, J. (2009). Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society*, *14*(2). Retrieved from http://www.ecologyandsociety.org/vol14/iss2/art32/

Roddis, P., Carver, S., Dallimer, M., Norman, P., & Ziv, G. (2018). The role of community acceptance in planning outcomes for onshore wind and solar farms: An energy justice analysis. *Applied Energy*, *226*(June), 353–364. https://doi.org/10.1016/j.apenergy.2018.05.087

Romero-Lankao, P., Wilson, A., & Zimny-Schmitt, D. (2022). Inequality and the future of electric mobility in 36 U.S. Cities: An innovative methodology and comparative assessment. *Energy Research & Social Science*, *91*(February), 102760. https://doi.org/10.1016/j.erss.2022.102760

Roy, A., & Law, M. (2022). Examining spatial disparities in electric vehicle charging station placements using machine learning. *Sustainable Cities and Society*, *83*(May), 103978. https://doi.org/https://doi.org/10.1016/j.scs.2022.103978

Rygg, B. J., Ryghaug, M., & Yttri, G. (2021). Is local always best? Social acceptance of small hydropower projects in Norway. *International Journal of Sustainable Energy Planning and Management*, *31*, 161–174. https://doi.org/10.5278/ijsepm.6444

Salim, H. K., Stewart, R. A., Sahin, O., & Dudley, M. (2020). Systems approach to end-of-life management of residential photovoltaic panels and battery energy storage system in Australia. *Renewable and Sustainable Energy Reviews*, *134*(July), 110176. https://doi.org/10.1016/j.rser.2020.110176

Salim, Hengky K., Stewart, R. A., Sahin, O., & Dudley, M. (2019). End-of-life management of solar photovoltaic and battery energy storage systems: A stakeholder survey in Australia. *Resources, Conservation and Recycling*, *150*(August), 104444. https://doi.org/10.1016/j.resconrec.2019.104444

Samarakoon, S. (2019). A justice and wellbeing centered framework for analysing energy poverty in the Global South. *Ecological Economics*, *165*(January), 106385. https://doi.org/10.1016/j.ecolecon.2019.106385

Sanguesa, J. A., Torres-Sanz, V., Garrido, P., Martinez, F. J., & Marquez-Barja, J. M. (2021). A review on electric vehicles: Technologies and challenges. *Smart Cities*, *4*(1), 372–404.

https://doi.org/10.3390/smartcities4010022

Saunders, M., Lewis, P., & Thornhill, A. (2009). Research methods for business students. In *Pearson Education Limited* (Fifth). England: Pearson Education. https://doi.org/10.1007/s13398-014-0173-7.2

Savannah Resources. (2021a). *Barroso Lithium Project: Integrated Waste Landform High Level Description*.

Savannah Resources. (2021b). *Environmental Impact Study*.

Savannah Resources. (2023). Barroso Lithium Project, Portugal. Retrieved July 3, 2023, from https://www.savannahresources.com/project/barroso-lithium-project-portugal/

Schlosberg, D., & Collins, L. B. (2014). From environmental to climate justice: Climate change and the discourse of environmental justice. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(3), 359–374. https://doi.org/10.1002/wcc.275

Schot, J., & Geels, F. W. (2008). Strategic niche management and sustainable innovation journeys: Theory, findings, research agenda, and policy. *Technology Analysis and Strategic Management*, *20*(5), 537–554. https://doi.org/10.1080/09537320802292651

Scopes Data. (2024). Portugal's Electrification Drive: Leading the Way in Sustainable Mobility. Retrieved March 8, 2024, from https://scopesdata.com/sustainability-country-information/portugal-2023

Scott, S., Nolan, B., & Fahey, T. (1996). *Formulating environmental and social indicators for sustainable development*. Dublin: The Economic and Social Research Institute.

Selvakkumaran, S., & Ahlgren, E. O. (2017). Understanding the local energy transitions process: A systematic review. *International Journal of Sustainable Energy Planning and Management*, *14*, 57–78. https://doi.org/10.5278/ijsepm.2017.14.5

Shafiei, E., Davidsdottir, B., Leaver, J., Stefansson, H., & Asgeirsson, E. I. (2014). Potential impact of transition to a low-carbon transport system in Iceland. *Energy Policy*, *69*, 127–142. https://doi.org/10.1016/j.enpol.2014.03.013

Shafiei, E., Davidsdottir, B., Leaver, J., Stefansson, H., & Asgeirsson, E. I. (2015a). Comparative analysis of hydrogen, biofuels and electricity transitional pathways to sustainable transport in a renewable-based energy system. *Energy*, *83*, 614–627. https://doi.org/10.1016/j.energy.2015.02.071

Shafiei, E., Davidsdottir, B., Leaver, J., Stefansson, H., & Asgeirsson, E. I. (2015b). Simulation of Alternative Fuel Markets using Integrated System Dynamics Model of Energy System. *Procedia Computer Science*, *51*, 513–521. https://doi.org/10.1016/j.procs.2015.05.277

Shafiei, E., Davidsdottir, B., Leaver, J., Stefansson, H., & Asgeirsson, E. I. (2017). Energy, economic, and

mitigation cost implications of transition toward a carbon-neutral transport sector: A simulation-based comparison between hydrogen and electricity. *Journal of Cleaner Production*, *141*, 237–247. https://doi.org/10.1016/j.jclepro.2016.09.064

Shafiei, E., Davidsdottir, B., Leaver, J., Stefansson, H., Asgeirsson, E. I., & Keith, D. R. (2016). Analysis of supply-push strategies governing the transition to biofuel vehicles in a market-oriented renewable energy system. *Energy*, *94*, 409–421. https://doi.org/10.1016/j.energy.2015.11.013

Shafiei, E., Leaver, J., & Davidsdottir, B. (2017). Cost-effectiveness analysis of inducing green vehicles to achieve deep reductions in greenhouse gas emissions in New Zealand. *Journal of Cleaner Production*, *150*, 339–351. https://doi.org/10.1016/j.jclepro.2017.03.032

Shafiei, E., Thorkelsson, H., Ásgeirsson, E. I., Davidsdottir, B., Raberto, M., & Stefansson, H. (2012). An agent-based modeling approach to predict the evolution of market share of electric vehicles: A case study from Iceland. *Technological Forecasting and Social Change*, *79*(9), 1638–1653. https://doi.org/https://doi.org/10.1016/j.techfore.2012.05.011

Shari, B. E., Dioha, M. O., Abraham-Dukuma, M. C., Sobanke, V. O., & Emodi, N. V. (2022). Clean cooking energy transition in Nigeria: Policy implications for Developing countries. *Journal of Policy Modeling*, *44*(2), 319–343. https://doi.org/10.1016/j.jpolmod.2022.03.004

Sharma, A., Shiwang, J., Lee, A., & Peng, W. (2023). Equity implications of electric vehicles: A systematic review on the spatial distribution of emissions, air pollution and health impacts. *Environmental Research Letters*, *18*(5). https://doi.org/10.1088/1748-9326/acc87c

Shaukat, N., Khan, B., Ali, S. M., Mehmood, C. A., Khan, J., Farid, U., … Ullah, Z. (2018). A survey on electric vehicle transportation within smart grid system. *Renewable and Sustainable Energy Reviews*, *81*(February 2016), 1329–1349. https://doi.org/10.1016/j.rser.2017.05.092

Shen, M., Ren, M., Wang, Y., Shen, F., Du, R., Quan, L., … Cao, Z. (2021). Identifying dust as the dominant source of exposure to heavy metals for residents around battery factories in the Battery Industrial Capital of China. *Science of the Total Environment*, *765*, 144375. https://doi.org/10.1016/j.scitotenv.2020.144375

Sheykhha, S., & Madlener, R. (2022). Flexibility scores for energy transition pathways: Integrating socio-technical factors in a long-term energy market model. *Energy Conversion and Management*, *258*(March), 115327. https://doi.org/10.1016/j.enconman.2022.115327

Silva, J. M., Carley, S., & Konisky, D. M. (2023). "I earned the right to build the next American car": How autoworkers and communities confront electric vehicles. *Energy Research and Social Science*, *99*(March), 103065. https://doi.org/10.1016/j.erss.2023.103065

Simões, H. M., & Erbach, G. (2025). *Portugal's Climate Action Strategy*. European Parliamentary Research Service - EPRS.

Singh, M., Tessum, C. W., Marshall, J. D., & Azevedo, I. M. L. (2024). Distributional impacts of fleet-wide change in light duty transportation: mortality risks of PM2.5 emissions from electric vehicles and Tier 3 conventional vehicles. *Environmental Research Letters*, *19*(3). https://doi.org/10.1088/1748-9326/ad2a1f

Sironval, V., Reylandt, L., Chaurand, P., Ibouraadaten, S., Palmai-Pallag, M., Yakoub, Y., … van den Brule, S. (2018). Respiratory hazard of Li-ion battery components: Elective toxicity of lithium cobalt oxide (LiCoO2) particles in a mouse bioassay. *Archives of Toxicology*, *92*(5), 1673–1684. https://doi.org/10.1007/s00204-018-2188-x

Skeete, J. P., Wells, P., Dong, X., Heidrich, O., & Harper, G. (2020). Beyond the EVent horizon: Battery waste, recycling, and sustainability in the United Kingdom electric vehicle transition. *Energy Research and Social Science*, *69*(April), 101581. https://doi.org/10.1016/j.erss.2020.101581

Slattery, M., Kendall, A., Helal, N., & Whittaker, M. L. (2023). What do frontline communities want to know about lithium extraction? Identifying research areas to support environmental justice in Lithium Valley, California. *Energy Research and Social Science*, *99*(March), 103043. https://doi.org/https://doi.org/10.1016/j.erss.2023.103043

Sokołowski, M. M., & Heffron, R. J. (2022). Defining and conceptualising energy policy failure: The when, where, why, and how. *Energy Policy*, *161*(December 2021). https://doi.org/10.1016/j.enpol.2021.112745

Sovacool, B., Hess, D., & Cantoni, R. (2021). Energy transitions from the cradle to the grave: A meta-theoretical framework integrating responsible innovation, social practices, and energy justice. *Energy Research and Social Science*, *75*(March), 102027. https://doi.org/10.1016/j.erss.2021.102027

Sovacool, B. K. (2019). The precarious political economy of cobalt: Balancing prosperity, poverty, and brutality in artisanal and industrial mining in the Democratic Republic of the Congo. *Extractive Industries and Society*, *6*(3), 915–939. https://doi.org/10.1016/j.exis.2019.05.018

Sovacool, B. K. (2021). Who are the victims of low-carbon transitions? Towards a political ecology of climate change mitigation. *Energy Research & Social Science*, *73*(December 2020), 101916. https://doi.org/10.1016/j.erss.2021.101916

Sovacool, B. K., Axsen, J., & Sorrell, S. (2018). Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design. *Energy Research and*

Social Science, *45*(October 2018), 12–42. https://doi.org/10.1016/j.erss.2018.07.007

Sovacool, B. K., & Dworkin, M. H. (2014). Global energy justice. In *Cambridge University Press*. https://doi.org/10.4324/9781315762203

Sovacool, B. K., & Dworkin, M. H. (2015). Energy justice: Conceptual insights and practical applications. *Applied Energy*, *142*, 435–444. https://doi.org/10.1016/j.apenergy.2015.01.002

Sovacool, B. K., Heffron, R. J., McCauley, D., & Goldthau, A. (2016). Energy decisions reframed as justice and ethical concerns. *Nature Energy*, *1*(5), 16024. https://doi.org/10.1038/nenergy.2016.24

Sovacool, B. K., Hook, A., Martiskainen, M., & Baker, L. (2019). The whole systems energy injustice of four European low-carbon transitions. *Global Environmental Change*, *58*(November 2018), 101958. https://doi.org/10.1016/j.gloenvcha.2019.101958

Sovacool, B. K., Hook, A., Martiskainen, M., Brock, A., & Turnheim, B. (2020). The decarbonisation divide: Contextualizing landscapes of low-carbon exploitation and toxicity in Africa. *Global Environmental Change*, *60*(December 2019), 102028. https://doi.org/10.1016/j.gloenvcha.2019.102028

Sovacool, B. K., Kester, J., Noel, L., & de Rubens, G. Z. (2019). Energy Injustice and Nordic Electric Mobility: Inequality, Elitism, and Externalities in the Electrification of Vehicle-to-Grid (V2G) Transport. *Ecological Economics*, *157*(October 2018), 205–217. https://doi.org/10.1016/j.ecolecon.2018.11.013

Sovacool, B. K., Lipson, M. M., & Chard, R. (2019). Temporality, vulnerability, and energy justice in household low carbon innovations. *Energy Policy*, *128*(January), 495–504. https://doi.org/10.1016/j.enpol.2019.01.010

Sovacool, B. K., Martiskainen, M., Hook, A., & Baker, L. (2019). Decarbonization and its discontents: a critical energy justice perspective on four low-carbon transitions. *Climatic Change*, *155*(4), 581–619. https://doi.org/10.1007/s10584-019-02521-7

Spittler, N., Davidsdottir, B., Shafiei, E., & Diemer, A. (2021). Implications of renewable resource dynamics for energy system planning: The case of geothermal and hydropower in Kenya. *Energy Policy*, *150*, 111985. https://doi.org/10.1016/j.enpol.2020.111985

Spittler, N., Davidsdottir, B., Shafiei, E., Leaver, J., Asgeirsson, E. I., & Stefansson, H. (2020). The role of geothermal resources in sustainable power system planning in Iceland. *Renewable Energy*, *153*, 1081–1090. https://doi.org/10.1016/j.renene.2020.02.046

Spittler, N., Gladkykh, G., Diemer, A., & Davidsdottir, B. (2019). Understanding the current energy paradigm and energy system models for more sustainable energy system development. *Energies*, *12*(8). https://doi.org/10.3390/en12081584

Statista. (2023). Production volume of lithium from mines in Portugal from 2010 to 2022. Retrieved from https://www.statista.com/statistics/1280483/lithium-production-in-portugal/

Stefaniec, A., Egan, R., Hosseini, K., & Caulfield, B. (2025). The challenge of making EVs just affordable enough: Assessing the impact of subsidies on equity and emission reduction in Ireland. *Research in Transportation Economics*, *109*(November 2023), 101495. https://doi.org/10.1016/j.retrec.2024.101495

Steinbach, S. A., & Blaschke, M. J. (2024). How grid reinforcement costs differ by the income of electric vehicle users. *Nature Communications*, *15*(1), 9674. https://doi.org/10.1038/s41467-024-53644-0

Sterman, J. (1981). *The Energy Transition and the Economy: A System Dynamics Approach*. Massachusetts Institute of Technology.

