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Review

A Review on the Internalization of Externalities in Electricity Generation Expansion Planning

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Abstract: This work addresses the internalization of externalities in energy decision making and in generation expansion planning (GEP). Although the linkage between externalities and energy is well recognized, the issue of the internalization in GEP models and from a sustainability perspective is still far from being fully explored. A critical literature review is presented, including scientific articles published in the period from 2011 to 2021 and selected from scientific databases according to a set of pre-defined keywords. The literature is vast and quite heterogeneous in the models and methods used to deal with these externalities, and therefore a categorization of these studies was attempted. This categorization was based on the methods used, the geographical scope, the externalities included in the planning model and the strategies for their inclusion. As a result, it was possible to perceive that most studies tend to focus on the internalization of externalities related to CO_2 and equivalent emissions from a national perspective. Departing from the critical analysis, pathways for future research were presented, highlighting the need to improve the internalization of social externalities to overcome environmental and economic bias, and also highlighting the importance of recognizing regional specificities and development priorities.

Keywords: sustainability; energy planning; energy modeling; impacts; optimization; multi-criteria decision

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Citation: Costa, C.R.d.S.; Ferreira, P. A Review on the Internalization of Externalities in Electricity Generation Expansion Planning. *Energies* **2023**, *16*, 1840. https://doi.org/10.3390/en16041840

Academic Editor: Peter V. Schaeffer

Received: 27 November 2022
Revised: 31 January 2023
Accepted: 5 February 2023
Published: 13 February 2023

1. Introduction

Contemporary society has sought more and more to reach economic development sustainably; therefore, the inclusion of social and environmental dimensions has become increasingly present in most business and government strategic decisions, similar to electric energy planning scenario planning tools that aim to develop and test alternate future scenarios which can then be used to design strategies and long-term sustainable energy policies. This is the case for generation expansion planning (GEP) problems that adopt a long-term perspective and therefore require the inclusion of different criteria in the decision-making process. The interlinkage between energy and sustainable development is evident and largely debated in the literature (see for example Cerqueira et al. [1], McCollum et al. [2], or Nerini et al. [3]). GEP problems also reflect this continuous pursuit of sustainable development and the need to adapt to new challenges [4,5].

In most studies, the traditional objective of GEP is to minimize the total cost, which consists of the investment and operation cost [5]. This approach does not fully capture the external costs associated with the environmental and social impacts caused by the construction and operation of new-generation plants and the necessary interconnection links. These impacts are mainly considered as restrictions to the system that will limit or prevent the installation of specific power plants in certain locations or on the overall system. Environmental and social costs are then classified as external in the sense that they are not captured by market mechanisms; as such, their negative or positive effects are not internalized by the economic agents that cause them, and may not be included in the traditional cost optimization. From this perspective, the fact that an expansion strategy is cost optimal does not mean that it is the best decision from a social point of view, as society bears the external costs of expanding the system [6]. The internalization of external costs can play a major role in the selection of energy technologies, as shown, for example, in the Istrate et al. [7] study on electricity production through municipal solid waste incineration, or in Oehlmann et al. [8] study on the elicitation of landscape externalities from renewable facilities. It can also significantly affect energy policymaking, as Matamala et al. [9] and Pietrapertosa et al. [10] pointed out. Pricing the environmental and societal effects of energy production is not an easy task, but it is fundamental for the clean energy transition, as Gies [11] pointed out.

Electricity planning has been the focus of several recent studies using different models and methods. Dranka and Ferreira [12] analyzed several renewable energy sources (RES) scenarios, including the 100% RES scenario, using the Energy Plan model. The case of 100% RES was also considered by Gils et al. [13] using the REMix model. The former authors concluded on the importance of accounting for seasonality, and underlined the relevance of also considering the Brazilian external energy dependency as an important criterion for decision making. The latter study showed the need to go beyond a pure cost analysis and to include other criteria, such as regional development, public acceptance, environmental impact, or industrial policy, without major impacts on system costs in energy decision making. In the same way, Moreira et al. [14] called attention to the importance of incorporating sustainability assessment into the formal process of energy decision making and, in Santos et al. [15], a multicriteria technique was coupled with a life cycle assessment (LCA) to compare energy scenarios in terms of global and local social and environmental impacts in Brazil.

This paper aims to review studies that addressed the internalization of externalities in GEP to better understand the approaches being followed and provide some guidelines to improve sustainable energy decision making. With this review, we aim to answer the following research question: How have externalities been internalized in GEP problems?

This literature review addresses the identification of the main methods used in GEP problems, the externalities included and the internalization approach and the geographical scope of the included studies. Based on critical analysis of the literature, avenues for future research are proposed.

The paper is organized as follows. Section 2 presents concepts about externalities in electricity generation and related technologies. Then, Section 3 presents the methodology used in this study. Section 4 presents an analysis of the studies carried out for the internalization of externalities in the GEP problem. Section 5 presents the critical analysis and discussion of the work. Section 6 presents the final considerations.

2. Externalities and Electricity Generation

The definition of externality is broad and well diversified; here, we will present some of these concepts, focusing on the case of electricity generation.

2.1. The Concept of Externalities

According to Ghosh et al. [16], although the term externality is widely used, it is difficult to provide a single precise definition. Cornes and Sandler [17] defined externality as a transaction between two economic agents which affects a third non-participating agent who does not receive any type of payment or compensation. In line with this, for Derani and Neto [18], externalities are "market failures in which the effects of a given activity affect third parties (external) not involved in it".

Almost 100 years ago, Pigou [19] was already spreading the idea of the existence of positive and negative externalities, suggesting the possibility of them being monetized for the good of society. Understanding these impacts and finding a balance between them is a major challenge, including in planning sustainable energy systems.

