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Low-Emission Energy Outlook in Small Island Developing States – The case of Sao Tome And Principe

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Abstract

This work proposes a combination of a cost-efficacy, multicriteria and partial equilibrium analyses, to support the evaluation of viable options for low-carbon and resilient development, in a Small Island Developing State. We present reference and mitigation scenarios to 2030, including measures of renewable electricity, both in the grid and isolated; transports replacement; and energy efficiency in households and services sectors, including improved stoves, efficient street lighting and implementation of household LEDs. We report the marginal abatement cost curve for such measures and the results of a multicriteria qualitative assessment, showing strong support for the implementation of 4MW of renewable electricity in mini-hydropower plants, 12MW in solar PV power, and 1MW in an isolated mini-hydropower plant. We quantify energy and emissions saved in the mitigation scenario and a new energy balance. Overall, we estimate possible reductions in emissions in 2030 of 29% in electricity generation, and 0.25% in final energy demand, totalizing 9% fewer emissions in the country in 2030. The combined methodology shows higher emission savings than those reported by the country in its National Determined Contribution to the UNFCCC. This study aims to support the idea that SIDS should put forth robust low-carbon development roadmaps, in addition to adaptation strategies.

Keywords: energy outlook; low emission scenarios; multi-criteria analysis; cost-efficacy analysis; LEAP; Small Island Developing States.

1 Introduction

Economic growth, energy supply and the need for specific demand management, are issues of critical concern to Small Island Developing States (SIDS). These countries face challenges related to their location and geography that cross the entire economy, such as food security, freshwater management, health and climate change [1]. On environment policies, Small Island Developing States in the Pacific, the Caribbean, Africa, the Indian Ocean, and the South China Sea, though different in their cultural and socio-economic contexts, have shown significant concerns over adaptation measures, as a consequence of their particular vulnerability to climate change effects [2-5]. Relying heavily on energy imports, SIDS are more exposed than others to changes in world energy prices, and supply availability [6, 7], and have revealed an awareness of the global importance to build sustainable national energy systems, proactively participating in global solutions, such as the Paris Agreement. Decision 1/CP.21 [8], states all parties, including developed countries, developing countries, least developed countries and SIDS, agree to mitigation compromises that will lead to a reduction in global warming and of the adverse impacts of climate change. Under this context, most National Determined Contributions (NDC) of these countries include both adaptation and mitigation measures, as in the case of the Maldives, Seychelles, Comoros, Mauritius and Sao Tome and Principe, examples of Atlantic, Indian Ocean, Mediterranean and South China Sea (AIMS) SIDS.

To deal with the abovementioned issues, these island countries consider that strategies for low-carbon development provide long-term efficient solutions, and have, thus, started to focus on energy access, and, on the supply side, on the possible use of renewable energy sources [9]. Thorough studies on renewable energy implementation have evidenced good outcomes, providing power at lower costs and allowing the development of more sustainable economies [6, 10, 11]. Other solutions, such as energy efficiency measures or actions related to land use sector and forestry, have been considered for the long-term goals of reducing energy dependence and the carbon intensity of Gross Domestic Product (GDP) and were included in the referred countries' NDCs.

On policy development and research, a critical and cross-cutting issue in scenarios analysis, in less developed countries, regards the lack of reliable data, with the desired frequency and for a significant time series. Without proper information, countries tend to apply isolated and unarticulated solutions that lack valid quantitative reasoning. Hence, international institutions and stakeholders now recognise the importance of transparency, urging parties to participate in the existing measurement, reporting and verification processes developed under the Cancun

Agreements. To achieve efficient decisions, mitigation options should be properly assessed, quantified, and discussed by local stakeholders. The goal is to ensure compliance with the established goals, as stated in numbers 98 and 105 of Decision 1/CP.21 of the Paris Agreement [8].

Under this framework, in this work, we analyse the case of Sao Tome and Principe, an African SIDS, with a total population of 187 356 inhabitants, of which more than 65% is considered below the poverty line, and fewer than 50% have access to electricity services [12]. The growth of the country's GDP was 4% in 2013 [13]. Geographically, Sao Tome and Principe has an area of 1001 km^2, consisting of two islands and several islets, located in the Gulf of Guinea. On issues related to climate change, the country recognised the importance of the subject and the need for solutions, being part of the United Nations Framework Convention on Climate Change since 1998. Since then, the country has integrated the common fight against the global warming process [12]. Included in the national communications to the UNFCCC, Sao Tome and Principe produced two national inventories of greenhouse gases (GHG), with data from 2002 and 2005. The country is a net sink of GHG emissions, where carbon absorption levels from changes in forest and other woody biomass stocks (-606 kt CO_2eq.), are greater than emissions originating in the demand for energy and electricity generation (259 kt CO_2eq.). Also, despite the country not having commitments to reduce or limit their anthropogenic emissions, Sao Tome and Principe decided to include quantified climate change mitigation measures in its Nationally Determined Contribution (NDC), of approximately 24% national emission reduction by 2030 related to 2005, to be implemented between 2020 and 2030 [12].

Within the current bottom-up approach that has been conventional since the Lima Climate Change Conference in 2014, in our analysis, we first selected mitigation actions to then build mitigation scenarios and an energy outlook. We combine a cost-efficacy and a multicriteria analysis for the individual assessment of solutions, and include them in a partial equilibrium model, to obtain a projection of the energy and emissions balance of the country in 2030.

On the selection of mitigation measures, previous arguments testify situations in which rural electrification with national grid extension are not the best solution for SIDS [9] while others show demand-side management and distributed generation may be viable options [6]. After thorough stakeholder discussion, in this study we analyse solutions on renewable energy generation (4MW mini-hydro power plant, 9MW hydropower plant, 1MW isolated micro-hydro power plant and 12MW of solar PV); transports improvement (substitution of 1000 gasoline vehicles and 500 diesel vehicles); and energy efficiency (100 000 LED units, 1000 improved stoves and 2000 units of efficient public street lighting).

Following Dietz and Hepburn [14] and Heinrich Blechinger and Shah [15], we evaluated the mitigation options based on the marginal cost per tonne of carbon spared by each action. To this purpose, we gathered results from the Greenhouse gAs Costing MOdel (GACMO) based on a classical cost-efficacy analysis and studied the discrete solutions [16]. GACMO was the methodology used to make projections of emissions in the NDC of Sao Tome and Principe. For the individual assessment of mitigation measures, we complemented the cost-efficacy analysis with a multi-criteria study. Our results enhance the contribution of the selected mitigation measures to the reduction of vulnerability of communities and local economies, and also to other factors that contribute to sustainability, such as poverty alleviation.

The development of an energy outlook for the country required an effective analysis of the energy demand and supply relation. In this aspect, the GACMO model, with a sequential method that calculates results for three years (2020-2025-2030), is not sufficient for a dynamic analysis of the partial equilibrium of the energy sector. Additionally, the calculation of a mitigation goal through the sum of individual amounts of GHG savings, from each action, may lead to erroneous conclusions, mostly for energy-related measures, where supply and demand are narrowly linked. To overcome this issue, we consider that, on the medium and long runs, actions on the supply side will affect emissions on the demand side and vice versa. We also consider reasonable that changes in the energy supply mix of a country will immediately adjust some emissions originated in energy demand. By using the Long-range Energy Alternatives Planning System (LEAP) model [17], a partial equilibrium model for the energy sector, we input the previously calculated GHG individual savings to specific sections of the reference scenarios, thus computing new scenarios that include mitigation measures and result in lower emissions. Finally, we compare both reference and mitigation scenarios and obtain GHG savings. Nigeria, Zimbabwe and Albania, have already used this cost-efficacy and LEAP combined approach in their NDCs. Previous authors apply this idea to the electricity sector of Panama [18] while Huang, Bor [19] consider an energy outlook with and without mitigation measures for Taiwan, whereas formerly they had analysed greenhouse gas (GHG) emissions targets [20]. There is no previous indication of similar published research studies in SIDS.