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modeling for a complex world*. McGraw-Hill Companies.

Stevis, D., & Felli, R. (2015). Global labour unions and just transition to a green economy. *International Environmental Agreements: Politics, Law and Economics*, *15*(1), 29–43. https://doi.org/10.1007/s10784-014-9266-1

Strapasson, A., Woods, J., Meessen, J., Mwabonje, O., Baudry, G., & Mbuk, K. (2020). EU land use futures: modelling food, bioenergy and carbon dynamics. *ENERGY STRATEGY REVIEWS*, *31*, 100545. https://doi.org/10.1016/j.esr.2020.100545

Stuehlen, C., & Anderl, F. (2024). Transnational companies in environmental conflicts: Rio Tinto, anti-mining resistance in Serbia, and the contradictions of Europeanization. *Zeitschrift Für Friedens- Und Konfliktforschung*. https://doi.org/10.1007/s42597-024-00114-5

Sundaram, A., Huang, Y., Cuppen, E., & Nikolic, I. (2024). Operationalizing justice in models used as decision-support tools in local and regional energy transition planning. *12th International Workshop on Simulation for Energy, Sustainable Development and Environment, SESDE 2024*, 1–10. https://doi.org/10.46354/i3m.2024.sesde.002

Süsser, D., Martin, N., Stavrakas, V., Gaschnig, H., Talens-Peiró, L., Flamos, A., … Lilliestam, J. (2022). Why energy models should integrate social and environmental factors: Assessing user needs, omission impacts, and real-word accuracy in the European Union. *Energy Research and Social Science*, *92*(April). https://doi.org/10.1016/j.erss.2022.102775

Sverdrup, H., Koca, D., & Ragnarsdottir, K. V. (2014). Investigating the sustainability of the global silver supply, reserves, stocks in society and market price using different approaches. *Resources,*

Conservation and Recycling, *83*, 121–140. https://doi.org/https://doi.org/10.1016/j.resconrec.2013.12.008

Sverdrup, Harald U, Ragnarsdottir, K. V., & Koca, D. (2014). On modelling the global copper mining rates, market supply, copper price and the end of copper reserves. *Resources, Conservation and Recycling*, *87*, 158–174. https://doi.org/https://doi.org/10.1016/j.resconrec.2014.03.007

Sverdrup, Harald U, Ragnarsdottir, K. V., & Koca, D. (2015). Aluminium for the future: Modelling the global production, market supply, demand, price and long term development of the global reserves. *Resources, Conservation and Recycling*, *103*, 139–154. https://doi.org/https://doi.org/10.1016/j.resconrec.2015.06.008

Sverdrup, Harald Ulrik. (2016). Modelling global extraction, supply, price and depletion of the extractable geological resources with the LITHIUM model. *Resources, Conservation and Recycling*, *114*, 112–129. https://doi.org/10.1016/j.resconrec.2016.07.002

Syal, S. M., Hennessy, E. M., Carrillo, E., Eggerman, K., & Gerritsen, M. G. (2024). Inclusive community selection for engagement in clean transportation initiatives: A multifaceted approach and case study. *Journal of Cleaner Production*, *472*(August), 143439. https://doi.org/10.1016/j.jclepro.2024.143439

Szarka, N., Wolfbauer, J., & Bezama, A. (2018). A systems dynamics approach for supporting regional decisions on the energetic use of regional biomass residues. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *36*(4), 332–341. https://doi.org/10.1177/0734242X18757626

Szulecki, K. (2018). Conceptualizing energy democracy. *Environmental Politics*, *27*(1), 21–41. https://doi.org/10.1080/09644016.2017.1387294

Tabelin, C. B., Dallas, J., Casanova, S., Pelech, T., Bournival, G., Saydam, S., & Canbulat, I. (2021). Towards a low-carbon society: A review of lithium resource availability, challenges and innovations in mining, extraction and recycling, and future perspectives. *Minerals Engineering*, *163*(February), 106743. https://doi.org/10.1016/j.mineng.2020.106743

Thomson, I., & Boutilier, R. G. (2011). Social license to operate. *SME Mining Engineering Handbook*, *1*, 1779–1796.

Toka, A., Iakovou, E., Vlachos, D., Tsolakis, N., & Grigoriadou, A.-L. L. (2014). Managing the diffusion of biomass in the residential energy sector: An illustrative real-world case study. *Applied Energy*, *129*(2014), 56–69. https://doi.org/https://doi.org/10.1016/j.apenergy.2014.04.078

Trutnevyte, E., Hirt, L. F., Bauer, N., Cherp, A., Hawkes, A., Edelenbosch, O. Y., ... van Vuuren, D. P.

(2019). Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. *One Earth*, *1*(4), 423–433. https://doi.org/10.1016/j.oneear.2019.12.002

Tsukiji, T., Zhang, N., Jiang, Q., He, B. Y., & Ma, J. (2023). A Multifaceted Equity Metric System for Transportation Electrification. *IEEE Open Journal of Intelligent Transportation Systems*, *4*, 690 – 707. https://doi.org/10.1109/OJITS.2023.3311689

UN Environment Programme. (2020). *Used vehicles and the Environment - A global overview of used light duty vehicles: Flow, Scale and Regulation*.

UNDP and UN Environment. (2018). *Managing mining for sustainable development: A sourcebook* (p. 116). p. 116. Bangkok: United Nations Development Programme. Retrieved from http://transparency.org.au/our-work/mining-for-sustainable-development/

US Geological Survey. (2021). *Mineral Commodity Summaries*. Retrieved from https://doi.org/10.3133/mcs2021

Valencia, V., Olaya, Y., & Arango-Aramburo, S. (2023). Is switching propulsion technologies the path to sustainable land transport? decarbonizing Bogotá. *Transportation Research Part D: Transport and Environment*, *122*(August), 103890. https://doi.org/10.1016/j.trd.2023.103890

Van Uffelen, N., Taebi, B., & Pesch, U. (2024). Revisiting the energy justice framework: Doing justice to normative uncertainties. *Renewable and Sustainable Energy Reviews*, *189*(PA), 113974. https://doi.org/10.1016/j.rser.2023.113974

Varghese, A. M., Menon, N., & Ermagun, A. (2024). Equitable distribution of electric vehicle charging infrastructure: A systematic review. *Renewable and Sustainable Energy Reviews*, *206*(August), 114825. https://doi.org/10.1016/j.rser.2024.114825

Vasovic, A., Sekularac, I., & Adler, L. (2024). Thousands in Serbia rally against Rio Tinto mine project. Retrieved December 4, 2024, from Reuters website: https://www.reuters.com/world/europe/thousands-serbia-rally-against-rio-tinto-mine-project-2024-07-29/

Vega-Perkins, J., Newell, J. P., & Keoleian, G. (2023). Mapping electric vehicle impacts: greenhouse gas emissions, fuel costs, and energy justice in the United States. *Environmental Research Letters*, *18*(1), 014027. https://doi.org/10.1088/1748-9326/aca4e6

Verrier, B., Smith, C., Yahyaei, M., Ziemski, M., Forbes, G., Witt, K., & Azadi, M. (2022). Beyond the social license to operate: Whole system approaches for a socially responsible mining industry. *Energy Research and Social Science*, *83*(September 2021), 102343. https://doi.org/10.1016/j.erss.2021.102343

Verrier, B., & Strachan, N. (2024). Sunset and sunrise business strategies shaping national energy transitions. *Renewable and Sustainable Energy Reviews*, *195*, 114330. https://doi.org/10.1016/j.rser.2024.114330

Visa, M. A., Camilleri, S. F., Montgomery, A., Schnell, J. L., Janssen, M., Adelman, Z. E., ... Horton, D. E. (2023). Neighborhood-scale air quality, public health, and equity implications of multi-modal vehicle electrification. *Environmental Research: Infrastructure and Sustainability*, *3*(3). https://doi.org/10.1088/2634-4505/acf60d

Walker, G. (2009). Beyond distribution and proximity: exploring the multiple spatialities of environmental justice. *Antipode*, *41*(4), 614–636.

Walzer, M. (1995). Thick and thin: Moral argument at home and abroad. *Philosophy*, *70*(273), 472–475.

Wang, X., & Lo, K. (2021). Just transition: A conceptual review. *Energy Research and Social Science*, *82*(March), 102291. https://doi.org/10.1016/j.erss.2021.102291

Wen, W., Yang, S., Zhou, P., & Gao, S. Z. (2021). Impacts of COVID-19 on the electric vehicle industry: Evidence from China. *Renewable and Sustainable Energy Reviews*, *144*(July 2020), 111024. https://doi.org/10.1016/j.rser.2021.111024

Williams, B. D. H. H. (2023). Assessing progress and equity in the distribution of electric vehicle rebates using appropriate comparisons. *Transport Policy*, *137*(April), 141–151. https://doi.org/10.1016/j.tranpol.2023.04.009

Wolters, L., & Brusselaers, J. (2024). The energy transition paradox: How lithium extraction puts pressure on environment, society, and politics. *Extractive Industries and Society*, *19*(June), 101498. https://doi.org/10.1016/j.exis.2024.101498

Wood, J., & Jain, A. (2021). Raceways, rebates, and retrofits: an exploration of several American cities' policies to facilitate electric vehicle purchase and usage. *International Journal of Urban Sustainable Development*, *13*(2), 148 – 158. https://doi.org/10.1080/19463138.2020.1843467

Wood, N., van Uffelen, N., Frigo, G., Melin, A., Milchram, C., Lee, J., & Bessa, S. (2024). Strengthening the foundations of energy justice scholarship: What can philosophy contribute? *Energy Research and Social Science*, *117*(August). https://doi.org/10.1016/j.erss.2024.103699

Wu, D., & Ning, S. (2018). Dynamic assessment of urban economy-environment-energy system using system dynamics model: A case study in Beijing. *Environmental Research*, *164*, 70–84. https://doi.org/10.1016/j.envres.2018.01.029

Wu, H., Peng, D., & Wang, L. (2021). Model for sustainable development based on system dynamics and energy–economy–environment coordination: A case study of Beijing, China. *Energy Science and*

Engineering, *9*(6), 828–842. https://doi.org/10.1002/ese3.837

Wu, Z., & Xu, J. (2013). Predicting and optimization of energy consumption using system dynamics-fuzzy multiple objective programming in world heritage areas. *Energy*, *49*(1), 19–31. https://doi.org/10.1016/j.energy.2012.10.030

Xiong, S., Ji, J., & Ma, X. (2019). Comparative life cycle energy and GHG emission analysis for BEVs and PHEVs: A case study in China. *Energies*, *12*(5), 1–17. https://doi.org/10.3390/en12050834

Zeng, Y., Liu, D., Guo, S., Xiong, L., Liu, P., Yin, J., & Wu, Z. (2022). A system dynamic model to quantify the impacts of water resources allocation on water–energy–food–society (WEFS) nexus. *Hydrology and Earth System Sciences*, *26*(15), 3965–3988. https://doi.org/10.5194/hess-26-3965-2022

Zhang, A., Measham, T. G., & Moffat, K. (2018). Preconditions for social licence: The importance of information in initial engagement. *Journal of Cleaner Production*, *172*, 1559–1566. https://doi.org/10.1016/j.jclepro.2017.10.323

Zhang, A., Moffat, K., Lacey, J., Wang, J., González, R., Uribe, K., ... Dai, Y. (2015). Understanding the social licence to operate of mining at the national scale: a comparative study of Australia, China and Chile. *Journal of Cleaner Production*, *108*, 1063–1072. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.07.097

Zhang, Y., & Fan, Y. (2025). Equity evaluation of community-based public EV charging services – A case study of the Sacramento region. *Energy Policy*, *198*(March 2024), 114495. https://doi.org/10.1016/j.enpol.2025.114495