In this study, we will adopt the definition by Pearce and Turner [20], who defined externalities as side effects that are unintentionally generated by production and consumption processes that will affect society positively or negatively. Positive externalities are considered beneficial, that is, they externalize benefits to third parties without them paying for the benefits received. As an example, we can mention the increase in the human development index (HDI), the generation of jobs, and the greater circulation of economic resources that occur in a place where a business unit is installed [21].

Negative externalities, on the other hand, occur when the construction/operation of a business unit affects its surroundings, reducing the availability of services and natural resources, and decreasing the wellbeing of the population or the production of other goods or services. As an example, we can mention the pollution of a river or the dispersion of particles in the air, actions that directly affect the quality of life of people who inhabit the affected region [21].

Externalities can be perceived as generating a cost (when the activity has an impact on the environment) or revenue (when the activity generates a benefit) [22]. Externalities, be they environmental or social, need to be counted in the implementation costs to allow more adequate decision making about which energy generation technologies will be used in each case. This approach will result in sustainable planning that guarantees the supply of energy for current needs, but without compromising the supply of future needs [16].

For Field and Olewiler [23], external costs are the real costs for society, which include social and environmental impacts but which are not borne by the generator and, consequently, are not passed on to consumers. As stated by Becker et al. [24], the analysis of the impact at a societal level is a much more complex task than at the level of the individual, since all "external costs and benefits" must also be included.

According to Nguyen et al. [25], when talking about externalities, the focus most often is on negative externalities, as these represent the depreciation of natural resources or social wellbeing. It can be said that negative externalities are those costs caused by environmental or social damages existing in the production process of a good or service, but which are not normally included in the respective market price and, therefore, are not passed on to consumers [26].

2.2. Externalities of Electricity Production

Regarding externalities in the energy sector, Elliott et al. [27] supports that these generated costs (or benefits) should gradually be incorporated into the final energy price. This attitude brings a better understanding of the real cost of energy to society and will help public managers in making decisions about the energy policies adopted.

Considering the concepts discussed above, the need to integrate externalities into the total costs of the enterprise is clear; this action is called internalization. Internalizing an externality consists of changing the incentives for people to take into account the external effects of their actions [28]. In a similar vein, Gies [11] recalls that externalities other than air pollution and climate change have received little attention for energy production, and human mortality dominates the economic models; they concluded on the need to translate all impacts into costs.

According to Söderholm and Sundqvist [29], the externalities resulting from the generation and use of electricity can be environmental, economic, political, and social. The authors claim that environmental externalities are directly related to impacts and changes in the climate and other ecological aspects, economic externalities are linked to actions of subsidies and fiscal incentives, political externalities involve wars and conflicts that can reach a global scale, and social externalities are related to the health and wellbeing of society.

The most debated externalities in the electricity sector are those related to environmental issues, which are those linked to the environmental impacts of the generation and use of available natural resources. These externalities are usually related to a negative impacts on the environment, although they can in some cases have a positive impact. CO_2 emissions, land and water use, climate change, and earthquakes are some examples of impacts that may be related to energy generation processes. We can also cite deforestation, diversion of rivers, and the creation of dams among others as examples of the impacts of the process of building energy production units [30]. As Streimikiene et al. [31] recalled, a power plant that generates emissions, causing damage to building materials, biodiversity, or human health, imposes an external cost on different members of society. In addition to these environmental externalities, the related to social issues must also be considered. Similar to environmental issues, some aspects will positively and negatively impact people, regions, and generations, and should therefore be considered in the energy planning model [29]. Social externalities can be related to job creation, human development in the region or society, loss or increase in local revenues, or any other aspect that may have a positive or negative impact on society in general or on local communities.

According to Streimikiene and Alisauskaite-Seskiene [32], renewable energy sources generate fewer externalities when compared to fossil fuel-based generation sources. Additionally, Sovacool and Monyei [33] concluded on the potential of low-carbon options to provide positive externalities compared to fossil fuels. However, as Bielecki et al. [34] recall, so-called clean energy production is not free from external impacts, and these impacts have to be taken into consideration when planning electricity generation. Therefore, the internalization of externalities is a fundamental step in the definition of energy policies. This process will allow us to define the real impacts of these externalities, and translate them into monetary values to be properly included in the benefit/cost models that will result in better solutions from the perspective of sustainability. Therefore, internalizing these factors in energy decision-making problems is a critical task to arrive at an adequate planning approach free from possible economic bias, making sure that external costs also reflect the region or case under analysis [34].

According to Sovacool et al. [35], low carbon electricity sources such as geothermal, solar thermal and solar photovoltaic, wind, hydro, and nuclear sources have fewer negative externalities compared to electricity generation from fossil fuels. In addition, the same authors present in their study the nine main categories of negative externalities linked to electricity generation: air pollution; climate change; chronic accidents; catastrophic accidents; aesthetic issues; land use; use of water; loss of species and destruction of habitats; and occupational exposure.

Sovacool et al. [35] also highlighted the existence of externalities linked to geopolitical issues, such as the increased probability of wars due to the extraction of natural resources, the guarantee of energy supply, the destruction of cultural icons such as national parks, recreational opportunities or activities such as fishing or swimming, the perhaps perpetual and extremely long-lasting maintenance of spent nuclear fuel depots, and changes in the local and regional economic structure through loss of labor and jobs and transference of wealth and reductions in GDP.

3. Methodology

This literature review was prepared with the aim of better understanding relevant issues related to the internalization of externalities in the GEP problem, possible modeling approaches and methods, and technological characterization of the electrical system. The research was carried out according to the steps elaborated in [36] and summarized in Figure 1.

Based on the problem question, the authors selected words that would allow obtaining studies relevant to the subject to be analyzed. For the keyword selection, we focused on identifying the main concepts, looking for synonyms and abbreviations. From the research question, we highlighted the most important topic to guide our search, namely "generation expansion planning" and "externalities", and included other expressions frequently used in the literature with a close meaning.