To solve the problem of significant gaps of information, data used in this study were collected and validated in its integrity in Sao Tome and Principe. Stakeholders in energy and forestry issues were consulted, including state institutions, private actors, and local communities, while current literature was thoroughly reviewed. This work was developed under a three-year research project, 2013-2016, on low-carbon strategies, in Sao Tome and Principe, Cabo Verde and Mozambique [21], and aims to present a robust mitigation framework created for the analysis of low-carbon and resilient development options, for the medium and long-term, in SIDS. The results have direct implications for the energy and climate policies and enable the selection of priority actions while identifying the need for capacitation and transparency.

In Chapter 2 we present the collected data and develop the methodology, in Chapter 3, we show the main results relating to the analysis of the marginal cost of mitigation measures, and the energy outlook results, and finally, the work is concluded in Chapter 4 by establishing final policy remarks.

2 Data and methodology

The energy outlook of Sao Tome and Principe for 2030 required the development of a reference scenario, the analysis of mitigation actions, and the expansion of the reference situation to an alternative scenario that includes such actions. We start by reviewing the methodologies used at the measure-level and then look to the scenario building methodology.

2.1 Marginal cost and multicriteria analyses

The Intended Nationally Determined Contributions (INDCs) submitted to the UNFCCC Conference of the Parties at Paris, COP21, in 2015, later converted to NDCs s when a country joins the Paris Agreement, provide clear information on specific national actions to reduce GHG emissions. Most countries who had not previously developed a mitigation strategy where impelled to do so in 2014-2015 in line with the pre-Paris Agreement appeals. The climate change mitigation solutions considered in our work were also initially obtained from the studies of the Intended National Determined Contribution of Sao Tome and Principe [12]. We listed possible measures and accounted for their cost-effectiveness in reducing emissions.

The cost-effectiveness analysis (CEA) is a standard methodology to compare costs and results of a measure or project. It was created in the 60's to assist the United States military in making allocation decisions and has been largely used in the health and environmental sectors. In the case of mitigation measures, the effects are measured in units of GHG emissions saved, i.e. tones of CO_2 equivalent ($tCO_2eq.$) saved. We estimated costs of each possible solution throughout its lifetime, discounting values, and finding the present cost of the project. On the other hand, we estimate the emissions that the project will save, compared to a reference situation. With information on project costs and emissions saved, we find the cost per tCO_2eq. saved.

At this point, we used the Greenhouse gAs Costing MOdel (GACMO), a bottom-up Greenhouse Gas (GHG) emissions scenario analysis spreadsheet, developed by the UNEP Centre for Energy and Environment [16, 22]. It is a standard sheet for CEA of mitigation options, previously loaded with data from mitigation options mostly submitted as Clean Development Mechanisms projects (CDM), which allows the selected measures to have a *quasi*-guarantee of acceptance from the UNFCCC. This methodology was used in the sectoral published research of Maya and Fenhann [23], and Markovska, Todorovski [24], for the development of abatement cost curves; by Dedinec, in studies on renewable energy [25], transport sector [26] and waste sector [27]; and also in review studies by Springer [28] and Huang and Lee [20], the latter in 2009.

Under the GACMO analysis, reduction amounts are estimated considering the region's main parameters (generation mix, GDP growth, and population growth). Abatement costs (AC) calculations follow typical cost-effectiveness analysis, including levelized investment costs (I), operation and maintenance costs (OM), fuel costs (F), and emissions (GHG) for the reference (r) and mitigation (m) options, $AC = (I_m + OM_m + F_m) - (I_r + OM_r + F_r)/(GHG_r - GHG_m)$, as previous authors have described [20, 28, 29].

Combining the results for several mitigation measures, the model calculates a Marginal Abatement Revenue Curve. However, we consider it is clearer to maintain the classic cost interpretation of the curve, so, the formula results in negative costs when benefits exceed costs. Marginal Abatement Cost Curves (MACC) have been widely used in bottom-up analyses, including in NDC cost-benefit analysis [30], providing information to assign priorities to selected mitigation measures.

Given the developing socio-economic stage of the country, a further look into the qualitative aspects of the measures allowed for a brief capacitation of stakeholders in climate change mitigation. To this end, a multi-criteria analysis (MCA) was additionally performed, considering previously developed models on electricity and renewables [31-33], and already published literature review [34-36]. MCA is a structured approach that determines preferences between alternative options through a scoring system. The scale and indicators to be evaluated are specified, and participants are required to systematically and comparably weight the measures, to produce a final 'ranking'. A more recent review study by Kumar, Sah [37] on multi-criteria decision was taken into account.

The choice of indicators focused on the classical aspects of evaluation of development and climate projects, namely regarding inputs and outputs of the project. The input aspects were evaluated in 25% of the final grade, and the output in 75%. The indicators chosen to represent the input aspects are the need for public and private funding and the barriers to implementation. Outputs included economic, social, political and institutional, climatic and environmental indicators. For dissemination purposes, in the Annex we disclose the scoring table used, with a complete list of indicators.

2.2 Scenario framework

The adopted CEA-MCA procedure is sufficient to estimate emissions reductions when the mitigation options are individually considered. However, several interdependencies exist between energy demand and supply measures that cannot be neglected when developing an energy outlook. The integration of energy demand solutions with energy transformation actions creates bidirectional impacts, and only a model that optimises the production of demanded energy can quantify final energy and emissions. Thus, the integration of climate change mitigation options in a reference scenario, creating a mitigation scenario, makes it possible to analyse how energy supply and use, and consequent emissions, may evolve.

The work we present shows historical data on energy use and electricity generation in Sao Tome and Principe, from 2005 to 2015, and projections up to 2030. To build the scenarios we used the Long-range Energy Alternatives Planning System (LEAP) model [17]. LEAP is a simulation model used to represent the energy system of an area and develop projections. In the last years, LEAP became a standard tool in integrated resource planning, in the evaluation of GHG reduction options, and in the development of low-emissions developing strategies, especially in the developing world.

LEAP models have been commonly used in two perspectives, the first in sectoral analyses of transport [38-40] and electricity generation measures [41-44], and the second in national energy outlooks, as in the cases of Taiwan [19], Mozambique [45], Greece [46], China [47] and Nigeria [48]. In this context, review studies have also been previously published, including an applied review analysis of power and renewables measures in Pakistan [44, 49], of transport and energy portfolio in Korea [50, 51], and in energy policy scenarios in Nigeria [48] and

Bulgaria [52]. On the particular combination of a multicriteria analysis with LEAP scenarios, partially considered in this paper, a study by Rahman, Paatero [53] stands out.

Amongst the referred studies there is no previous published scenario analysis in Small Island Developing States (SIDS), making it a significant part of the added value of this paper. Scenarios in developing islands countries are interesting to examine for they require an enclosed analysis that cannot be optimised using imports and exports of electricity or other energies. Previous LEAP research on developing islands includes one study in the Philippines[54], and other in Indonesia [41], two large countries. Small islands scenarios may be even more interesting because the countries' size causes models to be particularly sensitive to assumptions and other variables. In this sense, the measures to be applied have to be consistent and robust, so that the model does not calculate impossible outcomes. In this context, our work presents a methodological development, by looking at sustainable measures and energy outlook scenarios in the SIDS of Sao Tome and Principe.

On LEAP operation, the model requires the building of a reference situation, by specifying historical data on final energy use, on energy transformation, and on macroeconomic variables. The baseline scenario is obtained by establishing an expected future trend, and comparison scenarios are built by changing values on the reference scenario. In this paper, we included historical data from 2005 until 2012. As mentioned, there are previous good reviews of the software's architecture, which may provide useful insights and additional information [17, 48]. For this reason, in the following paragraphs, we only briefly describe the main aspects that characterise the scenario design, duly reflected in our case study.