Zhao, Y., Pohl, O., Bhatt, A. I., Collis, G. E., Mahon, P. J., Rüther, T., & Hollenkamp, A. F. (2021). A Review on Battery Market Trends, Second-Life Reuse, and Recycling. *Sustainable Chemistry*, *2*(1), 167–205. https://doi.org/10.3390/suschem2010011

Zhou, Y., & Cao, S. (2019). Energy flexibility investigation of advanced grid-responsive energy control strategies with the static battery and electric vehicles: A case study of a high-rise office building in Hong Kong. *Energy Conversion and Management*, *199*(August), 111888. https://doi.org/10.1016/j.enconman.2019.111888

Ziemele, J., & Dace, E. (2022). An analytical framework for assessing the integration of the waste heat into a district heating system: Case of the city of Riga. *Energy*, *254*, 124285. https://doi.org/10.1016/j.energy.2022.124285

10 Appendixes

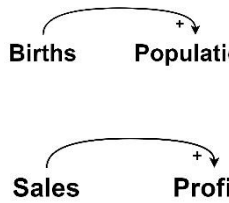
10.1 Appendix I. System Dynamics Modeling

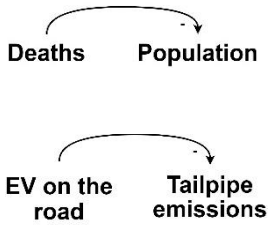
According to Haraldsson and Sverdrup, a "*model is a simplified representation of real-world phenomena and the consequence or interpretations as the result of a set of observations or experiences. [...] models are first and foremost mental models, a conceptual understanding of a system that in a continuation phase can be converted into mathematical models*" (Haraldsson & Sverdrup, 2021, p. 14). The conceptual limitations of models are perhaps more evident in system dynamics models than other modeling approaches. This is because system dynamics models can be considered "*white-box*" models in opposition to "*black-box*" models (Barlas, 1996) – they attempt to explain the mechanisms and causal relations that give rise to a certain behavior instead of assuming an input generates an output through a mathematical relation. In this regard, system conceptualization has an incredibly important role in system dynamics modeling. One of the systems thinking tools available to aid the modeling conceptualization phase is CLDs.

10.1.1 Causal loop diagrams

CLDs consist of cause-and-effect diagrams in which variable *A* is causally linked to variable *B*, this causal link is represented by an arrow. Causal relationships are defined based on the theoretical and empirical knowledge that exists about the system (i.e., literature, reports, experts' opinion, stakeholder feedback, etc.). Each causal link is understood as a holder of a polarity that can be positive (+) or negative (-). This polarity indicates how the dependent variable changes with changes in the independent variable as explained in **Table 10-1**.

Table 10-1. Definitions and examples of positive (+) and negative (-) link polarities. Source: Adapted from (Sterman, 2000).

Symbol	Interpretation	Mathematics	Examples
	All else equal, if A increases (decreases), then B increases (decreases). In the case of accumulations, A adds to B.	$\partial B/\partial A > 0$ In the case of accumulations, $B = \int_{t_0}^{t} (A + \cdots) ds + B_{t_0}$	

	All else equal, if A increases (decreases), then B decreases (increases). In the case of accumulations, A subtracts from B.	$\partial B/\partial A > 0$ In the case of accumulations, $B = \int_{t_0}^{t} (-A + \cdots) ds + B_{t_0}$	

A closed chain of causality forms a feedback loop, which can be reinforcing (R) or balancing (B). A feedback loop is defined as reinforcing or balancing after tracing how effect changes in one variable propagate around it. If the feedback reinforces the original change, it is a positive or reinforcing loop (e.g., exponential growth or decay); if it opposes the original change, it is a negative or balancing loop (e.g., goal-seeking behavior) (Sterman, 2000). There is also a more technical understanding of loop polarity based on control theory (Sterman, 2000), which is not discussed herein. **Figure 10-1** presents the population example to illustrate a reinforcing and a balancing feedback loop: The larger the population, more births, and the population increases (R); The larger the population, more deaths, and the population decreases (B).

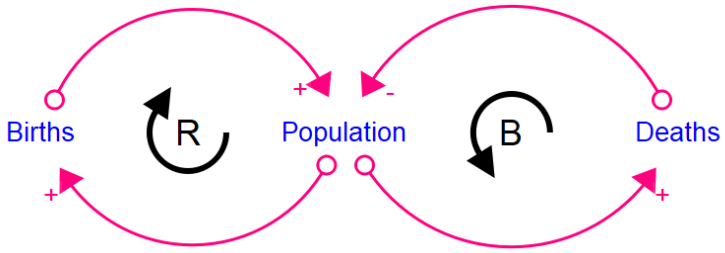


Figure 10-1. Example of a balancing (B) and a reinforcing (R) feedback loop. CLD developed in Stella Architect software.

In tandem with feedback loops, time delays create important dynamic aspects within systems. "*Delays give systems inertia, can create oscillations, and are often responsible for trade-offs between the short- and long-run effects of policies*" (Sterman, 2000, p. 150). In a CLD, they are visually represented as two bars "||" over an arrow, representing a delayed cause-and-effect relationship in face of the considered time horizon. For instance, a delay of two days in a time horizon of 10 years is not significant, whereas the same delay is critical within one week. In summary, these are the main components of a CLD:

variables, arrows, polarities, feedback loops, and delays. A CLD was employed in **Chapter 6** to capture the dynamics between mining, social acceptance, economic and environmental impacts.

Furthermore, CLDs can aid the development of a dynamic hypothesis for the system dynamics model under development and aid the establishment of reference modes for the key model variables (Haraldsson & Sverdrup, 2021). In other words, they help open the "*white box*" of system dynamics models. However, they are not able to quantify system elements or differentiate between variable types. In this regard, SFDs become useful.

10.1.2 Stock-and-flow diagrams

Although SFDs can be understood as visual representations of the system under analysis just like CLDs, they have a key difference in the way the system structure is represented. SFDs are composed by stocks, flows, and converters or auxiliary variables, and they bring more attention to accumulation and flow processes (Sterman, 2000). Stocks represent accumulation in the system; thus their future behavior is impacted by its "*history*" or "*memory*". They can be tangible (e.g., carbon emissions) or intangible (e.g., social stress (Jay W. Forrester, 1971)). Flows modify stock values through inflows, which represents the rate at which the stock increases over time, and outflows, which represents the rate at which the stock decreases over time. **Figure 10-2** illustrates the notation of stocks and flows and provides an example using the account balance in a bank. The balance increases with deposits of money and decreases with withdrawals. The "*clouds*" in **Figure 10-2** represents what is out of the modeling boundary or out of scope.

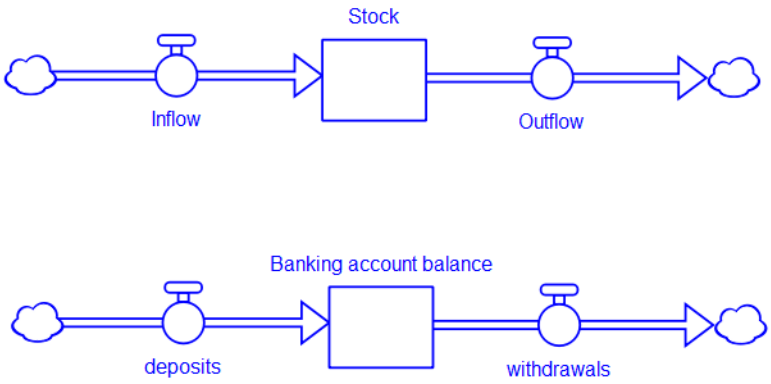


Figure 10-2. Standard notation and example of stocks and flows in a SFD, developed in Stella Architect software.

Mathematically speaking, a stock is the integral of the net flow added to the initial value of the stock, as shown in **Equations 10-1 and 10-2** in its integrative and derivative form, respectively.

$$Stock\ (t) = \int_{t_0}^{t} [Inflow(t) - Outflow(t)]\, dt + Stock(t_0) \qquad \textbf{(Equation 10-1)}$$

$$\frac{d(Stock)}{dt} = Inflow(t) - Outflow(t) \qquad \textbf{(Equation 10-2)}$$

A system dynamics model typically uses the structure from the SFD but goes a step further by defining the mathematical relationships between variables and running simulations to study the system's behavior.

10.1.3 Simulation

A system dynamics model consists of a system of nonlinear differential and integral equations (Choopojcharoen & Magzari, 2012, p. 7), which are solved numerically using methods such as Euler and Runge-Kutta. These methods approximate solutions to differential equations representing the behavior of stocks over time, from an initial time (t_0) until the end of the simulation (t_n). The choice of the integration method affects the accuracy of the simulation, especially through the choice of an appropriate time step Δt.

Let's assume the net rate of change ($netflow(t) = inflow(t) - outflow(t)$) to a stock is given by $\frac{dS}{dt} = f(S,t)$, where S is the amount in the stock, t is time, and $f(S,t)$ is a function that depends on S and t.

According to Euler's method, $\frac{dS}{dt}$ can be approximated by **Equation 10-3** for a very small time step Δt:

$$\frac{dS}{dt} \approx \frac{\Delta S}{\Delta t} = \frac{S_{k+1} - S_k}{t_{k+1} - t_k} = f(S_k, t_k) \qquad \textbf{(Equation 10-3)}$$

Where S_{k+1} is the stock at time t_{k+1} and S_k is the stock at the time t_k. Therefore, the stock value at time t (S_t) is given by **Equations 10-4** and **10-5**:

$$S_{k+1} = S_k + (t_{k+1} - t_k).f(S_k, t_k) \quad \textbf{(Equation 10-4)}$$

$$S_{k+1} = S_k + f(S_k, t_k).\Delta t \quad \textbf{(Equation 10-5)}$$

Assuming the initial stock at time t_0 is S_0, **Equation 10-6** shows the stock at the first time step S_1 as equal to:

$$S_1 = S_0 + f(S_0, t_0).\Delta t \quad (\textbf{Equation 10-6})$$

Likewise, S_2 represents the value of the stock at the second time step Δt, which is given by **Equation 10-7**:

$$S_2 = S_1 + f(S_1, t_1).\Delta t \quad (\textbf{Equation 10-7})$$

Where $t_1 = t_0 + \Delta t$.

Conversely, the 2nd-order Runge-Kutta (RK2) method calculates an intermediate slope (m) equal to the average between k_1 and k_2 to improve the estimate of the next value according to **Equations 10-8, 10-9 and 10-10**.

$$k_1 = f(S_n, t_n) \quad \textbf{(Equation 10-8)}$$

$$k_2 = f(S_n + \Delta t_n \cdot k_1, t_n + \Delta t,) \quad \textbf{(Equation 10-9)}$$

$$S_{n+1} = S_n + \frac{(k_1 + k_2)}{2} \cdot \Delta t = S_n + m \cdot \Delta t \quad \textbf{(Equation 10-10)}$$

Where k_1 is the slope at the current point, k_2 is the slope at the next point, using the information from k_1, and m is the average of both slopes.

Although Euler's method is the simplest numerical method for solving ordinary differential equations, RK2 is more accurate than Euler's. One particularity of numerical integration methods, Euler's method in particular, refers to the size of the time step. The time step must be small enough to minimize the error

between the real and the mathematical solution of the differential equation. This aspect will be demonstrated with the following example.

Example: Assuming the net flow of a stock S is given by $\frac{dS}{dt} = 0.2 \cdot S$ with an initial value $S(0) = S_0 = 1$, the analytical solution of this differential equation is given by **Equation 10-11**:

$$S(t) = e^{0.2 \cdot t} \qquad \textbf{(Equation 10-11)}$$

Nonetheless, let's calculate the value of S over the time range from $t = 0$ to $t = 2$ using a time step $\Delta t = 1$ using Euler's method, as shown in **Equations 10-12, 10-13, and 10-14**.

$$S_1 = S_0 + f(S_0, t_0).\Delta t \qquad \textbf{(Equation 10-12)}$$

$$S_1 = 1 + (0.2 \cdot 1) \cdot 1 = 1.2, t_1 = 1.2 \qquad \textbf{(Equation 10-13)}$$

$$S_2 = S_1 + f(S_1, t_1).\Delta t = 1.2 + (0.2 \cdot 1.2) \cdot 1 = 1.44, t_2 = 2 \qquad \textbf{(Equation 10-14)}$$

Therefore, the value of the stock at time $t_2 = 2$ is $S_2 = 1.44$ when the time step is 1.

Now, let's consider a time step $\Delta t = 0.5$. The calculation process for this time step is given in **Equations 10-15, 10-16, 10-17, and 10-18**.

$$S_1 = 1 + (0.2 \cdot 1) \cdot 0.5 = 1.1\ ,\ t_1 = 0.5 \qquad \textbf{(Equation 10-15)}$$

$$S_2 = S_1 + f(S_1, t_1).\Delta t = 1.1 + (0.2 \cdot 1.1) \cdot 0.5 = 1.21,\ t_2 = 1 \qquad \textbf{(Equation 10-16)}$$

$$S_3 = S_2 + f(S_2, t_2).\Delta t = 1.21 + (0.2 \cdot 1.21) \cdot 0.5 = 1.331,\ t_3 = 1.5 \qquad \textbf{(Equation 10-17)}$$

$$S_4 = S_3 + f(S_3, t_3).\Delta t = 1.331 + (0.2 \cdot 1.331) \cdot 0.5 = 1.464,\ t_4 = 2 \qquad \textbf{(Equation 10-18)}$$

Therefore, the value of the stock at time $t_4 = 2$ is $S_4 = 1.464$ when $\Delta t = 0.5$. Conversely, the value according to the analytical solution of the differential equation $S(t) = e^{0.2t}$ at $t = 2$ is approximately 1.4918. Consequently, using a smaller step size gives a slightly more accurate result.