The following keywords were identified: ("generation expansion planning" OR GEP OR "electricity planning" OR "power planning" OR "electrical plan" or "electricity energy plan) AND (externality OR "externalities OR "external cost" OR "external tax"). For the choice of keywords, the need to obtain as many articles as possible that answer the research question was considered. Although there is the possibility that some researchers approach the subject without mentioning keywords identical to those described, the selected keywords represent the focus of the study and led already to a significant number of articles that should allow us to look critically at the issue of externalities' inclusion in GEP.

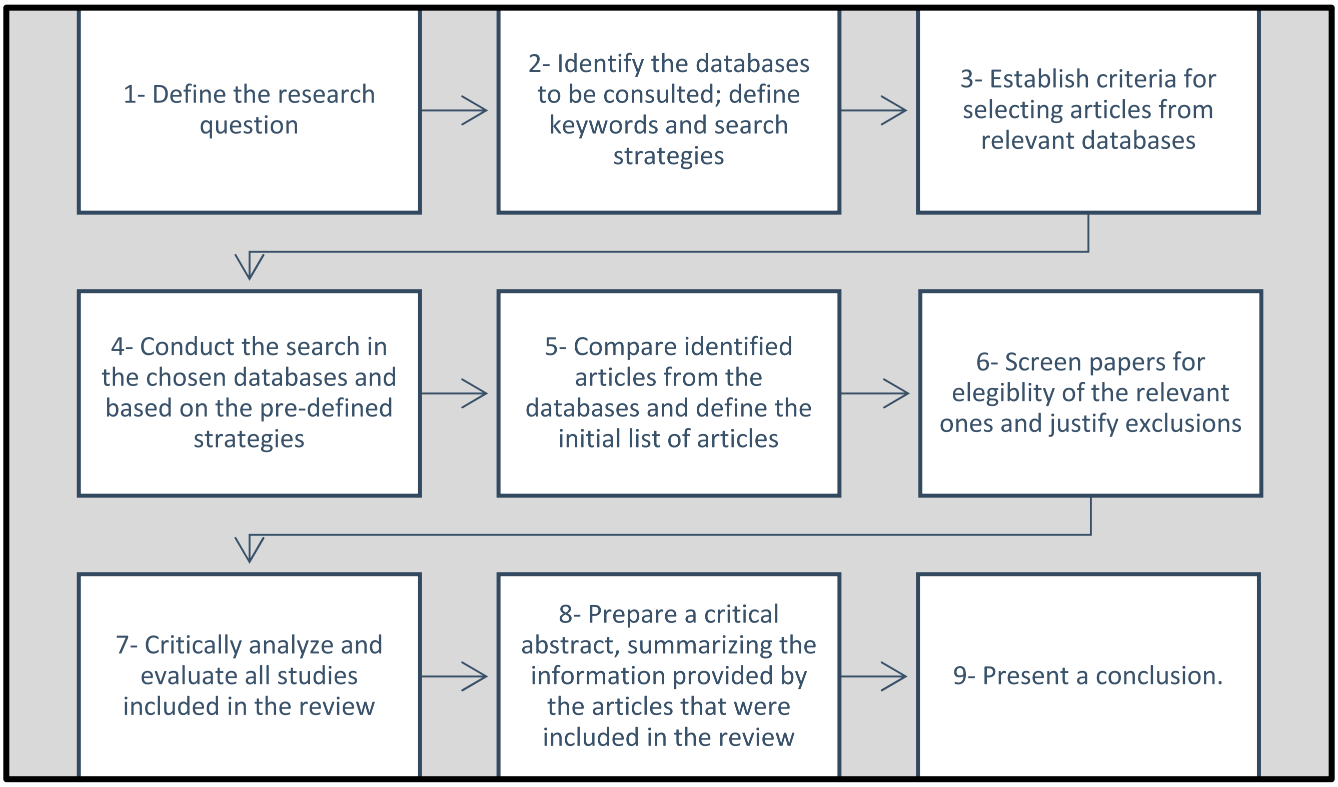

Figure 1. Methodological follow-up of the research..

The keywords were used in research carried out in academic indexes, libraries, and other available means to locate studies that relate to the theme of the problem. Material published in English and Portuguese was used for this research. Given the proliferation of studies on energy planning and related topics, the research focused on recent studies, and only articles published from 2011 to 2021 were considered.

Following Petrou et al. [37], for the selection of studies to be reviewed in detail, the following steps were taken: (1) Examine titles and abstracts to remove irrelevant documents; (2) Obtain the complete texts of all potentially relevant articles; (3) Gather several reports from the same study; (4) Examine whether the studies meet the eligibility criteria; (5) Contact the authors, when appropriate, to clarify the eligibility of the study; (6) Make final decisions on the inclusion of studies before proceeding with data extraction.

The data for each study were extracted into an electronic form in the Excel software. At this stage, it was necessary to read the articles in full. An information report was prepared to contain a summary of the results of the individual studies included in the systematic review.

As can be seen in Table 1, the keywords were initially searched in the Science Direct and Web of Science indexer, initially obtaining more than 14,000 articles; this number was reduced at each stage of insertion of new keywords. After the insertion of all keywords previously defined by the authors, 3012 articles in Science Direct and 4909 articles in Web of Science were obtained for analysis.

Table 1. Number of articles found in each filtering step based on keywords.