The LEAP model is structured in three modules, including energy demand, energy transformation, and non-energy. The two energy modules are dynamically related, and reach an equilibrium, whereas the non-energy module is independent, only existing to the purpose of including non-energy related emissions.

On energy demand, the model considers a sum of individual, sectoral, quantities of energy demanded in the country, which will require energy delivered in the same amount. Energy demand is always accounted in final energy units and is supplied by the transformation module. In this module, final energy is produced from primary energy, in the demanded quantities, either for national, or international use. Sao Tome and Principe does not export any energy, so, in this framework, we only considered imports of untransformed fossil fuels.

LEAP is oriented to final energy demand analysis, meaning that the model operation starts from the use of final energy. The region is divided into a tree structure of sectors or modules, sub-sectors, and devices, to simplify the description of energy demand. Historical data and previous trends in energy demand, per sector, are used to estimate future demands, also considering the role of expected GDP growth rate and sectoral GVA. Based on this information, we estimate growth for sectoral energy demand, per fuel. Future scenarios can be developed by changing demand parameters, by specifying new annual growth rates, or by using different drivers.

In the energy transformation module, we included energy processes, their efficiencies, and losses. In the Sao Tome and Principe case study, there is one transformation process regarding electricity generation. The production of electricity considers installed capacity, dispatch, and an energy balance. In our model, installed capacity has been set exogenously by specifying the current and future capacity of the country, per energy type. We consider a dispatch rule based on installed capacity, which will comply with an accounting system that balances the flows of energy, during a given period. Produced energy (E_S) plus net imports (NI) equals demanded energy (E_D) plus losses in transport and distribution (L): $E_S + NI = L + E_D$.

As mentioned, the software also includes a non-energy module, which is considered for the calculation of total emissions of the country. This module reflects emissions originated in other activities than the burning of fossil fuels for energy transformation and use. Sao Tome and Principe emits GHG from land use, land-use change and forestry (as well as absorbs GHG in this case), agriculture, and waste disposal, which were duly included in the scenarios.

Finally, to translate the region’s energy system into GHG units, and directly link the energy outlook to a low-carbon strategy, LEAP includes a technology database with costs, environmental impacts and other characteristics collected from the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA), and several other sources.

This work presents a mitigation energy outlook for Sao Tome and Principe for 2030, following the cost-effectiveness analysis reflected in the country’s NDC, complemented by a qualitative multicriteria analysis. We will follow by looking at collected data.

2.3 Data and sources

The analysis of mitigation options and the development of an energy outlook requires detailed historical macroeconomic, socio-demographic and energy data, as well as projections of economic growth. The difficulties associated with the lack of research studies and reliable data on energy and climate issues, a typical situation in most developing nations, are sometimes only overcome with *in loco* validation of assumptions and results.

The work presented here partially regards the results of a larger project EBAC – Low Carbon Strategies implemented in Sao Tome and Principe, Cabo Verde and Mozambique. The work required continuous contact with stakeholders located on the islands of Sao Tome and Principe, for thorough data collection and validation. The study went through three main stages, including the development of the reference scenario, the analysis of the mitigation measures, and the building of the mitigation scenario. Historical data was needed for the reference scenario, specific evidence was required for the mitigation analysis, and finally, clear perception of local trends was necessary for both reference and mitigation scenarios.

Initially, we looked into the country's main development and environment strategies. They include the First and Second National Communications to the UNFCCC; the Action Plan for Adaptation to Climate Change; the Proposals for Measures for the State of Preparation (R-PP) presented by the countries participating in the REDD + program; the National Strategy for Poverty Reduction in 2002; and the Strategy for the Integration of Climate Change and Disaster Risk Management into the National Strategy for Poverty Reduction. These documents exist in most SIDS, providing a framework on the country's climate concerns and their readiness for action, helping to select the mitigation measures, and also structuring the projection scenarios.

2.3.1 Socio-economic data

The developed scenario model renders a partial equilibrium in the energy sectors, to which it requires an exogenously defined level of economic activity. For this purpose, we used values of the purchasing power parity GDP at 2011 constant prices, growing from 0.384 in 2005, to 0.534 in 2012, measured in 2011 billion international dollars (World Development Indicators 2012 (WDI) - World Bank national accounts data). We note that the GDP of Sao Tome and Principe grew reasonably in the last decade, reaching an annual average growth (AGR) rate of 4.30% in 2013. From 2002 to 2013, the GDP AGR averaged 5.02%, peaking at 12.60% in 2006, and reaching a minimum of 1.60% in 2005 (Trading Economics, 2013).

In complement to historical data, GDP growth projections are critical for the development of energy scenarios. We collected different GDP forecasts for Sao Tome and Principe from the World Bank, the African Development Bank (AfDB), the Energy Information Agency of the United States (EIA), an agency of economic indicators information (Trading Economics), and the Intergovernmental Panel on Climate Change (IPCC), which reports gross values from 148 scenarios in world regions. After thorough analysis, projections of 5% average annual growth rate for 2014 and 5.5% for 2015 and following years, were obtained from local Government, reflecting the country's studies [13].

Sectoral gross value added is also relevant, because sectors are distinct in their greenhouse gas emissions intensity. In Sao Tome and Principe, we consider GDP as the sum of (GVA) of industry, agriculture and services. The industry is organised by subsectors, and transport by mode. The only existing information of the country's sectoral GVA, which we included in the model, is from World Development Indicators 2012 of the World Bank national accounts data, reporting, for 2005, shares of 17.26% to Agriculture, 62.66% to Services and 20.08% to Industry. In 2006, values change to 15.85%, 67.30% and 16.85% respectively. The subsectors' GVA was calculated as a proportion of their energy use. We also assumed that the growth of sectoral GVA is proportional to the growth of GDP, keeping the same ratio as in 2006.

The LEAP model creates scenarios based on socio-economic growth, as explained in the following section. It is, therefore, necessary to account for historical and expected population growth, on which we incorporated the United Nations reporting of 178000 persons in 2010 and the scenario of average growth for future years, reaching 278000 persons in 2030 (UN Population Prospects 2012 Revision).

2.3.2 Energy data

Sao Tome and Principe has a mostly thermal electricity generation mix. The installed capacity for electricity production is constant since 2005 for hydropower, at 2.3MW, while thermal capacity increased in 2012 from 12MW (in years 2005-2011) to 27MW [55, 56]. In 2016 there were no other electricity sources in Sao Tome and Principe. National electricity generation from 2005 to 2012 shows relevant variations in hydropower production, though confirmed values point to an average of 7.25 GWh between 2005 and 2012. Thermal production in the country grows from 35 GWh in 2005 to 49 GWh in 2012 [55, 57].

Energy losses in transport and distribution are calculated by the difference between generation and use, and averaged a high value of 37% between 2006 and 2012 in Sao Tome and Principe, peaking at 41% in 2008 [55]. Energy loss is a critical variable in SIDS and most developing nations, because it is an opportunity for immediate efficiency growth, though usually requiring high investment levels.

Energy demand per fuel and economic sector is also vital information for the energy outlook model, for it is where the destination sectors of final energies become perceptible. The shares of sectoral energy are considered in the scenarios of final energy demand, and it is technically where demand mitigation measures are considered. We calculated the values based on information from the country's White Book on Energy for 2012 [55] because no previous study or raw data existed. The energy demand sectors considered include residential, agriculture, services (commerce, public administration and others), industry, and transports. We also assumed the ratios between fuels within sectors remain constant. The final energy demand values, per fuel and sector, are presented in Table 1.