Now, let's calculate the value of S at $t = 2$ using the RK2 method. The slope at the starting time (k_1) is given by **Equation 10-19**.

$$k_1 = \frac{dS}{dt_0} = 0.2 \cdot S_0 = 0.2 \cdot 1 = 0.2 \quad \textbf{(Equation 10-19)}$$

The stock value at the next time step using Euler's method is equal to **Equation 10-20** and the slope at the next time step is given by **Equation 10-21**:

$$S_1 = S_0 + k_1.\Delta t = 1 + (0.2) \cdot 1 = 1.2 \quad \textbf{(Equation 10-20)}$$

$$k_2 = \frac{dS}{dt_{0+\Delta t}} = 0.2 \cdot S_1 = 0.2 \cdot 1.2 = 0.24 \quad \textbf{(Equation 10-21)}$$

Therefore, the average slope (m) is given by **Equation 10-22**.

$$m = \frac{(k_1 + k_2)}{2} = \frac{(0.2 + 0.24)}{2} = 0.22 \quad \textbf{(Equation 10-22)}$$

And the stock value at $t = 1$ is equal to the stock value at the initial time (S_0) plus the average slope (m) times the time step (Δt), as shown in **Equation 10-23**:

$$S_1 = S_0 + m.\Delta t = 1 + (0.22) \cdot 1 = 1.22 \quad \textbf{(Equation 10-23)}$$

The same process is repeated for $t = 2$ in **Equations 10-24, 10-25, 10-26, 10-27, and 10-28**.

$$k_1 = \frac{dS}{dt_1} = 0.2 \cdot S_1 = 0.2 \cdot 1.22 = 0.244 \quad \textbf{(Equation 10-24)}$$

$$S_2 = S_1 + k_1.\Delta t = 1.22 + (0.244) \cdot 1 = 1.464 \quad \textbf{(Equation 10-25)}$$

$$k_2 = \frac{dS}{dt_1} = 0.2 \cdot S_2 = 0.2 \cdot 1.464 = 0.2928 \quad \textbf{(Equation 10-26)}$$

$$m = \frac{(k_1 + k_2)}{2} = \frac{(0.244 + 0.2928)}{2} = 0.2684 \quad \textbf{(Equation 10-27)}$$

$$S_2 = S_1 + m.\Delta t = 1.22 + (0.2684) \cdot 1 = 1.4884 \quad \textbf{(Equation 10-28)}$$

Therefore, the value of stock S at time $t = 2$ is 1.4884 according to the RK2 method with a time step of 1 and a percentage error $(\delta = |v_A - v_E|/v_E)$ of 0.22% . Compared to the results obtained with Euler's method with $\Delta t = 1$ $(\delta = 3.47\%)$ and $\Delta t = 0.5$ $(\delta = 1.86\%)$, it becomes clear that RK2 is more accurate than Euler's even when employing a larger or similar time step. Nonetheless, RK2 is more computationally demanding than Euler's method.

Both integration methods are available in system dynamics software, such as Vensim and iSee Stella, both used in the development of this thesis. Regarding the time step size, it is recommended that the time step assume values between one-fourth and one-tenth the size of the smallest time constant in the model (Sterman, 2000). Nevertheless, it is important to mention that the total numerical error in a simulation consists of the integration and the round-off error (Sterman, 2000). The latter implies that simulation accuracy cannot be increased by arbitrarily decreasing the time step, as smaller time steps can actually increase the cumulative effects of rounding-off, surpassing the integration error reduction. Therefore, there is a trade-off between both errors, which may decrease with faster and enhanced computers that handle smaller time steps and more precision points (Sterman, 2000).

In summary, a system dynamics model is a mathematical or computational model that simulates the behavior of a system over time, from an initial time (t_0) until the end of the simulation (t_n) using a time step (Δt) and a numerical method to solve the system of differential equations. As a simulation tool, system dynamics helps test scenarios, study the effects of policy changes, and understand the behavior of complex systems over time by simulating the real-world dynamics of those systems. Applications of system dynamics models can be found in **Chapters 6 and 7**.

10.2 Appendix II. Ethical Approval



Universidade do Minho

Conselho de Ética

Comissão de Ética para a Investigação em Ciências Sociais e Humanas

Identificação do documento: CEICSH 070/2023

Título do projeto: *Explorando os impactos sistêmicos de um setor de transporte de baixa emissão: Caminhos para uma transição energética justa (Exploring the Systemic Impacts of a Low-emission Transport Sector: Pathways to a Just Energy Transition)*

Equipa de investigação: Alaize Dall'Orsoletta (IR), Programa Doutoral em Engenharia Industrial e de Sistemas, Escola de Engenharia, Universidade do Minho; Paula Fernanda Varandas Ferreira (Orientadora), Escola de Engenharia, Universidade do Minho; Géremi Gilson Dranka (Orientador), Universidade Tecnológica Federal do Paraná, Brasil

PARECER

A Comissão de Ética para a Investigação em Ciências Sociais e Humanas (CEICSH) analisou o processo relativo ao projeto de investigação acima identificado, intitulado *Explorando os impactos sistêmicos de um setor de transporte de baixa emissão: Caminhos para uma transição energética justa.*

Os documentos apresentados revelam que o projeto obedece aos requisitos exigidos para as boas práticas na investigação com humanos, em conformidade com as normas nacionais e internacionais que regulam a investigação em Ciências Sociais e Humanas.

Face ao exposto, a Comissão de Ética para a Investigação em Ciências Sociais e Humanas (CEICSH) nada tem a opor à realização do projeto nos termos apresentados no Formulário de Identificação e Caracterização do Projeto, que se anexa, emitindo o seu parecer favorável, que foi aprovado por unanimidade pelos seus membros.

O Presidente da CEICSH

Assinado por: EMANUEL PEDRO VIANA BARBAS DE ALBUQUERQUE
Num. de identificação: [illegible]
Data: 2023.07.05 10:43:33 +01'00'

Anexo: Formulário de identificação e caracterização do projeto

Comissão de Ética para a Investigação em Ciências Sociais e Humanas (CEICSH)

Universidade do Minho

Formulário de identificação e caracterização do projeto

Identificação do projeto

Título do projeto	**Exploring the Systemic Impacts of a Low-emission Transport Sector: Pathways to a Just Energy Transition** *(Explorando os impactos sistémicos de um setor de transporte de baixa emissão: Caminhos para uma transição energética justa)*		
Data prevista de início	**01/11/2022**	**Data prevista fim**	**01/11/2025**

Investigador principal e filiação	Alaize Dall'Orsoletta, Programa Doutoral em Engenharia Industrial e de Sistemas, Universidade do Minho
Orientador(es) e filiação	Paula Varandas Ferreira, Universidade do Minho Géremi Gilson Dranka, Universidade Tecnológica Federal do Paraná UTFPR

Nota: No caso de projetos de mestrado ou doutoramento deve ser indicado o estudante como investigador principal e o nome do mestrado ou doutoramento

Instituição proponente	Universidade do Minho
Instituição(ões) onde se realiza a investigação	Universidade do Minho

Entidades financiadoras	Fundação para a Ciência e Tecnologia – FCT, Bolsa de Doutoramento (Ref. 2022.11468.BD)

Questões relativas ao envolvimento de investigadores exteriores		
Estão envolvidos no projeto, colegas de outra (s) Escola(s)/Instituição(ões)?	S	**N**
Se sim, este pedido de parecer cobre o seu envolvimento?	S	**N**

Qualificação dos investigadores

Alaize Dall'Orsoletta é estudante de doutoramento em Engenharia Industrial e Sistemas na Universidade do Minho, especializada em Gerenciamento de Projetos (2020, Greyztone College), e bacharel em Engenharia de Petróleo (2019, Universidade do Estado de Santa Catarina). Atualmente, é bolsista de doutoramento pela FCT

(2022.11468.BD) a pesquisar os impactos socioeconómicos da expansão dos veículos elétricos ao longo do ciclo de vida da tecnologia com o auxílio da ferramenta de dinâmica de sistemas. Aloiza tem dois cursos em dinâmica de sistemas (2022, University of Bergen e 2023, ATC-Innova) e quatro publicações em revistas internacionais de alto impacto. O presente projeto é crucial para a validação metodológica de sua fase de doutoramento. Como investigadora responsável, Aloiza será responsável por: identificar e contatar participantes, formalizar procedimentos, organizar encontros, realizar entrevistas e moderar workshops, manter e analisar dados, desenvolver modelos de dinâmica de sistemas, simular e sintetizar resultados, projetar e escrever publicações científicas.

Paula Varandas Ferreira é Ph.D. em Engenharia Industrial e Sistemas (2008, Universidade do Minho), Mestre em Gestão Financeira (2002, Universidade do Porto) e Licenciada em Engenharia Química (1995, Universidade do Porto). Atualmente, é professora associada do Departamento de Produção e Sistemas da Escola de Engenharia da Universidade do Minho, investigadora do Centro de Investigação ALGORITMI, e diretora do Programa Doutoral em Engenharia Industrial e Sistemas desde 2019. Os seus interesses de investigação são a avaliação do impacto socioeconómico de sistemas industriais e energéticos, planeamento energético e avaliação de projetos alinhados com os objetivos de desenvolvimento sustentável. Já supervisou no papel de orientadora e co-orientadora 16 alunos de doutoramento e 45 de mestrado. Já participou em vários projetos nacionais e internacionais em que efetuou-se a coleta de dados por meio de questionários e entrevistas, os quais resultaram em publicações internacionais. Tem uma vasta rede de contatos no setor industrial, académico e governamental e ampla experiência em trabalhar com diferentes stakeholders. Como orientadora, Paula será responsável por: coordenar e supervisar o projeto, ajudar a identificar e contatar potenciais participantes, ajudar a definir o protocolo das entrevistas e workshops, manter os dados em confidencialidade, contribuir para a conceptualização dos modelos de dinâmica de sistemas, e projetar e escrever publicações científicas.

Géremi Gilson Dranka é Ph.D. em Engenharia Industrial e Sistemas (2021, Universidade do Minho), Mestre em Engenharia Elétrica (2014, UTFPR) e Bacharel em Engenharia Elétrica (2012, UTFPR). Atualmente é pesquisador do Centro de Investigação ALGORITMI e Professor Adjunto do Departamento de Engenharia Elétrica da Universidade Tecnológica Federal do Paraná (UTFPR). Seus interesses de pesquisa e especialização estão relacionados à energia, incluindo energia renovável, planeamento energético e abordagens multidisciplinares para sustentabilidade energética. Já supervisou no papel de orientador e co-orientador mais de 10 alunos de graduação e 1 de doutoramento. Tem várias publicações em revistas internacionais e já participou em vários projetos em que efetuou-se coleta de dados por meio de questionários e entrevistas. Tem uma rede de contatos considerável na academia e indústria. Como co-orientador, Géremi será responsável por: coordenar o projeto, ajudar a identificar e contatar potenciais participantes, ajudar a definir o protocolo das entrevistas e workshops, manter os dados em confidencialidade, contribuir para a conceptualização dos modelos de dinâmica de sistemas, e projetar e escrever publicações científicas.

Caracterização do projeto e questões de carácter ético relativas à sua execução

Introdução justificativa do projeto e sumário dos seus objetivos

O projeto tem como objetivo geral avaliar os impactos socioeconómicos da expansão de veículos elétricos em Portugal, considerando as diferentes etapas do ciclo de vida dessa tecnologia. A minimização dos impactos negativos desta mudança tecnológica está diretamente relacionada com uma transição energética justa. Para a análise, são consideradas as etapas envolvidas no ciclo de vida dos veículos elétricos, incluindo a extração e refino de matéria-prima, a manufatura, a operação e o fim de vida, bem como as atividades relacionadas a essas etapas que são mais relevantes em Portugal. Isso inclui a mineração de lítio (**Etapa 1**), a expansão do setor automotivo (**Etapa 2**) e a utilização de veículos elétricos, bem como a gestão de resíduos de baterias (**Etapa 3**).

Estas atividades serão avaliadas separadamente e modeladas com o auxílio da ferramenta de dinâmica de sistemas, que permite a modelagem e simulação de problemas complexos e não-lineares. O desenvolvimento dos modelos conta com o processo de validação e recolha de opiniões junto a especialistas (i.e., pessoas com conhecimento sobre as diferentes etapas, sejam elas da indústria, academia, ou outras organizações) através da realização de entrevistas semiestruturadas online e/ou presenciais e workshops online e/ou presenciais, a serem conduzidos durante as diferentes etapas da pesquisa (i.e., **Etapa 1, 2, e 3**).