Keywords	Number of Articles Science Direct	Number of Articles Web of Science
"Generation expansion planning" OR GEP	10,734	3701
"Generation expansion planning" OR GEP OR "electricity planning"	11,460	9806
("Generation expansion planning" OR GEP OR "electricity planning" OR "power planning" OR "electrical plan" or "electricity energy plan")	14,451	10,974
("Generation expansion planning" OR GEP OR "electricity planning" OR "power planning" OR "electrical plan" or "electricity energy plan) AND (externality OR "externalities OR "external cost" OR "external tax")	3289	4909

Figure 2 presents the flow diagram based on the preferred reporting items for the systematic reviews and meta-analyses (PRISMA) statement and summarizes the main steps for the studies' selection and inclusion in the review [38].

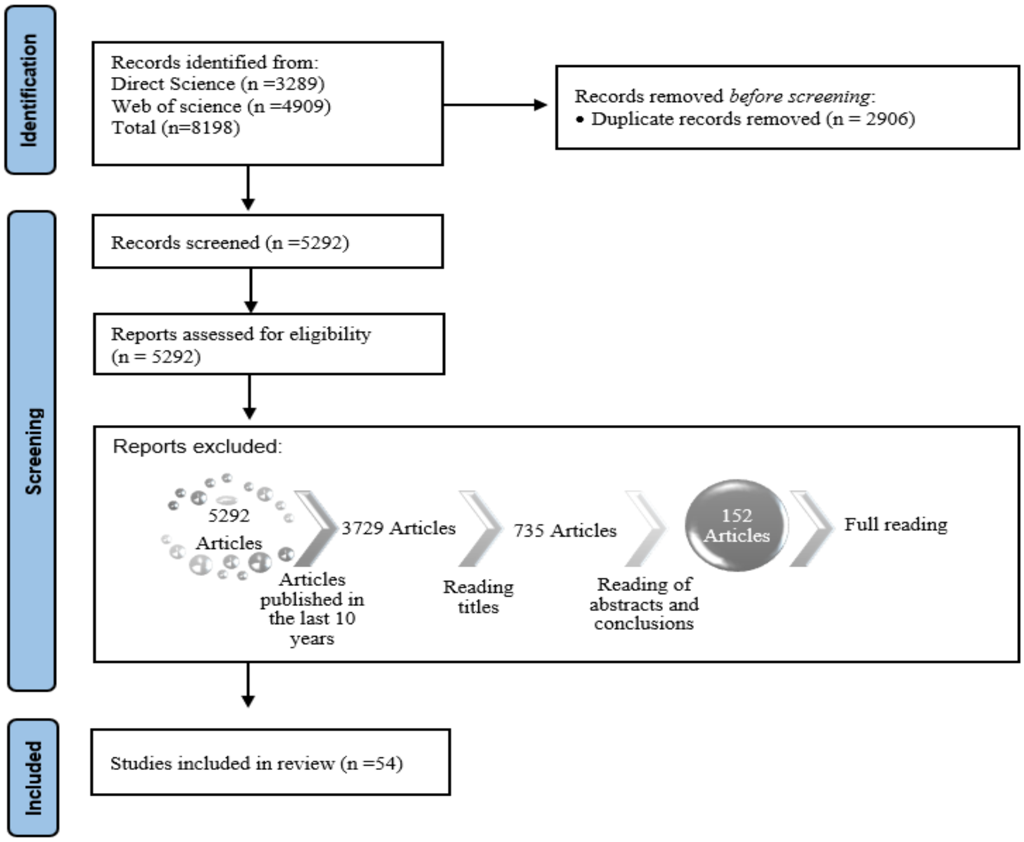

Figure 2. Diagram of analysis based on the PRISMA statement.

For the inclusion of articles in the review, the following eligibility criteria were previously elaborated on and defined from the research question:

- Published in the defined timeframe for the analysis;
- Related to the generation of electricity;
- Clear definition of the geographical scope of the work;
- Clear definition of which externalities were included in the study; and
- Research papers published in journals (conferences and review papers excluded).

To identify duplicate articles and manage the articles found and analyzed, Mendeley software was used. After excluding duplicate articles, selection filters were applied. The articles published in the last 10 years were selected, resulting in 3729 articles. All the titles of the articles found in the previous step were read to verify the link between the article and the theme in this literature review, and 735 articles were selected. From there, all abstracts and conclusions were read, and 152 articles were selected. These articles were read in full, and based on their results and similarity with the proposed theme, 54 articles were selected for the literature review.

4. Results

This section details and critically analyses the reviewed studies. Given the large number of papers, and to simplify the analysis, the methods were classified as "optimization" in the case that the problem looks for the maximization or minimization of an objective function, or "multi-criteria decision analysis (MCDA)" if a set of discrete alternatives are being evaluated and characterized against a set of criteria to support the selection of the best alternatives. An additional category coined as "Scenario Analysis" was included for papers that simulate or address different scenarios or alternatives using, for example, sensitivity analysis, but without attempting criteria aggregation or optimization of the system. In some cases, the model used was also presented.

Table 2 summarizes the articles found and characterizes them according to the method used on the GEP problem, the externalities considered, and the approach used for the inclusion of these externalities.

Table 2. Reviewed studies on the internalization of externalities in GEP.

Authors	Year	Method for GEP	Socio-Environmental Effects Addressed	Inclusion of Externalities	Region
[39]	2011	Optimization	CO_2 emissions (life cycle)	Objective function (emissions)	Unspecified case study
[40]	2011	Optimization (Wien Automatic System Planning-WASP-IV)	CO_2 emissions, particulate matter (PM), NO_x, and SO_2,	Objective function (cost)	Israel
[41]	2012	Optimization	CO_2 emissions	Objective function (cost)	Korea
[42]	2013	Optimization	CO_2 emissions	Objective function (emissions)	Hypothetical case
[6]	2013	Optimization	Unspecified estimated total environmental cost	Objective function (cost)	Brazil
[43]	2013	MCDA	Employment, visual impact, noise pollution, local income, CO_2 emissions, land use, public health, water consumption	Independent criteria. Participation of decision makers	Portugal
[44]	2014	MCDA	CO_2 emissions, PM, NO_x, SO_2, nuclear waste	Independent criteria. Participation of decision makers	Tunisia
[45]	2014	Scenario analysis	NO_x, PM, greenhouse gas (GHG)	Levelized cost of energy scenarios	Fujian, China
[46]	2014	Optimization	CO_2 emissions	Objective function (cost)	Portugal
[47]	2014	Optimization	CO_2, NO_x and SO_2 emissions, other unspecified estimated total environmental cost	Objective function (cost) and restrictions	China