Table 1 – Sectoral energy use, by source, tons of oil equivalent (toe), 2012

Sectors / Energy source	Wood	Charcoal	Butane Gas	Electricity	Oil	Gasoline	Diesel	Total
Domestic	69 214	21 333	-	2 158	4 880	-	-	**97 585**
Industry	-	-	-	184	-	-	6 818	**7 002**
Services	-	-	200	1 861	-	-	-	**2 061**
Commerce	-	-	*200*	*562*	-	-	-	*762*
Public Ad.	-	-	-	*611*	-	-	-	*611*
Other	-	-	-	*688*	-	-	-	*688*
Transports	-	-	-	-	-	7 665	20 453	**28 118**
Total	**69 214**	**21 333**	**200**	**4 204**	**4 880**	**7 665**	**27 270**	**134 765**

Due to the rural communities existing in Sao Tome and Principe, we considered specific energy conversion factors, specifically 13.800 GJ per tonne of wood, and 30.800 GJ per tonne of charcoal (data from United Nations Food and Agriculture Organization and Berkeley University, CA). Remaining conversion factors are typical, collected from IPCC information.

Emissions of non-energy sources, including emissions from industrial processes and waste, land use and forests, and agriculture and livestock, available for 1998 and 2005, were retrieved from the 2nd National Communication to the UNFCCC [58]. The importance of forestry sinks in Sao Tome and Principe is visible, reaching 728 kt CO_2eq. absorbed, versus 197 kt CO_2eq. emitted in 2005, making the country a net-sink SIDS. Nonetheless, stakeholders consider necessary to address the emissions responsibility of all other sectors, which is reflected in this study.

3 Results

3.1 Mitigation measures

Solutions to reduce the country's emissions were selected by looking at the national socio-economic and environmental features of the reference scenario, by using the input from the NDC, and with thorough local stakeholder consultation. The final list of measures used in the analysis is shown below in Table 2, and include efficiency measures in residential, services and transport sectors, and renewable electricity generation, linked to the national grid or isolated.

Table 2 – Initial mitigation options in STP

Category	Measure	Quantity
Energy in the residential and service sectors	Efficient residential lighting with LEDs	100 000 units
	Improved stoves	1 000 units
	Efficient street lighting	2 000 units
Energy in transports	Automobile fleet update, with more efficient vehicles (taxis fleet)	1 000 petrol 500 diesel
Renewable electricity production linked to the national grid	Mini-hydropower plant	4 MW
	Hydropower plant	9 MW
	Solar photovoltaic panels (PV)	12 MW
Renewable electricity production, outside the national grid	Isolated mini-hydro power plant	1 MW

For individual assessment, we followed the above-described cost-effectiveness methodology within the GACMO model [12].

The implementation of efficient LED lighting in the country includes the supplying of 3 lamps per 20 000 of the poorest families, over ten years, resulting in 100 000 lamps. The measure is estimated to save 1.1GWh/year of electricity, at a revenue of 34.77 US$/t$CO_2$eq. We note that the base values used in the NDC were kept for consistency reasons, though if considering that the LED prices are decreasing, it could allow for further costs savings.

The supply of wood-fuelled improved stoves aims to substitute the "three-stone stove", commonly used in the rural communities in the country. In similar larger projects, the measure has been proved to save between 1 and 2 tCO_2eq./year/stove (benchmark cases from the GACMO database), though in our case, the country's conditions allow savings of 6 tCO_2eq./year/stove. The measure considers the linear substitution of 1000 stoves between 2020 and 2030, costing 0.25 US$/t$CO_2$eq. saved.

The efficient public lighting solution considers the substitution of 2000 lamp fixtures during seven years. Considering the baseline information from the STP model developed for the NDC, this measure is estimated to save 3.94GWh per year in electricity. It is worthy of note that the high level of revenues associated with this measure, of 259.20 US$/t$CO_2$eq., is conservative concerning the CDM project referred to "N. 8415: Bundled Street Lighting Energy Efficiency Projects implemented by AEL in India ". However, for consistency reasons, it was decided to keep the country's main assumptions.

The transports measures consider the replacement of 1000 gasoline vehicles and 500 diesel vehicles from a fleet of taxis. Following local calculations, this measure is considered to save 0.17 ktoe per year in gasoline (0.14ktoe) and diesel (0.03ktoe), with high levels of associated gains (187 and 248 US$/t$CO_2$eq. for gasoline and diesel respectively).

Lastly, on renewable electricity measures, we recall that Sao Tome and Principe has an electricity generation mix intensive in petroleum products. In this context, the use of renewable energy for electricity generation stands out as an opportunity to mitigate climate change and promote sustainable development. Given the geophysical and geographic characteristics of the country, it was considered an implementation of five 1MW small hydroelectric power plants, four connected to the power grid and one isolated, one 9MW power plant connected to the grid, and 12MW of solar power plants. Hydroelectric power plants with a capacity of up to 10 MW have the potential to provide endogenous energy in developing regions with low operating costs. Though these mini-hydro systems can have relatively high initial capital costs, much is channelled to human and material resources locally available for site preparation. The technical advantage of such systems in a SIDS is that the hydropower plant can usually be installed quickly and does not require flooding of large areas. On the other hand, the technology of production of electric energy by solar panels has evolved at great speed in recent years, which leads to a reduction in the prices of solar modules, their installation costs, and a rise in the efficiency rates of equipment. The financial advantages of such a system allowed savings of 27.24 GWh/year, at a revenue of 143 US$/t$CO_2$eq. saved.

The results from the cost-effectiveness analysis, considering a gradual implementation of measures between 2020 and 2030, are shown in the following Table 3. It discloses information regarding the number of emissions that each measure partially saves, as well as its cost per unit of GHG abated, necessary to build the Marginal Abatement Cost Curve (MACC), presented in Figure 1. The negative costs, or profitability, of the majority of measures, stand out, with the particular impact of the street lighting measures, mini-hydro in the grid (4MW), solar PV

(12MW) and mini-hydropower (15MW). Results are in line with previously developed MACCs for technology analysis. We achieved expected results, except for the solar PV measure, which typically shows negative costs for solutions of fuel efficiency in vehicles and efficient lighting measures and positive costs for solar PV. Hydropower costs per emissions reductions vary greatly, though near zero values, depending on the case study, and the improved stoves measure has not included in previous analyses. The result of the solar PV measure, and also, the high savings associated with the mini-hydropower plant connected to the grid, are closely related to the country's electricity supply features. In this study, we report losses in electricity distribution of 36%, and a combined margin of power grid emissions of 0.75 tCO2eq./MWh. Thus, the emissions savings achieved with the solar PV renewable power solution overcompensates the required high investment costs. The same happens in the mini-hydropower plant connected to the grid.

Considering the particularities of developing a low carbon strategy in a SIDS, namely, the island features and the size limitations, the mitigation actions were also evaluated in a qualitative perspective, including socio-economic and environmental aspects, among others, through a multicriteria analysis (MCA). The main purpose was to perceive the stakeholders' preferences to differentiate between solutions. Final results are presented in Figure 2.

The grid-connected hydropower generation and the isolated mini-hydro are the two best-scored actions in qualitative aspects. Then, in descending order of score, we find the improved ovens, LED lighting, grid-connected mini-hydro, solar PV, efficient street lighting, and finally diesel and petrol vehicles. Stakeholders valuated options that promoted access to electricity, in detriment of transport measures, clearly not of much relevance to stakeholders.