Participantes

a) Os participantes do estudo serão especialistas de diferentes áreas e *backgrounds* conforme o foco da etapa da pesquisa (i.e., Etapa 1, 2, e 3), como melhor descrito na secção "Procedimento". Não há qualquer critério de exclusão em relação a sexo, etnia, língua materna e nível educacional.
b) Apenas pessoas maiores de idade, saudáveis, e voluntários poderão participar nas entrevistas.
c) Os participantes poderão realizar as entrevistas em português ou inglês de acordo com as suas preferências.
d) Não deseja-se efetuar qualquer tipo de análise estatística sobre os dados recolhidos, assim que a amostra de participantes não será definida por meio de métodos estatísticos.
e) A amostra de participantes não será pré-determinada, mas sim estabelecida iterativamente conforme os *insights* emergentes e o conceito de *data saturation*, como sugerido pelo método de *Purposeful Sampling*. Este método permite que o investigador responsável selecione deliberadamente os participantes que possuam conhecimento sobre o sistema a ser modelado. Conforme o progresso das entrevistas, os dados coletados são analisados continuamente de forma a identificar temas emergentes e verificar se novas informações ainda estão sendo obtidas dos participantes. Se novos participantes fornecerem perspetivas e *insights* similares àquelas já entrevistados, isto sugere que o ponto de *data saturation* foi alcançado e o tamanho da amostra é suficiente. Entretanto, se novas informações continuarem a surgir a partir das entrevistas adicionais, isto sugere que o ponto de *data saturation* não foi atingido e a amostra deve ser expandida de forma a assegurar um conhecimento abrangente do sistema a ser modelado.

Recrutamento e triagem

- Potenciais participantes serão identificados por meio de existentes networks do investigador responsável, da sua orientadora, e do seu coorientador, por meio de publicações anteriores (no caso de pesquisadores e académicos), assim como sugestões dos próprios participantes.
- De acordo com as diferentes etapas do projeto, especialistas de diferentes *backgrounds* serão convidados a participar no estudo, como explicado a seguir:
  Etapa 1) Especialistas da área de mineração e preocupados com aspetos sustentáveis da mineração, incluindo profissionais da indústria e académicos, governo, organizações não-governamentais, e associações.
  Etapa 2) Especialistas do setor automóvel e preocupados com o desenvolvimento sustentável do setor, incluindo profissionais da indústria e académicos, governo, e associações.
  Etapa 3) Especialistas do setor elétrico e automóvel e pessoal envolvido na expansão da frota de veículos elétricos, incluindo profissionais da indústria e académicos, governo, e associações.
- O processo de identificação e primeiro contato com potenciais participantes será feito entre os meses de Abril de 2023 e Outubro de 2024 para as Etapas 1, 2 e 3 e será formalizado via email enviado pelo investigador responsável. O email contará com uma breve apresentação do investigador responsável e disponibilizará um breve sumário do projeto e da Etapa em questão (i.e., Etapa 1, 2, ou 3). Emails serão enviados em inglês e português.

- Sendo a colaboração voluntária, os participantes serão livres para decidir se participam ou não no estudo.
- Caso decidam participar, será enviado ao participante um email com o consentimento informado (em inglês ou português, de acordo com a preferência de idioma do participante). Quando as entrevistas e workshops forem presenciais, será solicitado aos participantes que assinem o consentimento informado "Consentimento Informado – Presencial", em anexo. Para encontros online, ao participar das entrevistas marcadas os participantes dão consentimento aos termos do estudo, como esclarecido no anexo "Consentimento Informado – Online".

Compensação e custos

a) Não será oferecida qualquer tipo de compensação pela participação no estudo.
b) Não haverá qualquer custo para os participantes.

Procedimento

Segue a descrição do procedimento referente às diferentes etapas da pesquisa (i.e., Etapas 1, 2, e 3) e suas estimadas durações, passíveis de modificação durante o decorrer do projeto:

Etapa 1 (01/04/2023 a 01/05/2023)

a) Identificar potenciais participantes (i.e., especialistas da área de mineração e preocupados com aspetos sustentáveis da mineração, incluindo profissionais da indústria e académicos, governo, organizações não-governamentais, e associações) por meio de existentes networks do investigador responsável, da sua orientadora, e do seu coorientador, por meio de publicações anteriores (no caso de pesquisadores e académicos), assim como sugestões dos próprios participantes.
b) O investigador responsável irá contatar potenciais participantes via email, telemóvel, ou presencialmente em inglês ou português, apresentando-se, esclarecendo o objetivo do projeto e da etapa em questão, perguntando sobre o interesse em participar e sobre o conhecimento de outras pessoas com *background* apropriado e possível interesse em participar do estudo.
c) Caso o sujeito concorde em participar no estudo, será enviado por e-mail o consentimento informado. Em seguida, será agendado o dia e horário da entrevista, que poderá ser realizada tanto online como presencialmente. Ao aceitar o convite da entrevista online, nota-se o consentimento do participante aos termos do estudo (como descrito no anexo "Consentimento Informado – Online"). Enquanto que para encontros presenciais, será necessária a assinatura do participante (como descrito no anexo "Consentimento Informado – Presencial").
d) Realiza-se a entrevista semiestruturada individual online ou presencial com duração de 1-2h (seguindo "Etapa 1 – Entrevistas" do Guião em anexo). As entrevistas serão gravadas (áudio para entrevistas presenciais e áudio ou áudio-vídeo para entrevistas online) com o consentimento do participante e poderão contar com o auxílio de uma apresentação em PowerPoint. Novos participantes serão convidados a participar no estudo até que seja alcançado o ponto de saturação, ou seja, até que novas informações sobre o sistema a ser modelado (i.e., variáveis-chave e relações) não sejam adicionadas pelos participantes. Tratando-se de um método de pesquisa qualitativo, as entrevistas serão gravadas para que possam ser revisitadas pelo investigador responsável, quando este estiver buscando as principais variáveis e relações do sistema a ser modelado, mencionados pelos participantes. Trechos das entrevistas poderão ser transcritas verbatim em publicações resultantes do projeto para justificar a adição de relações entre variáveis no modelo (i.e., *coding*).

por exemplo: *Participante 1*: "Os conflitos entre as populações locais e as mineradoras são causados pela falta de transparência" são codificados no modelo como: "transparência" →" "conflitos", que se entende como "a falta de transparência afeta a existência de conflitos: quanto mais transparência, menos conflitos".

e) Depois de alcançado o ponto de saturação e encerrado o processo de entrevistas, o investigador irá reunir as perpetivas de todos os participantes e assimilá-las em um *causal loop diagram (CLD)*, o qual representará de forma visual e qualitativa as principais variáveis e relações do sistema a ser modelado.

f) De acordo com a complexidade do sistema e divergência de perspetivas entre os participantes, será considerado a realização de um workshop com o principal objetivo de validar o CLD (i.e., a representação visual e qualitativa das variáveis do sistema e suas relações) junto aos participantes. O workshop será considerado caso o investigador tenha experimentado dificuldades ao combinar as perpetivas dos participantes (e.g., perpetivas divergentes) e julgue necessário a discussão de certas relações do sistema e/ou da importância de certas variáveis para o funcionamento do sistema com os participantes (como um grupo) de forma a alcançar concordância. Neste caso, os entrevistados serão convidados a participar de um workshop online ou presencial com duração de 2-3h para discussão do modelo conceptual resultante (i.e., CLD) (seguindo "Etapa 1 – Workshop" do Guião em anexo). A participação é opcional. O idioma do workshop será inglês ou português, de acordo com a preferência dos participantes. Para tal, os participantes das entrevistas serão contatados via email para estabelecer dia e hora do evento. O evento contará com o auxílio de uma apresentação em PowerPoint e uma ferramenta para visualização e modificação do CLD (e.g., Vensim, Stella, etc.). Caso o evento ocorra no modo online, o mesmo será gravado para posterior consulta do investigador ao refinar o CLD e avaliação e aprimoramento das técnicas de facilitação utilizadas durante o workshop. Da mesma forma que as entrevistas, é possível que parte das discussões entre participantes do workshop seja transcrita verbatim em publicações resultantes do projeto para justificar a re-modelação ou inclusão de relações entre variáveis.

g) Os dados dos participantes assim como as gravações das entrevistas e workshops serão mantidas pelo investigador responsável, armazenados no computador pessoal do investigador responsável e em pasta do projeto na nuvem associada ao email institucional do investigador responsável, compartilhada com orientador e coorientador. Dados e gravações serão destruídos um ano após a publicação dos resultados.

Etapa 2 (01/05/2023 a 01/05/2024)

Segue-se os mesmo passos descritos para a Etapa 1, entretanto os especialistas descritos no item a) são agora especialistas do setor automóvel e preocupados com o desenvolvimento sustentável do setor, incluindo profissionais da indústria e académicos, governo, e associações. Além disso, seguem-se os guiões para entrevistas e potencial workshop apresentados no Guião em anexo, "Etapa 2 – Entrevistas" e "Etapa 2 – Workshop", respetivamente.

Etapa 3 (01/10/2023 a 01/10/2024)

Segue-se os mesmo passos descritos para a Etapa 1, entretanto os especialistas descritos no item a) são agora especialistas do setor elétrico e automóvel e pessoal envolvido na expansão da frota de veículos elétricos, incluindo profissionais da indústria e académicos, governo, e associações. Além disso, seguem-se os guiões para entrevistas e potencial workshop apresentados no Guião em anexo, "Etapa 3 – Entrevistas" e "Etapa 3 – Workshop", respetivamente.

Benefícios, Riscos e Desconforto

a) Não espera-se nenhum benefício aos participantes outro que a expansão de perspetiva pessoal sobre o tema discutido durante as entrevistas.

b) O único desconforto que poderia ser decorrente dos procedimentos do estudo estaria relacionado à perda do anonimato durante os workshops online. Enquanto que a probabilidade de ocorrência é alta, considera-se que este seja um risco de baixo impacto, visto que o investigador responsável tomará todas as medidas necessárias para que os participantes estejam confortáveis e em concordância com os procedimentos em que estejam envolvidos.

Confidencialidade

a) Todas as informações e dados recolhidos durante o projeto serão confidenciais e só poderão ser utilizados no âmbito deste estudo.

b) A investigadora responsável, orientadora e coorientador serão as únicas pessoas com acesso aos registos dos participantes, os quais estarão guardados em computador pessoal do investigador responsável e em pasta do projeto na nuvem associada ao email institucional do investigador responsável e compartilhada com orientador e coorientador.

c) Dados identificadores são considerados apenas para os processos de entrevista e workshops e não serão apresentados em publicações científicas decorrentes deste projeto e/ou no âmbito da própria tese de doutoramento em que este projeto se enquadra.

d) As entrevistas semiestruturadas serão gravadas (áudio para entrevistas presenciais e áudio ou áudio-vídeo para entrevistas online) e os potenciais workshops, quando virtuais, também serão gravados (áudio e vídeo) com o consentimento dos participantes. As gravações serão mantidas pelo investigador responsável, e armazenadas no computador pessoal do investigador e pasta do projeto na nuvem compartilhada com orientador e co-orientador.

h) Os dados e gravações recolhidos ao longo deste estudo serão destruídos um ano após a publicação dos resultados/a data prevista de fim do projeto (01/11/2025).

Conflito de interesses

Declara-se a ausência de conflitos de interesses que podem estar relacionados com o presente projeto.

Consentimento informado

A investigação envolve apenas voluntários saudáveis?	**S**	N
A investigação envolve grupos vulneráveis: crianças, menores, idosos ou outras pessoas com incapacidade temporária ou permanente?	S	**N**
O pedido de parecer inclui a declaração de consentimento informado, livre e esclarecido?	**S**	N

Aqui tem de escolher o formato de consentimento informado

[X] Consentimento informado, livre e esclarecido para participação em investigação - de acordo com a Declaração de Helsínquia e a Convenção de Oviedo

[X] Consentimento informado não assinado - E.g. formulário para questionários preenchidos online. Deverá adicionar a informação incluída e o modo de os participantes concordarem em participar

[ ] Consentimento informado alterado - Um formulário de consentimento informado que omite informação requerida. E.g., se não indica o objetivo do estudo para evitar o viés na resposta dos participantes. Deve explicar o racional no procedimento e os processos de *debriefing*

[ ] Isenção de consentimento – quando não é obtido consentimento informado – esta opção pode ser apropriada para utilização de dados já disponíveis. Justifique

Anexe o formulário de consentimento informado e outro material informativo relevante quando adequado, ou justifique a isenção de consentimento

Assinatura do Investigador Responsável

Assinado por: **Alaize Dall'Oroletta**
Num. de Identificação: PASSP-FT
Data: 2023.06.10 16:18:31 +01'00'

.....

Documentação a anexar

i. Cópia dos questionários ou formulários de recolha de dados a utilizar, quando aplicável;
ii. Modelo de consentimento informado, de acordo com as declarações, diretivas e regulamentos internacionais, europeus e nacionais, se aplicável, devidamente ajustado linguística e culturalmente às populações a que é dirigido;
iii. Declaração do(s) responsável(eis) pelo projeto, explicitando que os dados obtidos são confidenciais e usados apenas no âmbito do estudo em questão;
iv. Modelo de declaração de compromisso para outros investigadores ou colaboradores na investigação, se aplicável, destinada a documentar o seu envolvimento nas garantias de confidencialidade dadas pelo(s) responsável(eis) do projeto no âmbito do processo apresentado;
v. Informação a que se refere o número 3 do artigo 4.º das normas orientadoras da CEICGH, sobre o enquadramento, apoio e viabilidade do projeto, facultada pelo responsável da unidade/subunidade orgânica e/ou serviço onde se vai desenvolver o projeto e/ou onde serão recolhidos os dados;
vi. Declaração do(s) orientador(es) científico(s) do estudo, se aplicável, de acordo com o estabelecido no número 4 do artigo 4.º das normas orientadoras da CEICGH;
vii. Cópia de notificações a autoridades nacionais (e.g., Direção-Geral da Educação, no caso dos inquéritos em ambiente escolar) europeias ou internacionais competentes, se aplicável, juntamente com o parecer/autorização das mesmas, se emitido;
viii. Curriculum vitae resumido do(s) responsável(eis) pelo projeto e dos restantes membros da equipa de investigação.