Table 2. *Cont.*

Authors	Year	Method for GEP	Socio-Environmental Effects Addressed	Inclusion of Externalities	Region
[48]	2014	Scenario analysis (System advisor Model-SAM)	Land use	Life cycle cost, scenarios	California, USA
[49]	2014	Scenario analysis (Long-range Energy Alternatives Planning-LEAP)	CO_2 emissions	Scenarios	Bangladesh
[50]	2014	Optimization	GHG (life cycle), ozone layer, acidification and photochemical pollution	Objective function (CHG emissions)	UK
[51]	2015	Optimization	CO_2 emissions	Objective function (cost)	Iran
[52]	2016	MCDA	Several (20), e.g., job creation, economic security, contribution to education, science and culture, social acceptance and perception, climate change and pollution, waste creation, or adaptation to local natural conditions	Independent criteria. Participation of decision makers	Lithuania
[53]	2016	Optimization	CO_2 emissions	Objective function (cost)	Portugal
[54]	2016	Optimization	Unspecified estimated environmental cost of emissions	Objective function (cost) and restrictions	India
[55]	2016	Optimization	CO_2 emissions and others (unspecified)	Objective function (cost)	China
[56]	2016	Optimization	CO_2 emissions, PM, NO_x, and SO_2,	Objective function (cost)	Kietrz, Poland
[57]	2016	Optimization	CO_2 emissions and nuclear waste, land and water use, job creation, social acceptance, and security	Objective function (cost)	Iran
[58]	2016	Optimization	CO_2, NO_x, and SO_2 emissions	Objective function (cost) and restrictions	Greece
[59]	2016	Optimization	CO_2 emissions	Restrictions	Taiwan
[60]	2016	Optimization	CO_2 emissions	Objective function (cost)	Poland
[61]	2016	Optimization	CO_2 emissions. nuclear accidents	Objective function (cost) and restrictions.	Japan
[62]	2017	Optimization	CO_2, CH_4, N_2O, NH_3, non-methane emissions volatile organic compounds (NMVOC), SO_2, NO_x, and PM_{10} (life cycle)	Objective function (cost)	Italy
[63]	2017	Optimization	CO_2 emissions	Objective function (cost)	Portugal
[64]	2017	Scenario analysis (LEAP)	CO_2 emissions	Scenarios	Ghana
[65]	2017	Optimization	CO_2 emissions	Objective function (cost) and restrictions	Ghana

Table 2. *Cont.*

Authors	Year	Method for GEP	Socio-Environmental Effects Addressed	Inclusion of Externalities	Region
[66]	2017	Optimization	CO_2 emissions	Objective function (cost) and restrictions	China
[15]	2017	MCDA	employment, visual impact, noise pollution, local income, CO_2 emissions, land use, public health, water consumption (life cycle)	Independent criteria, participation of decision makers	Brazil
[67]	2018	Optimization (COBRA model)	Emissions of NO_X, SO_2, CO_2, CH_4) and public health	Objective function (cost) and restrictions	Northeast, USA
[68]	2018	Scenario analysis (input-output models)	CO_2 emissions, public health, loss of biodiversity, local effect on crops and damage to materials (life cycle)	Design/technology analysis	South Africa
[69]	2018	Optimization (LEAP and OSeMOSYS)	CO_2 emissions and human health (life cycle)	Objective function (cost)	Spain
[12]	2018	Scenario analysis (EnergyPLAN model)	CO_2 emissions	Scenarios	Brazil
[70]	2018	Optimization	CO_2 emissions	Objective function (cost)	China
[71]	2019	Optimization (LEAP and OSeMOSYS)	CO_2 emissions	Scenario analysis	China
[72]	2019	Optimization (COBRA model)	CO_2 emissions, PM, NO_x, SO_2 and ozone	Objective function (cost) and restrictions	Northeast, USA
[73]	2019	Optimization	CO_2 emissions, PM, NO_x, and SO_x	Objective function (cost)	Chile
[74]	2019	MCDA	Sevaral (19), e.g., job creation, noise, public health, regional development, relocation of people, water use, CO_2 emissions, or land use.	Independent criteria, participation of decision makers	Bangladesh
[75]	2019	Optimization	NO_x, and SO_2 emissions	Restrictions	China
[76]	2020	Optimization	CO_2 emissions, PM, NO_x, and SO_x,	Objective function (emissions)	Taiwan
[77]	2020	Scenario analysis (LEAP)	Emissions of CH_4, NO_x, CO, CO_2 and SO_2, N_2O, SO_x, volatile organic compounds and PM	Scenarios	Pakistan
[78]	2020	Optimization	CO_2 emissions	Objective function (cost)	Brazil
[79]	2020	Optimization	CO_2 emissions, NO_x, and SO_2,	Restrictions	Jiangsu, China
[80]	2020	Optimization	CO_2 emissions	Objective function (cost)	Chile
[81]	2020	Optimization	CO_2 emissions	Objective function (cost)	Iran
[82]	2020	Optimization	CO_2 emissions, NO_x, and SO_2,	Objective function (cost)	Hypothetical case in Nigeria
[83]	2020	Optimization	CO_2 emissions	Objective function (cost)	Ireland