Table 3 – CEA results of mitigation possibilities in STP

Subcategory	Solution	Description	Electricity generation	Saved energy	Investment	Annual Costs	Reduced emissions	Costs of emissions reductions
			GWh/year	(various)	M US$	M US$/ year	kt CO_2eq./year	US$/t$CO_2$eq.
Residential	LEDs lighting	100 000 lamps	-	Electricity: 1,1GWh /year	2,500	0	0,92	-34,77
	Improved stoves	1000 stoves	-	-	0,029	0	5,84	0,25
Services	Public lighting	2 000 light fixtures	-	Electricity: 3,9GWh /year	0,324	-0,9	3,31	-259,20
Transports	Gasoline vehicles	1000 vehicles	-	Gasoline: 0,14ktoe/year	15,000	-0,1	0,41	-248,36
	Diesel vehicles	500 vehicles	-	Diesel: 0,03ktoe/year	10,000	-0,02	0,09	-186,52
Hydropower	Isolated mini-hydropower plant	1 MW	4	-	4,000	-0,1	3,23	-26,21
	Mini-hydropower plant in grid	4x 1MW	16,00	-	18,000	-2,5	12,00	-210,83
	Hydropower plant in grid	9 MW	3,96	-	19,243	0,0	26,74	-0,21
Solar power	Solar PV	12x 1MW	27,24	-	18,000	-2,2	15,28	-143,00

Figure 1 – Marginal Abatement Cost Curve of proposed mitigation measures for STP

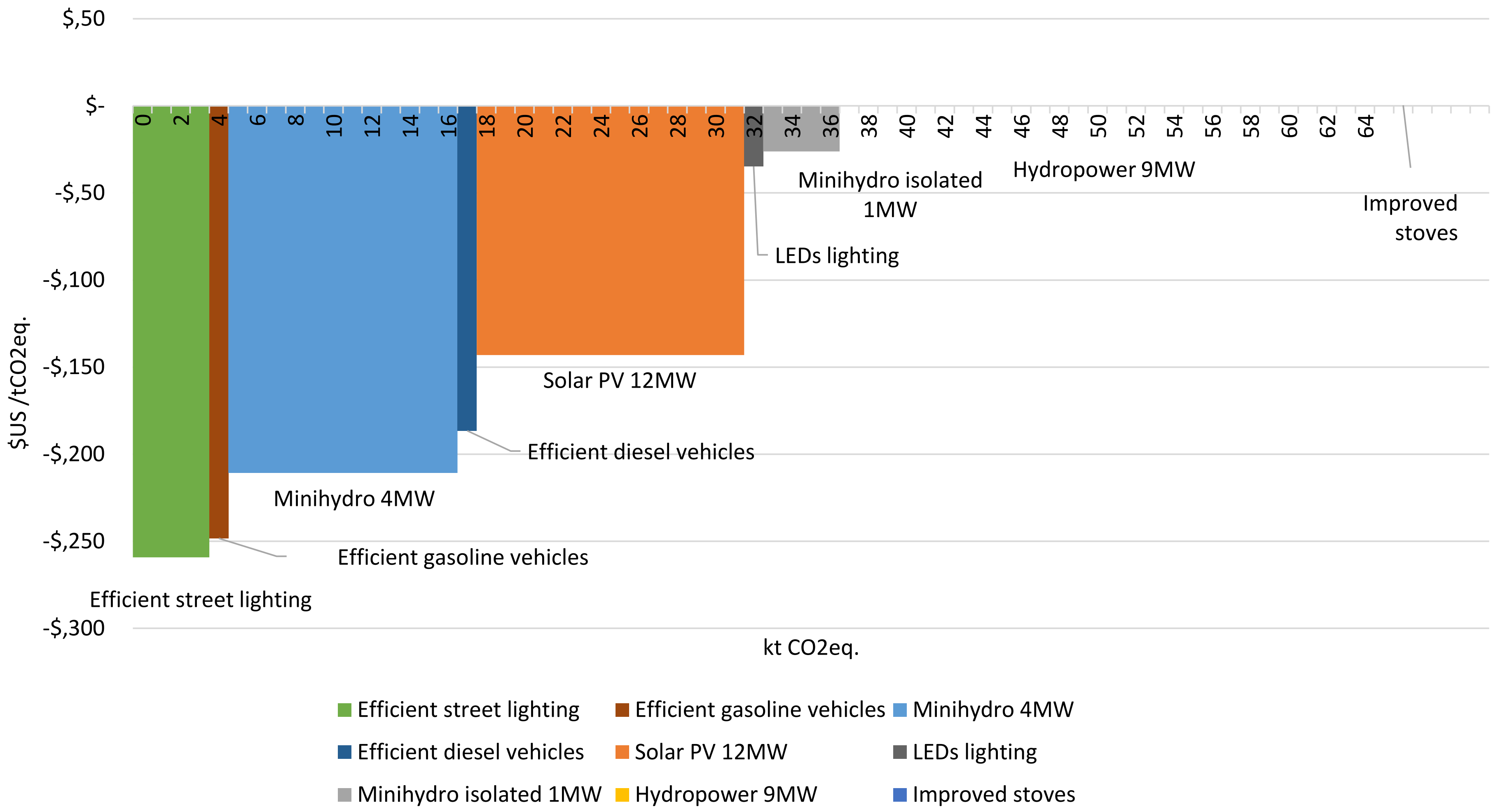
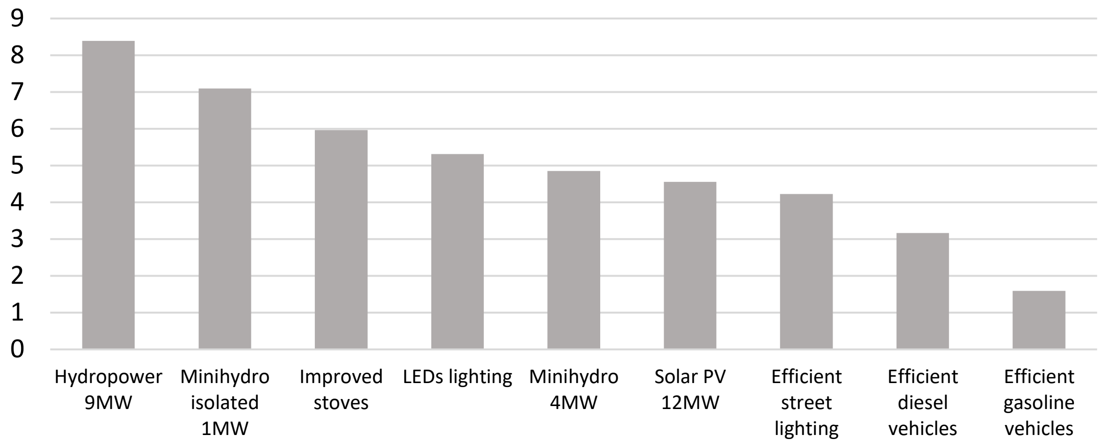


Figure 2 – Ranking of proposed mitigation measures for STP, per multicriteria evaluation points.



Comparing the MCA ranking to the $/$tCO_2$eq. ranking from the marginal cost curve, we observe that the measures proposed by Sao Tome and Principe are either more useful in qualitative aspects, or, on the other hand, more efficient regarding the cost of abated emissions. However, considering that most of these actions allow financial savings, translated by the negative costs, the qualitative ranking may be regarded as an interesting implementation order. Even the two measures with costs higher than zero (improved stoves and grid-connected hydropower) are so well qualitatively scored (respectively third and first places), that the advantages for the economic and social development of the country possibly outweigh the costs in its implementation.

3.2 Reference and mitigation scenarios

In the reference scenario, we developed a projection of economic and energy developments of Sao Tome and Principe, reflecting the expected evolution of the country's energy demand, associated with GDP and population growth. We considered the average estimate of population growth of the UN Population Prospects (2012 Revision), of 278 000 persons in 2030. On GDP, after careful analysis with local stakeholders, and based on the 2014 State budget and International Monetary Fund information, an annual average growth rate of 5,5% was considered for years 2015-2030.