Deverá ser seguido o Regulamento Geral de Proteção de Dados (RGPD), com entrada em vigor em 25 de Maio de 2018, - REGULAMENTO (UE) 2016/679 DO PARLAMENTO EUROPEU E DO CONSELHO, de 27 de abril de 2016, relativo à proteção das pessoas singulares no que diz respeito ao tratamento de dados pessoais e à livre circulação desses dados, que revoga a Diretiva 95/46/CE (Regulamento Geral sobre a Proteção de Dados).

10.3 Appendix III. Model documentation

Tables 10-2, 10-3, and 10-4 present the exogenous parameters, historical data used for calibration, and policy parameters, respectively, included in the system dynamics model developed in **Chapter 7**.

Table 10-2. Model exogenous parameters, their description, assumptions, and sources.

Group	Var.	Unit	Value	Comment	Uncertainty	Sources
Initial cost	new EV initial cost	EUR	37,746.00	This value was calculated as an average value of 21 EV models from different brands, battery capacities, and models.	High. Uncertain due to high variability in EV models and their initial cost, which can make an aggregated value little representative of real conditions.	https://withportugal.com/en/blog/eletrico-ou-gasolina; https://blazetrends.com/10-cheap-electric-cars-for-sale-in-portugal-in-2022/; https://www.nissan.pt/veiculos/novos-veiculos/ariya.html; https://www.tesla.com/pt_pt/modely/design#overview; https://www.lexus.pt/novos/nx; https://www.volvocars.com/pt/; https://caredge.com/guides/average-price-of-an-electric-car-2024; https://www.statista.com/forecasts/1309622/worldwide-e-vehicles-average-price;
Initial cost	EV 4y depreciation	Dmnl	0.5	This value was obtained as BEV 4y depreciation from CCI (2022). Another study from ISEE cars points to an average 5y depreciation of 49.1% for EVs.	Medium. Although different EV models are subject to different depreciation rates, studies seem to agree on an average value of 0.5 depreciation rate after 4 to 5y from purchase.	Car Cost Index 2022 (CCI, 2022); https://www.iseecars.com/cars-that-hold-their-value-study
Initial cost	used EV initial cost	EUR	18,873.00	Calculated based on EV 4y depreciation.	High. Uncertainty derived from new EV initial cost.	-
Initial cost	new ICEV initial cost	EUR	22,647.00	This value represents 60% of the value of a new EV.	High. Uncertainty due to high variability in ICEV models and their initial cost, which can make an aggregated value little representative of real conditions.	https://www.edmunds.com/car-buying/average-price-electric-car-vs-gas-car.html; https://www.town.westborough.ma.us/1170/Cost-Range-Comparison;

Initial cost	depreciation rate 2 to 5y	Dmnl	0.4	This value was obtained as the average between Petrol (0.42) and Diesel (0.39) 4y depreciation from CCI (2022). Another study from ISEE cars points to an average 5y depreciation of 38.8% for overall car market in 2023, compared to 49.6% in 2019.	Medium. Although different ICEV models are subject to different depreciation rates, studies seem to agree on an average value of 0.4 depreciation rate after 4 to 5y from purchase.	Car Cost Index 2022 (CCI, 2022); https://www.iseecars.com/cars-that-hold-their-value-study
Initial cost	depreciation rate 5 to 10y	Dmnl	0.6	Assumption.	High.	https://fountainware.com/Products/carbuyer/theory.htm
Initial cost	depreciation rate 10 to 20y	Dmnl	0.8	Assumption.	High.	https://fountainware.com/Products/carbuyer/theory.htm
Initial cost	depreciation rate >20y	Dmnl	0.9	Assumption.	High.	https://fountainware.com/Products/carbuyer/theory.htm
Fuel costs	fast charging electricity cost	EUR/kWh	0.69	0.79 EUR/kWh according to ACP (2022). Average MSP price of 0.59 EUR/kWh according to the AF Observatory for the Tesla Model 3. Average value of 0.69 EUR/kWh selected.	Low. Uncertainty is low, but time-base variability can be high.	https://www.acp.pt/eletricos/carregar-carro-eletrico/quanto-custa-carregar-um-carro-eletrico; https://alternative-fuels-observatory.ec.europa.eu/consumer-portal/electric-vehicle-recharging-prices
Fuel costs	private charging electricity cost	EUR/kWh	0.22	Average private charging price of 0.22 EUR/kWh according to the AF Observatory for the Tesla Model 3.	Low. Uncertainty is low, but time-base variability can be high.	https://alternative-fuels-observatory.ec.europa.eu/consumer-portal/electric-vehicle-recharging-prices
Fuel costs	slow charging electricity cost	EUR/kWh	0.46	0.43 EUR/kWh according to ACP (2022). Average MSP price of 0.49 EUR/kWh according to the AF Observatory for the Tesla Model 3. Average value of 0.46 EUR/kWh selected.	Low. Uncertainty is low, but time-base variability can be high.	https://www.acp.pt/eletricos/carregar-carro-eletrico/quanto-custa-carregar-um-carro-eletrico; https://alternative-fuels-observatory.ec.europa.eu/consumer-portal/electric-vehicle-recharging-prices;
Fuel costs	share of fast charging	Dmnl	0.371	In Portugal, 4.6% of charging stations are Ultra-fast and 32.5% are Fast. Data from Mobi.E Data. Accessed on 12/08/2024.	Medium. Current values are known, whereas values before 2020 are unknown (i.e., lack of historical data).	https://www.mobie.pt/en/mobidata/data

Fuel costs	expected use of public chargers	Dmnl	0.5	Estimate similar to another scientific paper. Mobi.E values checked at different times and weekdays were around 0.3.	Medium. Although Mobi.E provides data on usage of charging stations, usage varies throughout the day and week. This can hamper the establishment of an aggregated value.	https://doi.org/10.1016/j.trd.2023.103890; https://www.mobie.pt/en/mobidata/data;
Fuel costs	average yearly mileage	(km/vehicle)/year	11,000	According to an analysis performed by CarVertical, Portuguese vehicles had an annual average mileage of 20,568km. However, data from INE points to 55,431 M de v-km in 2016, which divided by the total car fleet in the same year (4.82926 M) results in 11,459.52 km. The same formula applied to 2023 results in 10,438.16 km per vehicle per year (59,123 M v-km/5.66412 M v). Therefore a value of 11,000km was selected also based on ACEA evaluation of the European fleet.	Low.	Estimativas do tráfego rodoviário, INE (2024); https://www.carvertical.com/blog/average-mileage-per-year-in-eu-and-us; Vehicles on European Roads, ACEA (2024);
Fuel costs	new EV consumption	kWh/km	0.16	An average electric car consumes 15 to 20 kWh per 100 km. 0.16 was the value taken from ACP (2022).	Low.	https://www.acp.pt/eletricos/carregar-carro-eletrico/quanto-custa-carregar-um-carro-eletrico; https://www.ayvens.com/en-pt/drive-electric/ev-costs/; https://ev-database.org/cheatsheet/energy-consumption-electric-car
Fuel costs	efficiency loss from new to used EV	Dmnl	0.05	Based on the average mileage considered, it was assumed that after 4-5 years, an EV would lose 5% of its battery capacity.	Medium.	https://www.caranddriver.com/features/a31875141/electric-car-battery-life/; https://batteryuniversity.com/article/bu-1003a-battery-aging-in-an-electric-vehicle-ev; https://www.standvirtual.com/diarioautomovel/quanto-custa-a-manutencao-de-um-carro-eletrico/;

Fuel costs	used EV consumption	kWh/km	0.168	Calculated based on efficiency loss.	Medium.	-
Fuel costs	average diesel cost	EUR/L	1.4	Average diesel price from 2013 to 2021 (Statista, 2022). Current diesel price (August 2024) is 1.53 EUR/L.	Low. Uncertainty is low, but time-base variability can be high.	https://www.statista.com/statistics/603727/diesel-fuel-prices-portugal/; https://pt.globalpetrolprices.com/Portugal/diesel_prices/;
Fuel costs	new ICEV consumption	L/km	0.065	Average obtained from petrol (5.8L/100km) and diesel (5.2L/100km) average consumption (ACP, 2022). Other values point to 6L/100km to diesel cars and 7L/100km to petrol ones (Cupra, 2024). Therefore, 0.065 was selected as an estimate.	Low.	https://www.acp.pt/eletricos/carregar-carro-eletrico/quanto-custa-carregar-um-carro-eletrico; https://www.cupraofficial.pt/nosso-adn/consumo-de-energia;
Fuel costs	fuel efficiency loss from new to used ICEV	Dmnl	0.03	Estimate. It may vary based on maintenance and user profile.	High.	-
Fuel costs	used ICEV consumption	L/km	0.067	Calculated based on efficiency loss.	High.	-
Repair, maintenance, and tire costs	Insurance	EUR/year	360	Mandatory insurance is around 10 EUR/month. Higher-coverage insurance can reach different values based on the driver's profile and the vehicle model and year. An average value of 30 EUR/month was assumed.	High. Insurance plans vary broadly according to vehicle models, age, consumer experience and preference, etc.	https://www.jornaldenegocios.pt/mais/analises-deco/detalhe/seguro-automovel-o-que-e-que-o-meu-seguro-paga; https://caetanoretail.pt/blog/quanto-custa-manter-carro/
Repair, maintenance, and tire costs	Inspection	EUR/year	35.89	Mandatory vehicle inspection.	Low.	https://www.acp.pt/veiculos/manutencao-automovel/precos-da-inspecao-automovel

Repair, maintenance, and tire costs	new ICEV maintenance	EUR/ year	180	Approximately 11% of the TCO (Mid-size standard segment (D1 & SUV D1)) for Portugal in 2022, obtained from CCI (2022). The average TCO for petrol and diesel cars in Portugal is 1415 EUR per year. Estimate for yearly maintenance costs. Values found range from 660 EUR to 180 EUR.	Medium. Maintenance costs can vary broadly. Aggregate value based on report reduces uncertainty.	https://www.deco.proteste.pt/auto/carros-eletricos/noticias/manutencao-carro-custa-200-500-euros; https://caetanoretail.pt/blog/quanto-custa-manter-carro/; https://www.prio.pt/pt/custo-de-manutencao-carros-eletricos_236.html?idb=598; https://www.acp.pt/eletricos/tudo-sobre-eletricos/manutencao-de-um-eletrico/detalhe/custos-de-manutencao-de-carros-eletricos-vs-carros-de-combustao
Repair, maintenance, and tire costs	new EV maintenance	EUR/ year	100	Approximately 11% of the TCO (Mid-size standard segment (D1 & SUV D1)) for Portugal in 2022, obtained from CCI (2022). The average TCO for BEV is 898 EUR. Estimate for yearly maintenance costs. Values found range from 50 to 440 EUR.	Medium. Maintenance costs can vary broadly. Aggregate value based on report reduces uncertainty.	https://poupaenergia.pt/en/dicas/electric-vehicles/#1539600064231-0b90204e-d418; https://www.prio.pt/pt/custo-de-manutencao-carros-eletricos_236.html?idb=598; https://www.acp.pt/eletricos/tudo-sobre-eletricos/manutencao-de-um-eletrico/detalhe/custos-de-manutencao-de-carros-eletricos-vs-carros-de-combustao;
Repair, maintenance, and tire costs	used ICEV maintenance	EUR/ year	240	A 30% increase in maintenance costs was assumed for used ICEV. This is based on an increased probability of major repairs with vehicle age.	High.	https://www.bls.gov/opub/btn/volume-3/pdf/americans-aging-autos.pdf; https://caredge.com/cadillac/ct6/maintenance; https://www.finax.eu/en/blog/when-is-the-right-time-to-buy-and-sell-a-car;
Repair, maintenance, and tire costs	used EV maintenance	EUR/ year	130	A similar figure (30% increase from new EV) was assumed for used EVs. However, it seems repair costs may be higher for EVs than ICEVs, according to the report (see cell to the right). Recommendation is to include sensitivity in operational costs.	High.	https://www.repairerdrivennews.com/2022/07/12/ccc-report-repair-costs-turnaround-times-higher-for-evs/
Yearly vehicle taxes	IUC new ICEV	EUR/ year	150	IUC varies based on model, engine size, emissions, and age. Therefore an average value of 150 EUR was assumed for a new ICEV.	High.	https://impostosobreveiculos.info/iuc/imposto-unico-circulacao-iuc-2024/