Table 2. *Cont.*

Authors	Year	Method for GEP	Socio-Environmental Effects Addressed	Inclusion of Externalities	Region
[84]	2021	Scenario analysis (LEAP)	Emissions of CH_4, NO_x, CO, CO_2 and SO_2, N_2O, SO_x, volatile organic compounds and PM	Scenarios	Pakistan
[85]	2021	Optimization	CO_2 emissions	Objective function (cost)	Chile
[86]	2021	Optimization (LEAP and OSeMOSYS)	CO_2 emissions	Scenario analysis	Sumatra, Indonesia
[87]	2021	Optimization	CO_2 emissions (life cycle)	Objective function (cost) and restrictions	Kenya
[88]	2021	Optimization (LEAP)	CO_2 emissions	Scenario analysis	Gilgit-Baltistan, Pakistan

Externalities can be considered in the model as a restriction [59,75,79], or they can be included in the cost function to be optimized (e.g., [40,63]). In other cases, a mixed approach is used and some externalities are addressed as restrictions, and others are included in the objective function [58,66].

The internalization of CO_2 emissions in the models developed remains a common factor. Most of the reviewed articles included CO_2 emissions, although using different approaches for its inclusion in the model formulation and being based either on monetized or non-monetized assessment. The revision also shows that there are a wide variety of well-established mathematical models to deal with the GEP problem and assist in decision making concerning developed energy policy.

The multi-objective MESEDES model for example, proposed by Unsihuay-Vila [39], seeks to minimize the costs of expansion and operation of energy generation and transmission. According to the authors, the inclusion of life cycle GHG emissions can cause a significant impact on the energy planning process. When considering the positive impact that the reduction of GHG emissions generates, it is argued that the use of RES (renewable energy sources) has the potential to promote the reduction of emissions with a low effect on cost.

Becker et al. [40] used the WASP-IV (Wien Automatic System Planning) model with a focus on defining the best mix of energy sources, with the inclusion of the costs of various externalities, and applied it to an Israeli case. The work aimed to minimize costs (private or social, depending on the scenario), subject to a set of restrictions related to pollutants (particulate matter (PM), NO x, CO_2, and SO_2). In the analysis, each pollutant was considered as an objective in itself, and a specific tax rate was considered for each scenario. The cost of the damage was provided from the literature, and the authors analyzed different weight scenarios for the pollutants. The study allowed discussion of the trade-off between pollution reduction and increased generation cost.

Kim et al. [41] included the costs of producing and trading CO_2 emissions in the objective function for optimizing energy plans in South Korea. This allowed for the economic evaluation of conventional and renewable energy, considering uncertainties that were modelled by a Monte Carlo simulation. Randomly sampled CO_2 prices were applied in the analysis. The results confirmed the importance of renewable energy systems from both a cost and environmental perspective.

Santos et al. [53] sought to demonstrate how the uncertainty of renewable energies can be included in long-term planning; for this, the authors used a combination of a Monte Carlo simulation and a deterministic optimization model. The purpose of this combination was to analyze uncertain parameters that could affect electrical systems and that should be included in the planning process. CO_2 costs were included in the objective function, and the problem was formulated as non-linear optimization.

Santos et al. [15] study demonstrated the use of MCDA for the inclusion of different social, economic, and environmental dimensions in GEP. The authors concluded that although cost was still a main criterion for the analysis, the internalization of externalities in the model should not be neglected, as it will significantly affect decision making in energy planning.

MCDA is often based on expert feedback for the assessment of scenarios or technologies and weightlifting, as can be seen in the work of Unsihuay-Vila et al. [39], Ribeiro et al. [43], (Brand and Missaoui [44], Štreimikiene et al. [52] and Khan [74]. The involvement of experts contributes to a more comprehensive and qualitative understanding of the impacts that will occur according to the decisions made concerning energy planning [74]. Ribeiro et al. [43] for example, pointed out the importance of including criteria such as job creation, local development and public health on sustainable electricity planning. As an example, the authors indicated that the high unemployment rate during an economic crisis makes the opportunity costs of social labor close to zero, which may determine the decision of specialists to privilege generation of jobs in a certain location or during a certain period. In this way, MCDA analysis contributes to a broader analysis of the scenario and will lead to decisions guided not only by quantitative aspects but also by more qualitative aspects that are difficult to quantify using a numerical scale.

Different optimization models stand out as the most common approach to deal with GEP and internalize externalities in the decision-making process. Georgiou [58] used MILP (Mixed Integer Linear Program) to develop a cost optimization model for energy planning for the case of the Greek electricity sector. In the study, externalities were included in the objective function by including the allowance costs of the GHG emission rights of all conventional power generation plants (new, old, and scheduled), and the restrictions included ceilings and emission targets. In the study, only equivalent CO_2 external environmental costs were monetized and included in the objective function. However, Georgiou [58] underlined that the objective function could be advanced by incorporating additional external cost categories to express both the environmental and social costs of electricity generation. Another suggestion by the author is the construction of a multi-objective MILP model that adopts a multi-criteria approach through updating the environmental dimension as a second objective function or/and adding any other criteria such as energy security, employment, etc.

Afful-Dadzie et al. [65] developed a MILP model for Ghana to allow for the analysis of the impact of budget constraints on the optimal and time-based combination of power generation types, and the associated level of unmet electricity demand, incorporating the cost of CO_2 emissions into the objective function. In the restrictions of the proposed model, CO_2 emission limits were established.

Tang et al. [66] used a MILP model for power generation in China, addressing in particular coal-fired generation units and the internalization of CO_2 emissions related externalities in the model. The restrictions of the model included CO_2 capture costs and CO_2 emission limits. With the internalization of externalities, the authors could conclude that the government should prioritize the development of low carbon units through the development of efficient production units and closing of inefficient units.