After individually assessing the selected climate change mitigation measures, in summary, for the construction of the mitigation scenario, we applied to the reference scenario, between 2020-2030, a new mix of energy use by the residential sector, increased amounts of energy consumption by the services sector, new energy ratios use by the transport sector and new productions of renewable electric energy. For most measures, we considered a linear growth of the variable until reaching the goal at the established date. Energy needs are recursively calculated, and the necessary energy amount is supplied. The island considered does not have endogenous production of primary fossil energies, so all quantities of petroleum or derivatives, coal and others, need to be imported.

In the following sections, we present the results of energy demand and transformation, and of GHG emissions, considering that the island is a net sink of emissions, thus requiring particular attention.

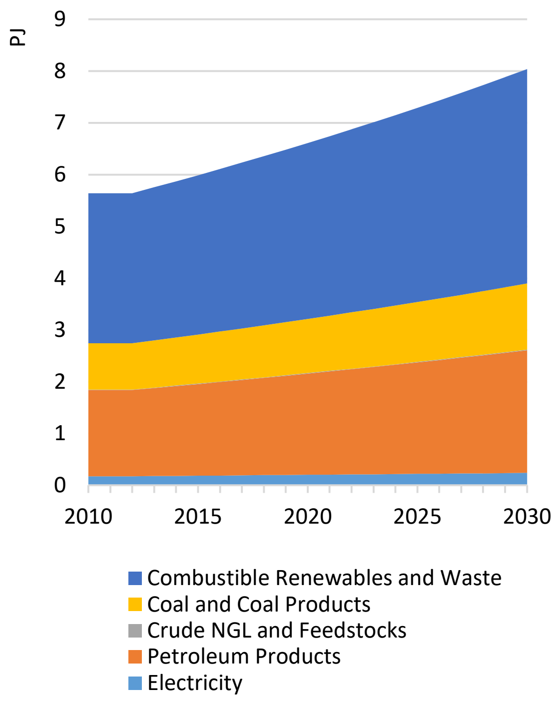
3.2.1 Energy results

Considering the critical developing needs of a SIDS, energy demand shows very similar values in both reference and mitigation scenarios, as expected. To support the country's development, even if with control of GHG emissions, the energy use in services, industry and transport, grows comparably to the growth of their Gross Value Added (GVA), whereas in the residential sector is linked to the increase in the per capita income. Results show that in both scenarios half of the energy demand, per final energy, concerns the use of biomass, growing until 4PJ in 2030, visible in the left graphic of Figure 3. Petroleum products are in second place, corresponding to 2.37 PJ of energy, with the remaining 1.6 PJ attributed to electricity, coal and crude LNG products. All energies follow a similar growth trend, linked to the economic progress of the country. Regarding energy demand per sector, presented in the right graphic of Figure 3, residential is the largest energy user, reaching 5.8 PJ in 2030, followed by transport, with 1.7 PJ, and finally, industry and services, with 0.4 PJ and 0.1 PJ, respectively.

Under this context, the road towards sustainable growth and development compels production of electricity from renewable sources. In Figure 4, we compare scenarios in the energy transformation activities, in three years, showing the visible impact of mitigation measures in energy transformation such as the increase in hydropower and solar PV production.

A final piece of data is the energy balance, presented in the Sankey graphic for the mitigation scenario in 2030, in Figure 5. It stands out the disproportion between the import value of fossil fuels, reaching 4.3 PJ, the production of biomass (mainly for residential consumption) of 4.1 PJ and the small renewable electricity amount of 0.05 PJ. The weight that the residential and transportation sectors will continue to have on the use of energy in Sao Tome and Principe in 2030, of 73% and 21% respectively, is also very noticeable.

Figure 3 – Energy demand per final energy (left) and per sector (right), PJ



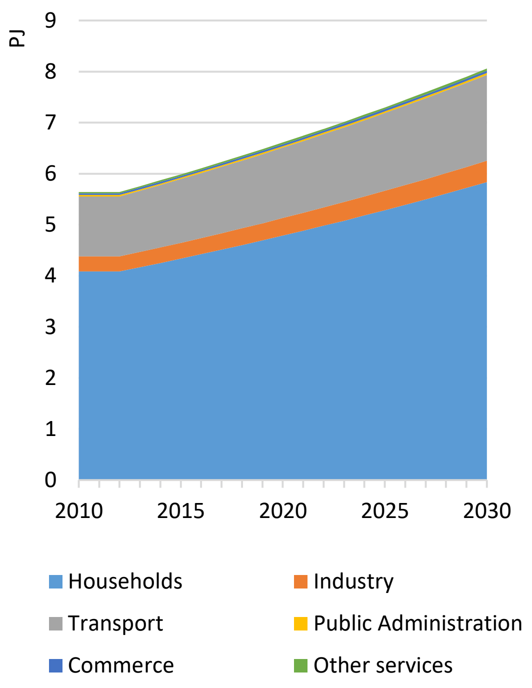


Figure 4 – Electricity generation in scenarios 'reference' and 'mitigation', per fuel, 1000GJ

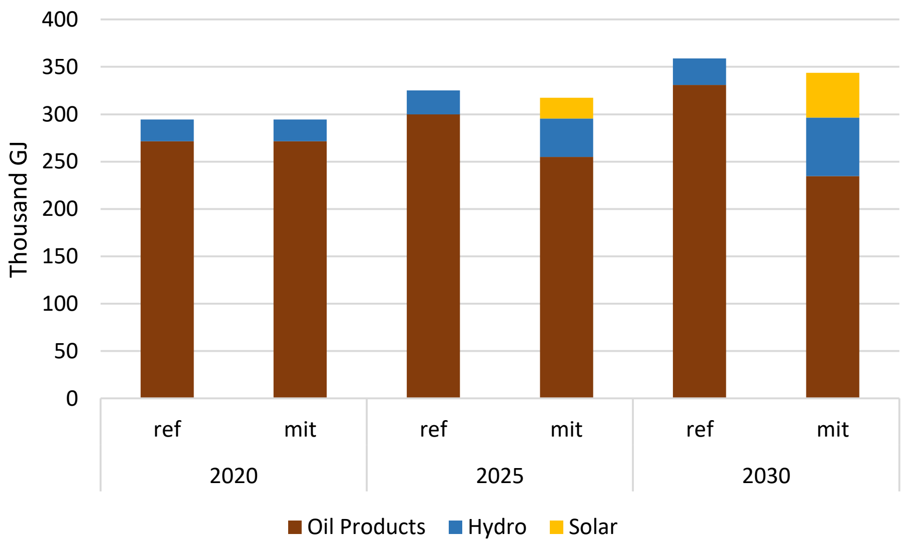
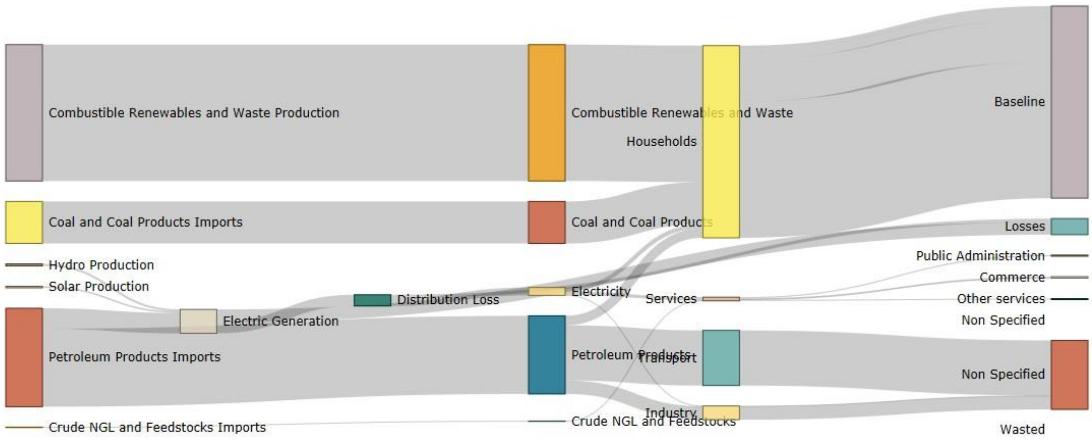


Figure 5 – Sankey diagram of the energy flow in 2030, mitigation scenario.