Yearly vehicle taxes	IUC used ICEV	EUR/ year	75	As the IUC decreases over time, it was assumed as half the value of a new ICEV.	High.	https://impostosobreveiculos.info/iuc/imposto-unico-circulacao-iuc-2024/
Yearly vehicle taxes	IUC new EV	EUR/ year	0	EVs are exempt of IUC in Portugal	Low.	https://impostosobreveiculos.info/iuc/imposto-unico-circulacao-iuc-2024/; https://www.acp.pt/eletricos/incentivos-e-beneficios/impostos-dos-carros-eletricos-em-portugal;
Yearly vehicle taxes	IUC used EV	EUR/ year	0	EVs are exempt of IUC in Portugal	Low.	https://impostosobreveiculos.info/iuc/imposto-unico-circulacao-iuc-2024/; https://www.acp.pt/eletricos/incentivos-e-beneficios/impostos-dos-carros-eletricos-em-portugal;
Yearly vehicle taxes	ISV new ICEV	EUR	5000	ISV varies broadly according to emissions, vehicle model, and age. A value of 5,000 EUR for registering a new vehicle was assumed.	High.	https://impostosobreveiculos.info/isv/imposto-sobre-veiculos-isv-2024/#TabelaA
Yearly vehicle taxes	ISV used ICEV (if imported)	EUR	3000	ISV for used vehicles applies only when they are imported (first registration in Portugal) and are smaller than for new vehicles. A value of EUR 3,000 for registering an imported vehicle was assumed.	High.	https://impostosobreveiculos.info/isv/imposto-sobre-veiculos-isv-2024/#TabelaA
Yearly vehicle taxes	ISV new EV	EUR	0	EVs are exempt of ISV in Portugal	Low.	https://www.acp.pt/eletricos/incentivos-e-beneficios/impostos-dos-carros-eletricos-em-portugal
Yearly vehicle taxes	ISV used EV (if imported)	EUR	0	EVs are exempt of ISV in Portugal	Low.	https://www.acp.pt/eletricos/incentivos-e-beneficios/impostos-dos-carros-eletricos-em-portugal
Range	ICEV Range	km/ EVCS	600	It was assumed that ICEV could run 600km after refueling.	Low.	https://doi.org/10.1016/j.trd.2023.103890

Range	initial EV Range	km/EVCS	180	It was assumed that EV could run 180km after recharging in 2013.	Low.	https://doi.org/10.1016/j.trd.2023.103890; https://www.sustainabilitybynumbers.com/p/electric-car-range; https://ev-database.org/cheatsheet/range-electric-car; https://www.topgear.com/car-news/electric/here-are-12-longest-range-electric-cars-you-can-buy-today;
Range	year of EV range parity	Year	2040	It was assumed that EVs would reach range parity with ICEVs in 2035. The evolution of EV range till then would follow linear growth.	High.	Assumption.
Charging	fast charging duration	Minutes	40	It was assumed that fast charging would take 40 minutes.	Low.	https://www.evconnect.com/blog/slow-charge-vs-fast-charge-ev-charging; https://doi.org/10.1016/j.trd.2023.103890; https://www.eca.europa.eu/Lists/ECADocuments/SR21_05/SR_Electrical_charging_infrastructure_EN.pdf;
Charging	slow charging duration	Minutes	420	It is assumed that slow charging takes 7h or 420minutes.	Low.	https://www.evconnect.com/blog/slow-charge-vs-fast-charge-ev-charging; https://doi.org/10.1016/j.trd.2023.103890; https://www.eca.europa.eu/Lists/ECADocuments/SR21_05/SR_Electrical_charging_infrastructure_EN.pdf;
Charging	share of fast charging[Urban]	Dmnl	0.371	In Portugal, 4.6% of charging stations are Ultra-fast and 32.5% are Fast. Data from Mobi.E Data. Accessed on 12/08/2024.	Medium. Although this value is known for 2024, no data is available before 2020. Additionally, there is no information considering urban/rural regions.	https://www.mobie.pt/en/mobidata/data
Charging	share of fast charging[Rural]	Dmnl	0.371	In Portugal, 4.6% of charging stations are Ultra-fast and 32.5% are Fast. Data from Mobi.E Data. Accessed on 12/08/2024.	Medium. Although this value is known for 2024, no data is available before 2020. Additionally, there is no information considering urban/rural regions.	https://www.mobie.pt/en/mobidata/data

Charging	operational charging time per year (minutes)	Minutes/ Year	259,200	The charging stations are supposed to operate an average of 12 hours per day, every day of the year	Medium.	https://doi.org/10.1016/j.trd.2023.103890;
Charging	time required to perceive need for new charging points	Year	0.5	It is assumed that it takes 6 months to perceive the need for new charging points based on the gap in capacity.	High.	https://doi.org/10.1016/j.trd.2023.103890;
Charging	time required to build new charging stations	Year	0.3	It is assumed it takes 4 months to build a new charging station.	Medium.	https://doi.org/10.1016/j.trd.2023.103890;
Charging	average charging station lifetime	Year	12	It is assumed that a charging stations has an average lifetime of 12 years.	Medium.	https://danlec.uk/ev-chargers/what-is-the-lifespan-of-a-ev-charging-station/; https://doi.org/10.1016/j.trd.2023.103890;
Charging	initial charging points[Urban]	EVCS	100	Initial number of charging stations. Estimated values for urban and rural locations in 2013.	High.	Assumption;
Charging	initial charging points[Rural]	EVCS	20	Initial number of charging stations. Estimated values for urban and rural locations in 2013.	High.	Assumption;
Charging	rural area	km^2	696,009	Calculated based on district-level classification of APR areas.	High.	Own calculations based on TIPAU Classification from INE.
Charging	urban area	km^2	194,879.3	Calculated based on district-level classification of APU and AMU areas.	High.	Own calculations based on TIPAU Classification from INE.

Charging	additional charging infrastructure rate	1/Year	0.230178	Calibrated value. An additional investment to increase the number of EVCS by 23% per year was assumed until the gap in charging capacity was positive was the simulation year was larger than 2022.	High.	https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/portugal; https://www.mobie.pt/en/mobidata/data;
Ownership	share of EVs owned by rural population	Dmnl	0.25	It was assumed that 25% of all EVs bought from 2013 to 2022 was owned by rural populations.	High.	Assumption based on https://theicct.org/wp-content/uploads/2022/06/bev-access-europe-jun22.pdf;
Ownership	initial urban car ownership	Vehicle/Person	0.3865	Values calibrated based on historical data on car ownership and urban and rural populations, assuming that rural populations would have a higher car ownership rate given limited mobility options.	High	Assumption based on data from INE (2023);
Ownership	initial rural car ownership	Vehicle/Person	0.4891	Values calibrated based on historical data on car ownership and urban and rural populations, assuming that rural populations would have a higher car ownership rate given limited mobility options.	High	Assumption based on data from INE (2023);
Ownership	adjusted maximum urban car ownership rate 2022	Vehicle/Person	0.5539	Values calibrated based on historical data on car ownership and urban and rural populations, assuming that rural populations would have a higher car ownership rate given limited mobility options.	High	Assumption based on data from INE (2023); https://www.eea.europa.eu/data-and-maps/figures/car-ownership-rates-projections; https://www.sciencedirect.com/science/article/pii/S2590198223001392;
Ownership	adjusted maximum rural car ownership rate 2022	Vehicle/Person	0.584	Values calibrated based on historical data on car ownership and urban and rural populations, assuming that rural populations would have a higher car ownership rate given limited mobility options.	High	Data from INE(2023); https://www.eea.europa.eu/data-and-maps/figures/car-ownership-rates-projections; https://www.sciencedirect.com/science/article/pii/S2590198223001392;

Familiarity	share of population familiar with ICEV technology	Dmnl	1	100% of the population is familiar with ICEV technology.	Low.	-
Familiarity	technology market share[Urban]	Dmnl	0.000145	It is assumed that all EVs are owned by the urban population in 2013. Therefore, this market share represents the total EV market share in 2013.	Medium.	Assumption;
Familiarity	technology market share[Rural]	Dmnl	0	Initial EV market share in 2013 amongst the rural population	Medium.	Assumption;
Familiarity	innovation coefficient[Urban]	1/Year	4.27E-05	Bass diffusion parameters. Calibrated against historical EV stock data (2013 to 2022) assuming 25% of all EVs are owned by rural population.	High.	Assumption;
Familiarity	innovation coefficient[Rural]	1/Year	5.20E-05	Bass diffusion parameters. Calibrated against historical EV stock data (2013 to 2022) assuming 25% of all EVs are owned by rural population.	High.	Assumption;
Familiarity	imitation coefficient[Urban]	1/Year	0.51816	Bass diffusion parameters. Calibrated against historical EV stock data (2013 to 2022) assuming 25% of all EVs are owned by rural population.	High.	Assumption;
Familiarity	imitation coefficient[Rural]	1/Year	0.499	Bass diffusion parameters. Calibrated against historical EV stock data (2013 to 2022) assuming 25% of all EVs are owned by rural population.	High.	Assumption;

Familiarity	adjusting familiarity factor	Dmnl	6.54491	This adjusting factor indicates the number of people that are familiar with EV technology based on the share of EV ownership given by the Bass diffusion model. This value was calibrated so that vehicle sales and stocks would match historical data from 2013 to 2022.	High.	Assumption;
Vehicle aging chain	aging period 1	Year	2	-	-	-
Vehicle aging chain	aging period 2	Year	3	-	-	-
Vehicle aging chain	aging period 3	Year	5	-	-	-
Vehicle aging chain	aging period 4	Year	10	-	-	-
Vehicle aging chain	initial vehicle stock <2y[ICEV, Urban]	Vehicle	136160	Total stock: 194,514; Assumption: ICEV stock is 70% owned by urban population. Estimation of shares across vehicle age stocks between populations is based on calculated urban and rural vehicle ownerships.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock <2y[ICEV, Rural]	Vehicle	58354	Total stock: 194,514; Assumption: ICEV stock is 30% owned by rural population.	High.	Total stock from INE and Eurostat - Passenger cars by age.

Vehicle aging chain	initial vehicle stock 2 to 4y[ICEV, Urban]	Vehicle	348397	Total stock: 554,599; Assumption: ICEV stock is 63% owned by urban population.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock 2 to 4y[ICEV, Rural]	Vehicle	205182	Total stock: 554,599; Assumption: ICEV stock is 37% owned by urban population.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock 4 to 10y[ICEV, Urban]	Vehicle	487202	Total stock: 974,405; Assumption: ICEV stock split equally between populations.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock 4 to 10y[CEV, Rural]	Vehicle	487202	Total stock: 974,405; Assumption: ICEV stock split equally between populations.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock 10 to 20y[ICEV, Urban]	Vehicle	1.05E+06	Total stock: 2.09377e+06; Assumption: ICEV stock split equally between populations.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock 10 to 20y[ICEV, Rural]	Vehicle	1.05E+06	Total stock: 2.09377e+06; Assumption: ICEV stock split equally between populations.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock >20y[ICEV, Urban]	Vehicle	252816	Total stock: 505,632; Assumption: ICEV stock split equally between populations	High.	Total stock from INE and Eurostat - Passenger cars by age.

Vehicle aging chain	initial vehicle stock >20y[ICEV, Rural]	Vehicle	252816	Total stock: 505,632; Assumption: ICEV stock split equally between populations	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock <2y [EV, Urban]	Vehicle	435	It is assumed that all EVs in this age category are owned by urban populations.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock <2y[EV, Rural]	Vehicle	0	It is assumed that all EVs in this age category are owned by urban populations.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock 2 to 4y[EV, Urban]	Vehicle	20	It is assumed that all EVs in this age category are owned by urban populations.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock 2 to 4y[EV, Rural]	Vehicle	0	It is assumed that all EVs in this age category are owned by urban populations.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock 4 to 10y[EV, Urban]	Vehicle	0	It is assumed that there are no significant number of EVs older than 4y when the simulation starts in 2013.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock 4 to 10y[EV, Rural]	Vehicle	0	It is assumed that there are no significant number of EVs older than 4y when the simulation starts in 2013.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock 10 to 20y[EV, Urban]	Vehicle	0	It is assumed that there are no significant number of EVs older than 4y when the simulation starts in 2013.	Low.	Total stock from INE and Eurostat - Passenger cars by age.