A MILP model was also used by Quiroga et al. [73] to analyze the impact of implementing CO_2 and local pollutant emission rates in planning the expansion of a power system in Chile. An optimization model was formulated and implemented to establish the optimal strategy for expanding the energy system, considering the installation of large-scale plants and renewable distributed generation. Externalities were considered in the model by including, in the objective function, the values of the emission rates of CO_2, PM, SOx, and NOx. From the internalization of these externalities, the work suggests that there is a solid incentive for hydroelectric development in planning the expansion of the energy system in Chile.

Pereira and Sauma [80] also used a MILP to analyze the effects of implementing a two-stage carbon tax in a ten-year energy expansion planning model for the Chilean electricity system. Externalities were included in the objective function based on equivalent CO_2 emission rates. The inclusion of these externalities contributed to the conclusion that the expansion of the system tends to favor solar generation units complemented by combined cycle gas turbines. The work of Rodgers et al. [72] used the MILP model and included health damage explicitly in the objective function; these externalities are related to the health impacts generated by CO_2 emissions.

The work of Santos and Legey [6] aimed to represent the costs associated with environmental impacts in a system that encompasses many types of generation plants in Brazil. For that, it was necessary to elaborate on the MAPE model (an environmental model for planning electric expansion which is a model based on the traditional MELP, a model for long term expansion planning). The externalities were included in the objective function, and the values were obtained from the Furtado study [89] that carried out a contingent assessment study to assess willingness to pay to avoid the environmental impact of different types of electricity generation technologies.

Chen et al. [55] established a multi-period optimization model (PPOM-CHINA) to minimize the total cost of the energy sector. The authors included externalities in the objective function, and these costs were split between external carbon cost and non-carbon external cost. The external carbon cost included the carbon equivalent value of GHGs. The non-carbon external cost included the costs of health impacts, biodiversity, agricultural production losses, property damage, and land damage extracted from the New Energy Externalities Developments for Sustainability (NEEDS) database.

Patrizio et al. [62] focused on the external costs associated with atmospheric emissions throughout the biogas production chain. A spatial model was developed for the optimization of renewable energy systems, including externalities in the objective function and damage cost factors for a set of airborne emissions. For the conditions presented in the study, the results showed that internalizing the externalities of the biogas generation process has a limited impact, since the benefit of the energy vectors of biogas in terms of reduction of local and total emissions was low in comparison with other production costs.

The study by Garcia-Gusano et al. [69] aimed to evaluate the consequences of internalizing socio-environmental externalities associated with power generation in Spain. The authors presented a methodological framework which is based on the combination of life cycle assessment (LCA), external costs calculation, and energy systems optimization modeling. The internalization of externalities led to solutions that could accelerate the decarbonization process and favor renewables' inclusion in the system.

5. Discussion and Future Research Directions

From the analysis of the articles reviewed, with regard to the internalization of externalities, it is possible to highlight that most of the articles published in the last 10 years are exclusively focused on greenhouse gases, which can be justified by the growing concern with the climate change and the close energy–climate relationship. Another factor that may be related to this high frequency of internalization of these impacts is the existence of a well-defined methodology for pricing the cost of carbon in the world market, which can facilitate the inclusion of these impacts in the proposed planning models [80]. The internalization of externalities is then not yet fully considered in the literature, but the inclusion of GHG and the related CO_2 monetization tends to prevail over other social and other environmental externalities.

Most of the reviewed studies tend to use mathematical approaches to solve the GEP frequently based on optimization models. However, as Lund et al. [90] highlighted when referring to optimization and simulation models, each approach has its own advantages and drawbacks. Amongst the drawbacks of optimization models, we can mention the loss of non-optimal solutions that could be useful for informing decision makers and populations. MCDA, on the other hand, can play a fundamental role by allowing us to include some criteria that are hard to quantify and take into account the decision makers' perspective. Combining MCAD and optimization models can be a useful strategy; this may be done by analyzing optimal and close-to-optimal scenarios derived from the optimization problem as discrete alternatives included in a multicriteria exercise [15].

External costs frequently include environmental damage, individual and collective health impacts, and interferences in the social arrangement. These costs are often not internalized in the fossil fuel energy chain and other conventional technologies such as large hydroelectric and nuclear plants; thus, distortion is generated in the real costs of these processes. Therefore, decisions in the electricity market may be distorted, as energy prices may not reflect all supply chain costs [91]. Moreover, the emissions generated in different regions can have different effects and, consequently, different costs, depending on the location and characteristics of the source of pollution [34] and its dispersion (which also poses additional concerns on the region, country or frontier of the analysis). The same applies to social impacts that may be perceived and valued differently in different regions.

Based on the critical analysis of the articles presented in this study, some directions for further research and improvement of the GEP problem may be outlined, as follows.

5.1. A Regional Perspective Can Bring Additional Benefits to the GEP Problem

For most of the reviewed studies, the geographical scope refers to a country level, which calls attention to the need to bring a regional perspective to the energy planning problem and in particular to the assessment of externalities. This is particularly relevant for studies to be carried out in countries with a larger territorial dimension and heterogeneous characteristics, e.g., climate, environmental or socio-economic differences among regions. Nevertheless, even for smaller countries, these differences must be considered, and the local perspective should not be overlooked, as energy projects can bring important economic benefits but can also represent a source of conflict and discontentment [92]. Oree et al. [93] reinforce that the geographic availability of variable renewable energy resources should be incorporated into the GEP model. Other important variables to be considered are weather conditions, the regional correlation between them, and their effect on the generation mix. Moreover, regional disparities can be extremely relevant to the social dimension of the problem, as already discussed in the case of employment [94] and property values [95,96].