3.2.2 GHG emissions results

In line with previous energy results, residential and transportation have the highest energy demand associated emission levels over the years, with 182 and 122 kt CO_2eq. of emissions in 2030, respectively. The residential sector shows average emissions of 147 kt CO_2eq. /year, between 2005 and 2030, while the transport sector also emits significant amounts of GHG in the country, reaching an average of approximately 98 kt CO_2eq. /year, between 2005 and 2030. The expected emissions growth rate per sector is constant, of about 2% annual growth, a value directly associated with the energy intensity growth of the GDP in Sao Tome and Principe.

In total, it is estimated that energy demand categories are responsible for the emission of about 335 kt CO_2eq. in 2030, about five times more than the emissions of electricity generation in the country, as we show below. The considered mitigation measures relating to the use of energy, i.e. the measures incorporated in the residential sectors, services, and transport, in particular, lighting LEDs, improved furnaces, efficient lighting and car fleet renewal, show small effects, though allowing the accumulation of 4,60 kt CO_2eq. savings until 2030.

On the emissions from electricity generation, the reference scenario reflects the growth in thermal capacity, needed to answer the growth in demand. In a business-as-usual evolution, the proportions in the electric generation mix in the country are likely to remain the same as in the last known historical year (2012), with 92% of thermal capacity and 8% of hydropower capacity.

However, in the mitigation scenario, measures concerning energy transformation, in particular, the production of electricity from hydropower and solar PV, show high impacts on this SIDS. The promotion of renewable electricity will replace the existing production using petroleum products, resulting in almost 100 kt CO_2eq. of emissions savings until 2030, equivalent to a saving of approximately 29% of the sector's emissions.

In addition to the actual reduction in emissions in electricity production relative to the baseline scenario, the mitigation scenario itself presents an annual average emission reduction of 1.11% between 2020 and 2030. However, the same scenario also shows an annual increase in emissions from energy demand averaging 1.98% between 2020 and 2030. Overall, in the mitigation scenario, the country notes an average growth of 1.70% in emissions per year, between 2020 and 2030, whereas in the reference scenario reaches 2% per year.

To complete the emissions of the country, we consider non-energy emissions to be constant and equal to the most recent information, available in the 2nd National Communication of the SIDS to the UNFCCC, of 2005. These non-energy sector includes GHG emissions from industrial processes such as cement and other production, land use and waste treatment, and are out of the scope of this work. Because of existing sinks, Sao Tome and Principe shows a negative balance of emissions of -606.41 kt CO_2eq., which surpasses all emissions from energy demand and transformation.

In the following Table 4, we aggregate emissions of the various categories, becoming clear that significant emission savings arise from measures that make the electricity generation system more renewable. The remaining measures, on energy demand, make up for the final saving effect.

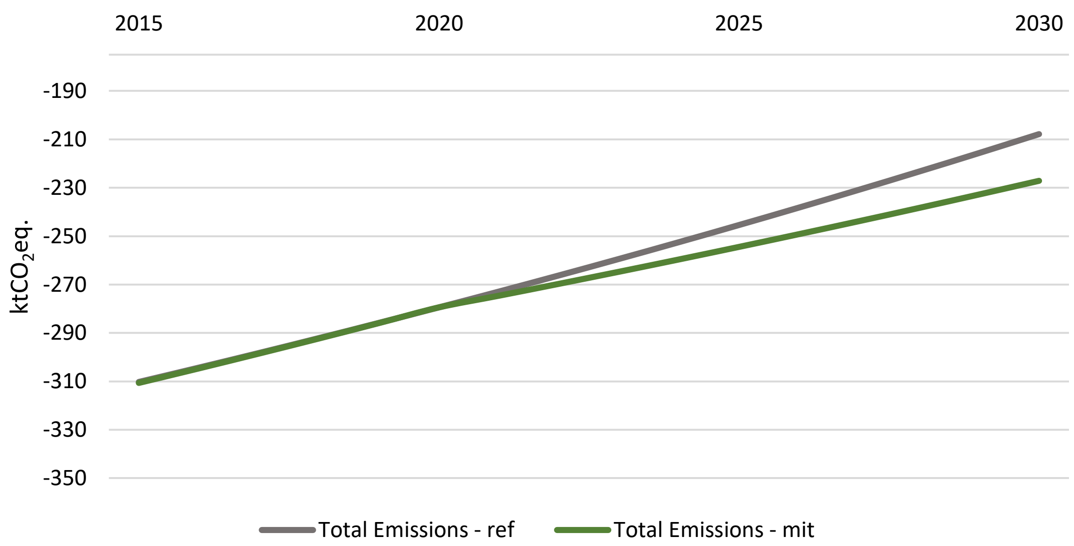
Table 4 – GHG emissions from energy demand (D), transformation (T), and total, in scenarios reference (r) and mitigation (m), ktCO₂eq., 2010-2030

Year	D_r	D_m	T_r	T_m	Total_r (inc. non-energy)	Total_r (inc. non-energy)
2010	234.68	234.68	33.77	33.77	-337.97	-337.97
2011	234.68	234.68	34.46	34.46	-337.28	-337.28
2012	234.68	234.68	48.93	48.93	-322.81	-322.81
2013	239.37	239.37	45.25	44.69	-321.79	-322.36
2014	244.16	244.16	46.16	45.66	-316.10	-316.59
2015	249.04	249.04	47.08	46.66	-310.29	-310.71
2016	254.02	254.02	48.02	47.68	-304.37	-304.71
2017	259.10	259.10	48.98	48.72	-298.33	-298.59
2018	264.28	264.28	49.96	49.78	-292.17	-292.35
2019	269.57	269.57	50.96	50.87	-285.88	-285.98

Year	D_r	D_m	T_r	T_m	**Total_r** (inc. non-energy)	**Total_r** (inc. non-energy)
2020	274.96	274.96	51.98	51.98	-279.47	-279.47
2021	280.46	280.38	53.02	51.38	-272.93	-274.65
2022	286.07	285.90	54.08	50.77	-266.27	-269.74
2023	291.79	291.54	55.16	50.13	-259.46	-264.74
2024	297.62	297.30	56.27	49.47	-252.52	-259.65
2025	303.58	303.16	57.39	48.79	-245.45	-254.46
2026	309.65	309.15	58.54	48.08	-238.23	-249.19
2027	315.84	315.26	59.71	47.34	-230.86	-243.82
2028	322.16	321.49	60.90	46.58	-223.35	-238.35
2029	328.60	327.84	62.12	45.78	-215.69	-232.79
2030	335.17	334.33	63.36	44.96	-207.88	-227.13