Vehicle aging chain	initial vehicle stock 10 to 20y[EV, Rural]	Vehicle	0	It is assumed that there are no significant number of EVs older than 4y when the simulation starts in 2013.	Low.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock >20y[EV, Urban]	Vehicle	0	It is assumed that there are no significant number of EVs older than 4y when the simulation starts in 2013.	Low.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial vehicle stock >20y[EV, Rural]	Vehicle	0	It is assumed that there are no significant number of EVs older than 4y when the simulation starts in 2013.	Low.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	scrapping rate 5 to 10y[ICEV]	1/Year	0	It is assumed that no ICEVs younger than 10y would be scrapped.	Low.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	scrapping rate 5 to 10y[EV]	1/Year	0.894968	It is assumed that a approx. 90% of EVs is scrapped per year in this age category because of battery performance.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	scrapping rate 10 to 20y[ICEV]	1/Year	0	Value calibrated based on a ICEV aging chain model.	Low.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	scrapping rate 10 to 20y[EV]	1/Year	1	It is assumed that all EVs between 10 to 20y are scrapped.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	initial ICEV scrapping rate >20y	1/Year	0.07	Value calibrated based on a ICEV aging chain model.	Low.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain	adjusted ICEV scrapping rate >20y	1/Year	1	Policy variable. It allows for a scrapping scheme that increases the scrapping rate for vehicles older than 20y.	High.	-

Vehicle aging chain	scrapping rate >20y [EV]	1/Year	1	It is assumed that all EVs older than 20y are scrapped.	High.	Total stock from INE and Eurostat - Passenger cars by age.
Vehicle aging chain [Imports]	availability of used vehicles 2 to 5y [ICEV]	Dmnl	1	Calibrated value.	Low. High availability of second-hand ICEV of different ages.	https://www.razaoautomovel.com/noticias/mercado-acap-portugal-idade-media-carros-continua-subir-2023/; https://www.acap.pt/index.php?route=base/pt/noticia/104/mercado-automovel; https://www.jornaldenegocios.pt/empresas/automovel/detalhe/acap-veiculos-importados-usados-foram-mais-de-dois-tercos-das-matriculas-novas-em-2022;
Vehicle aging chain [Imports]	availability of used vehicles 2 to 5y [EV]	Dmnl	0.01	Calibrated value.	High. The availability of second-hand EVs is unknown.	Assumption.
Vehicle aging chain [Imports]	availability of used vehicles 5 to 10y [ICEV]	Dmnl	1	Calibrated value.	Low. High availability of second-hand ICEV of different ages.	Assumption.
Vehicle aging chain [Imports]	availability of used vehicles 5 to 10y [EV]	Dmnl	0.795398	Calibrated value.	High. The availability of second-hand EVs is unknown.	Assumption.
MNLM	status [New ICEV]	Dmnl	13.3841	Calibrated value. New ICEVs were assumed to have the highest status amongst vehicle options, followed by new EVs. A Used EV is assumed to have a higher status than a second-hand ICEV, given it is likely to be less old than Used ICEVs.	High.	Assumption.
MNLM	status [New EV]	Dmnl	9.36887	Calibrated value.	High.	Assumption.

MNLM	status [Used ICEV]	Dmnl	1.60388	Calibrated value.	High.	Assumption.
MNLM	status [Used EV]	Dmnl	2.43779	Calibrated value.	High.	Assumption.
MNLM	beta1 [Urban]	Dmnl	-6.50E-05	Calibrated value. Beta coefficient of the Multinomial Logit Model (MLN) associated with the initial cost. It is negative as it indicates the lower the price the higher the utility. It is assumed that the rural/disadvantaged consumer group has a beta coefficient closer to zero (i.e., higher), as it is more affected by the initial technology cost.	High.	Assumption.
MNLM	beta1 [Rural]	Dmnl	-2.69E-05	Calibrated value. Beta coefficient of the Multinomial Logit Model (MLN) associated with the initial cost. It is negative as it indicates the lower the price the higher the utility. It is assumed that the rural/disadvantaged consumer group has a beta coefficient closer to zero (i.e., higher), as it is more affected by the initial technology cost.	High.	Assumption.
MNLM	beta2 [Urban]	Dmnl	-0.00029	Calibrated value. Beta coefficient of the MNLM associated with the operational cost. It is negative as it indicates the lower the operational cost the higher the utility.	High.	Assumption.

MNLM	beta2 [Rural]	Dmnl	-0.00035	Calibrated value. Beta coefficient of the MNLM associated with the operational cost. It is negative as it indicates the lower the operational cost the higher the utility.	High.	Assumption.
MNLM	beta3 [Urban]	Dmnl	0.003	Calibrated value. Beta coefficient of the MNLM associated with technologies' range. It is positive as it indicates the higher the range the higher the utility. It is assumed that the rural/disadvantaged consumer group has a larger beta coefficient, as it is more affected by range anxiety/constraints.	High.	Assumption.
MNLM	beta3 [Rural]	Dmnl	0.0125	Calibrated value. Beta coefficient of the MNLM associated with technologies' range. It is positive as it indicates the higher the range the higher the utility. It is assumed that the rural/disadvantaged consumer group has a larger beta coefficient, as it is more affected by range anxiety/constraints.	High.	Assumption.
MNLM	beta4 [Urban]	Dmnl	0.00139	Calibrated value. Beta coefficient of the MNLM associated with new EV charging availability. It is positive as it indicates the higher the availability the higher the utility. It is assumed that charging availability has a larger weight on the utility perception of EVs for rural populations than urban ones.	High.	Assumption.

MNLM	beta4 [Rural]	Dmnl	0.00265	Calibrated value. Beta coefficient of the MNLM associated with new EV charging availability. It is positive as it indicates the higher the availability the higher the utility. It is assumed that charging availability has a larger weight on the utility perception of EVs for rural populations than urban ones.	High.	Assumption.
MNLM	beta5 [Urban]	Dmnl	0.28809	Calibrated value. Beta coefficient of the MLNM associated with technology status. It is positive, as it indicates the higher the attributed status the higher the utility.	High.	Assumption.
MNLM	beta5 [Rural]	Dmnl	0.28574	Calibrated value. Beta coefficient of the MLNM associated with technology status. It is positive, as it indicates the higher the attributed status the higher the utility.	High.	Assumption.

Table 10-3. Existing historical data for selected model variables.

Variable	historical stock EV	historical new EV registrations	historical new car registrations	historical car imports
Unit	Vehicle	Vehicle/Year	Vehicle/Year	Vehicle/Year
Comment	Historical EV stock (Battery electric vehicles, hybrid plug-in excluded).	Historical new EV registrations. Computed as the yearly difference in the total EV stock.	Historical car registrations.	Historical car imports.
Source	EUROSTAT - Passenger cars (Cumulative); INE - Light passenger vehicles (Cumulative);	EUROSTAT - Passenger cars (Cumulative); INE - Light passenger vehicles (Cumulative);	EUROSTAT - Passenger cars (Cumulative); INE - Light passenger vehicles (Cumulative);	ACAP and BPSTAT - Matrículas de Automóveis Ligeiros Passageiros em Portugal
2010	36	0	223,339	23,918
2011	224	188	153,404	23,145
2012	285	61	95,309	15,006
2013	456	171	105,921	16,475
2014	672	216	142,826	28,674
2015	1,398	726	178,506	44,865
2016	2,383	985	207,332	58,719
2017	4,667	2,284	222,129	66,193

2018	9,980	5,313	228,327	77,241
2019	18,139	8,159	223,799	79,472
2020	26,949	8,810	145,417	58,138
2021	43,309	16,360	146,637	72,623
2022	67,347	24,038	157,295	104,951
2023			199,623	109,575

Table 10 3 (cont.). Existing historical data for selected model variables.

Variable	historical car ownership	historical stock ICEV	historical passenger car stock	historical share of ICEV	historical share of EV	historical total population	historical share of rural population
Unit	Vehicle/Person	Vehicle	Vehicle	Dmnl	Dmnl	Person	Dmnl
Comment	Calculated as the total stock of vehicles divided by the total population.	Historical ICEV stock (Petrol and Diesel Cars, hybrid non-plug in excluded).	Historical stock of passenger cars (all vehicle types included: petrol, diesel, hybrid, hybrid plug-in, battery electric, and others).	Computed as the stock of ICEV divided by the total passenger car stock.	Computed as the stock of EV divided by the total passenger car stock.	Historical total population.	Historical share of rural population.
Source	INE - Light passenger vehicles (Cumulative) and World Bank Data (Population)	EUROSTAT - Passenger cars (Cumulative); INE - Light passenger vehicles (Cumulative);	EUROSTAT - Passenger cars (Cumulative); INE - Light passenger vehicles (Cumulative);			World Bank Data;	World Bank Data;
2010	0	4,683,500	4,686,090			10,573,100	0.39
2011	0	4,702,680	4,705,430			10,557,600	0.39
2012	0	4,248,240	4,248,580			10,514,800	0.38
2013	0	4,322,920	4,323,470			10,457,300	0.38
2014	0	4,685,400	4,686,270			10,401,100	0.37
2015	0	4,704,190	4,706,260			10,358,100	0.36
2016	0	4,825,090	4,829,260			10,325,500	0.36
2017	0	5,021,880	5,031,140			10,300,300	0.35
2018	1	5,225,980	5,245,660			10,283,800	0.35
2019	1	5,367,210	5,402,870			10,286,300	0.34
2020	1	5,446,160	5,504,100			10,297,100	0.34
2021	1	5,459,980	5,551,040			10,361,800	0.33
2022	1	5,538,540	5,671,660			10,409,700	0.33
2023							0.32

Table 10 3 (cont.). Existing historical data for selected model variables.

Variable	historical stock ICEV+BEV	historical stock <2y	historical stock 2 to 5y	historical stock 5 to 10y	historical stock 10 to 20y	historical stock >20y	historical total charging points
Unit	Vehicle	Vehicle	Vehicle	Vehicle	Vehicle	Vehicle	EVCS
Comment	Historical stock of ICEV and BEV.	Historical stock of vehicles less than two years old.	Historical stock of vehicles between 2 and 5 years old.	Historical stock of vehicles between 5 and 10 years old.	Historical stock of vehicles between 10 and 20 years old.	Historical stock of vehicles older than 20 years old.	Estimated number of (AC+DC) charging points built in Portugal. The number of charging points is 2.5 times larger in 2020 than it was in 2015 in Europe.
Source	INE - Light passenger vehicles (Cumulative); EUROSTAT - Passenger cars (Cumulative);			EUROSTAT - Passenger cars by age			10.1016/j.trd.2021.102813; Mobi.E data (2024); https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/portugal/infrastructure;
2010	4,683,536						
2011	4,702,904						
2012	4,248,525						
2013	4,323,376	194,719		975,432	2,095,978	506,165	
2014	4,686,072	244,657	491,171	1,018,095	2,294,353	651,369	
2015	4,705,588	317,872	386,530	1,032,151	2,279,074	707,336	941
2016	4,827,473	386,602	391,236	1,004,200	2,267,397	800,794	
2017	5,026,547	435,008	484,312	936,891	2,274,530	928,731	
2018	5,235,960	455,323	600,063	837,759	2,487,090	902,735	
2019	5,385,349	455,739	687,992	929,226	2,317,743	1,061,418	
2020	5,473,109	369,769	722,158	890,773	2,374,961	1,208,302	2,353
2021	5,503,289	519,293	753,339	896,657	2,099,891	1,363,464	3,686
2022	5,605,887	460,556	765,306	981,100	2,047,795	1,523,827	6,533
2023							7,305

Table 10-4. Policy parameters and switches included in the model.

Variable	**Unit**	**Value**	**Comment**	**Source**
policy 1 switch	Dmnl	0/1	Binary variable (0/1). Policy 1 refers to a ban on new ICEV sales. It prohibits the purchase of new ICEVs from a certain year onwards.	-
year of ban on new ICEV sales	Year	2035	Year from which new ICEVs cannot be purchased.	https://www.carsales.com.au/editorial/details/2035-ban-on-combustion-cars-in-europe-could-be-relaxed-146651/

policy 2 switch	Dmnl	0/1	Binary variable (0/1). Policy 2 refers to subsidizing the purchase cost of EVs.	-
EV initial purchase cost subsidy	EUR	4000.00	Amount subsidized by the government, reducing the purchase cost of EVs.	https://www.acp.pt/eletricos/incentivos-e-beneficios/incentivos-para-particulares
policy 3 switch	Dmnl	0/1	Binary variable (0/1). Policy 3 refers to a scrapping scheme that increases the scrapping rate of vehicles older than 20y.	-
adjusted ICEV scrapping rate >20y	1/Year	0.2	New scrapping rate resulting from Policy 3. Value estimated and highly uncertain.	https://www.theportugalnews.com/news/2023-10-19/government-encouraging-the-scrapping-of-older-vehicles/82415
policy 4 switch	Dmnl	0/1	Binary variable (0/1). Policy 4 refers to a yearly increase in fossil fuel costs from 2025 to 2035. Value estimated and highly uncertain.	-
policy 4 annual percentage increase in fossil fuel cost	1/Year	0.1	Annual percentage increase in fossil fuel costs resulting from Policy 4. Value estimated and highly uncertain.	-
randomness in fossil fuel cost switch	Dmnl	0/1	Binary variable (0/1). When '1', it allows for random fossil fuel costs (EUR/L) based on historical values of diesel ("*gasóleo simples*" 2015-2023) prices assuming a normal random distribution.	Direção Geral de Energia e Geologia (DGEG)
randomness in electricity cost switch	Dmnl	0/1	Binary variable (0/1). When '1', it allows for random electricity costs (EUR/L) based on historical values of Banda DC assuming a normal random distribution.	Direção Geral de Energia e Geologia (DGEG)

growth in car ownership switch	Dmnl	0/1	Binary variable (0/1). When '1', it indicates a 24.0% growth in car ownership (vehicle/person) by 2050, from 2013 levels, following an S-curve growth.	The IEA/SMP Transportation Model 2004. 2013 value approximated as the average between 2010 and 2015 light-duty vehicle ownership rate in OECD European countries (459.41 cars per 1,000 people). 2050 projected car ownership rate is 570 cars per 1,000 people, indicating a 24.0% growth from 2013 levels.