Debnath et al. [97] already called attention to the need to recognize and consider the specific needs of each energy system. The authors claimed that in developing countries, energy planning models are predominantly concerned with increasing energy access, and not as much with GHG emissions. This is in line also with the findings of Urban et al. [98] that many models are biased towards industrialized countries and do not reflect the main characteristics and unique features of developing countries [99]. Therefore, future research must be directed toward the development or adaptation of energy models to the socio-economic, political, organizational, and resource context of the region or country under analysis, and to the suitable integration of the regional diversity that may compose one energy system.

5.2. Expanding the Models beyond GHG Is Fundamental for a Whole Sustainable Perspective

Another point to be highlighted is the need for further studies on other indicators such as land use, water use, deforestation, human health, job creation, education, etc.

As shown above, most of the internalization works focus on indicators linked to greenhouse gases. Despite them being a very important concern, to obtain a suitable plan for sustainability, addressing only those aspects is not enough. It is important to ensure a search for indicators that represent the three pillars of sustainability (the economic, environmental and social). The identification of which indicators are more suitable for this process of internalizing externalities with a focus on sustainability has been a major challenge for researchers. Currently, much of the research linked to the definition of these indicators has used the 17 sustainable development goals (SDG) as a reference for the creation of the selection criteria for these indicators. Santika et al. [100] identified 25 targets from the SDG that are directly related to obtaining or using energy. The authors claim that access to energy is essential to achieving the SDG, as it plays a fundamental role in ending poverty and hunger, ensuring health, education, and access to water, as well as being one of the pillars of support for economic development and protection of the environment.

The reviewed studies show then the existence of an externality bias linked to the pillar of the environment. Social externalities, when treated, are treated indirectly; that is, the focus is still on minimizing cost and reducing greenhouse gases. To improve the sustainability of electricity generation plans, it is clear that we need to carry out more studies that include social indicators (such as job creation, human development, health and education), allowing for better policy decision making.

This broader perspective of sustainability is also linked to the regional gap already mentioned. Different regions within a country may present different realities and, consequently, different development priorities in each of the regions may be required. Analyzing from the point of view of sustainability, a particular region in which installation of a power plant is intended may have particular concerns related, for example, to specific protected areas (e.g., indigenous lands or cultural icons), regional development needs, child labor or an under-educated population which may not be relevant to other regions. Understanding this local or regional reality is fundamental for decisions related to the implementation of new plant units and to ensure effective internalization of externalities, or, as Sovacool et al. [35] refer to them, the hidden social and environmental costs of electricity. Thus, further studies are required to help in the selection of the most appropriate indicators for each problem according to the defined frontier or geographical scope of the problem, the priorities assigned to each region, and the possibility of internalization in GEP models, whenever possible, with economic valuation.

One of the greatest difficulties in the process of internalizing externalities is obtaining the costs of each externality generated by each of the sources or technologies used for the energy generation process [101]. When we talk about social externalities, the costs are even more difficult to assess, which is why researchers frequently use quali-quantitative methodologies to obtain the approximate costs of externalities. The works that are most concerned with internalizing social externalities [15,43,52,74] frequently use MCDA and tend to rely on the collection of feedback from experts. As Wang et al. [102] recalled, MCDA is suitable for addressing complex problems under multi interests and perspectives, and can be used to complement externalities' valuation and a cost–benefit analysis when it is difficult to reflect outcomes and costs in measurable terms [103]. However, other approaches can be considered for the inclusion of social indicators, such as the use of the MILP model proposed by Shakouri G. and Aliakbarisani [57] and integrating aspects such as job creation. The key point that we must emphasize is that regardless of the model adopted for the development of a more sustainable electricity generation plan, the inclusion of the social dimension is fundamental.

6. Conclusions

This work presented a critical review of the literature, aiming to fill the gap on the internalization of externalities in GEP and consider an overall sustainability perspective. The results confirm that the complexity of the GEP comes not only from the need to include different aspects in addition to costs, but also from the specificities of each case under analysis, the availability of information and the importance attributed to the inclusion of externalities in the decision-making process. The main outcomes of the research show that the reviewed articles tend to prioritize the internalization of environmental impacts with concerns about GHG emission. This may derive from the significant attention given to the climate change aspects, countries' regulations or even the existence of well-defined methodologies and markets for pricing carbon.

As for the models used, these were classified under three main categories, namely the optimization, MCDA and scenario analysis. These optimization approaches allow the inclusion of externalities either in the objective function or as restrictions, with the quantification of the external impacts and in some cases with monetary valuation. However, the quantification and valuation of externalities is not an easy task, and some authors use MCDA to deal with this complexity and integrate a diverse set of impacts. The case of social aspects is particularly complex to assess and quantify. Some optimization models already attempt this internalization, for example, for the case of job creation, but the most common approach is still MCDA. Moreover, scenario analyses emerge also when no aggregation or optimization is attempted, and the scenarios are characterized according to a set of aspects.

The review showed that there is still great room for improvement in externalities' valuation and internalization in GEP in order to reach sustainable plans capable of maximizing social welfare. Different models may be used, but two main areas for future research are highlighted: (1) the required regional perspective of the models, taking into account the specific social conditions of each region and avoiding general assumptions that may overlook the local population's needs; and (2) the need to clearly include and value social aspects and environmental factors that go beyond climate change, which is also interlinked with the aforementioned regional perspective. The adequate representation of these externalities, whether positive or negative, is essential for the search for more efficient energy generation plans and policies.

As for the limitations of the study, we should recognize that the choice of the keywords could result on leaving out some relevant papers also addressing environmental and social impacts in GEP but not necessarily using the words "externalities" or "external costs". Despite this consideration, we believe that the main conclusions will not be significantly affected, and this review not only offers a clear vison on how externalities are being internalized in GEP problems, but has also allowed us to identify directions for future research.

Funding: This work has been supported by the FCT–Fundação para a Ciência e Tecnologia within the R&D Units Project Scope: UIDB/00319/2020.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationship that could have appeared to influence the work reported in this paper.

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