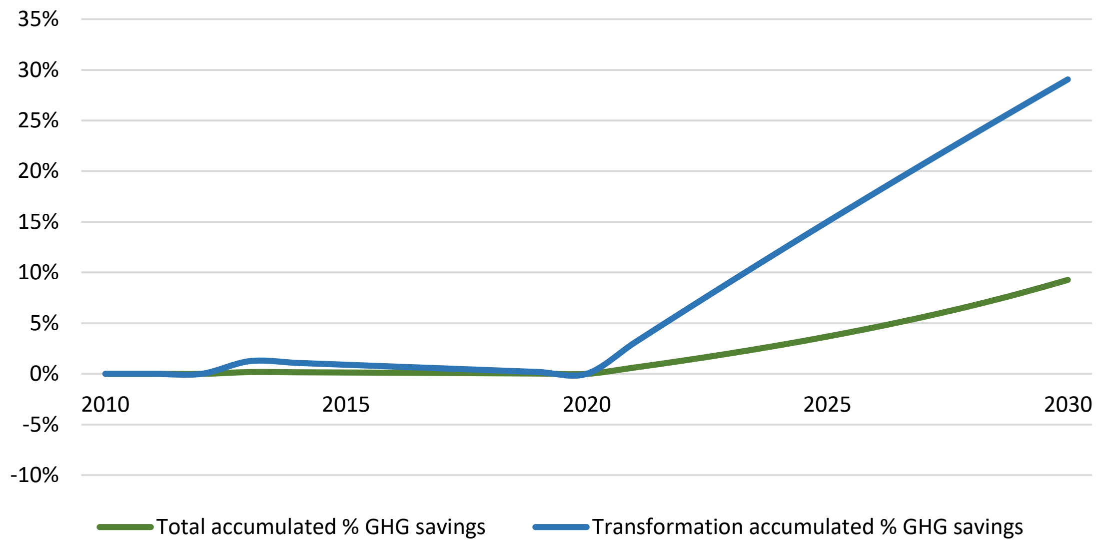
Overall, we estimate possible accumulated reductions in emissions in the country of 2.36 kt CO_2eq. until 2020, and 104.24 kt CO_2eq. until 2030, which may be seen by the gap between the two scenario lines in Figure 6, corresponding to savings of around 9.3% in the mitigation scenario relative to the reference scenario. Although both demand and transformation emissions grow, reaching 398.54 kt CO_2eq. in 2030, these are largely offset by the country's carbon sink level of (-) 606.41 kt CO2eq./year, which keeps the SIDS, over time, with an average of negative net emissions of -261.45 kt CO_2eq. between 2015 and 2030, reaching a net balance of (-) 207,88 kt CO_2eq. in 2030.

Figure 6 – Total GHG emissions in reference and mitigation scenarios, 2015-2030



A final interesting result of this analysis may be seen in Figure 7, where we compare the accumulated percentages of GHG savings from the transformation measures with their overall impact in the country. In fact, the 29% of emissions reduction achieved in electricity transformation in 2030, visible in the blue line, is reflected in a much smaller decrease of 9% in 2030, in the country's total emissions, as shown by the green line. There are no other significative reductions to add to the total. It is a consequence of the energy demand composition, mostly biomass-based, responsible for a large share of energy use, and consequent emissions, in which no mitigation measures were considered.

Figure 7 – Accumulated percentual GHG savings from mitigation measures, in energy transformation and total emissions



4 Conclusions and final policy remarks

The Small Island Developing States group, initially most concerned with climate change adaptation issues, presented mitigation solutions under the Paris Accord, duly adjusted to their development needs and island-related requirements. Historically, emissions from SIDS are not representative comparing to global amounts. Also, most SIDS do not have access to endogenous fossil energies, thus importing oil and coal, and rely on wood to supply a large part of their energy demand. In the particular case of Sao Tome and Principe, it adds that the country is a net sink of emissions. Nevertheless, under this framework, the country is willing to make efforts to reduce additional emissions.

Energy demand, economic development, and energy supply concerns, were analysed in this work, where we provide an adjusted mitigation scenario for 2030 in Sao Tome and Principe. We present a thorough review of works using similar methodologies in the development of low carbon roadmaps, and related subjects, in SIDS, proposing a combination of three techniques, namely a cost-efficacy, multicriteria and partial equilibrium analyses, which support both quantitative and qualitative goals of this study.

This work was developed under a two-year research project, 2014-2016, on low-carbon strategies, in Sao Tome and Principe, Cabo Verde and Mozambique, in close contact with the countries' national organisations for climate change subjects. The project was assessed by local stakeholders who supported the collection of previously inexistent data, validated estimates, and initially aided in the selection of mitigation solutions.

Selected mitigation measures include renewable electricity generation, both connected to the national grid and isolated, transports improvement, and efficiency measures in residential and service sectors. A cost-efficacy bottom-up analysis was applied, that delivers the costs per amount of emissions reductions, resulting in a marginal cost of abatement curve. The MACC highlights the negative cost of most measures, with a particular impact of solutions to produce renewable electricity (mini-hydropower grid (4MW), solar PV (12MW) and isolated mini-hydro (15MW)). In parallel, the same measures were evaluated under a multi-criteria framework (MCE) that included socio-economic and environment features and ranked the solutions by preference. The multi-criteria analysis provided robustness to the application of the measures, considering a critical aspect in SIDS regarding the direct intervention of stakeholders in the process. The hydroelectric generation in the grid and the isolated mini-hydropower were the two best-rated measures under this methodology. Comparing it with the ranking of the marginal cost curve, it can be observed that the measures proposed by the country are either more useful in qualitative aspects or, on the other hand, more cost-efficient. However, considering that most of the measures allow financial savings, the qualitative ranking can be considered as an interesting implementation decision rule.

Finally, we developed a reference scenario of the country's economic and energy development up to 2030, to which we applied the mitigation solutions, resulting in an alternative, mitigation scenario. In these scenarios, we consider both energy demand and transformation, and a recursive solution is found in the transformation module, to supply energy demand requirements. In the reference scenario, the country's GHG emissions are, for the most part, derived from energy consumption in the residential sector, though largely offset by the Forest and Land Use, with a value of -629.22 kt CO2eq./year, which keeps the country, over time, as a recognised net emission sink. It should be noted that the sink value presented has not been updated since 2005. However, local information indicates that the value is still of the same magnitude, despite the possibility of a decrease as a result of deforestation. The vast majority of the emission savings in the mitigation scenario comes from renewable energy production increases (29% savings compared to the baseline scenario in 2030), while measures in the energy demand category make a rather modest contribution (0.25%). In total, we achieve a decrease of 9% in 2030, in the country's emissions. Further issues to be developed include an update of non-energy data, and the consideration of new measures to promote the maintenance of sink values, reducing deforestation and stabilising agricultural emissions.

It is also important to note that emission savings reported in this study are higher than those calculated in the GACMO tool used for the NDC2015 of the country, which happens due to the use of different methodologies. In the NDC, a partial sum approach is used, through cost-efficacy analysis model, comparing each measure to a reference situation, regardless of their interconnection with other sectors of the economy. Consequently, the electric generation energy mix of fossil origin, such as that of São Tomé and Príncipe is under-valuated. To overcome this issue, in this work we proposed a combined methodology that recursively balances demand and supply, thus accounting for emissions of a real amount of energy needs, under a clear mitigation scenario.

In conclusion, the planned mitigation measures for São Tomé and Príncipe show a cross-cutting concern with sustainable supply and demand of energy in the country. The country is a net sink of emissions, and, as a SIDS, mostly needs climate change adaptation measures. However, the country still aims to engage in mitigation solutions, promoting a more efficient and renewable use of energy, and expressing concern about the sustainability of electricity production, by switching to renewable sources, to which they will require external finance and technology resources, and capacity building.

This study aims to support the idea that SIDS should put forth low-carbon development roadmaps, in addition to adaptation strategies, in order to become energetically independent. This suggestion materialised a shift in the paradigm of accountability of major emitting countries, in line with the proposals of the Paris Agreement, to which SIDS have advanced with their national contributions.

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Annex – Selected criteria for MC evaluation of mitigation projects in SIDS

Level 1	Level 2		Level 3
Input 25%	50%	Needs for public finance	Minimizes spending on technology
			Minimize other expenses, or, generates revenue
		Needs for private finance	Minimizes external dependency
	50%	Barriers to implementation	Enables easy deployment
			Technology is available
			Knowledge exists
			Consistent with political timing
			Has public acceptability
			It is sustainable
			There are data for MRV
			No tax incentives required
Output 75%	20%	Economic	Promotes private investments
			Improves economic performance (GDP), or decreases public spending
			Contributes to the trade balance
			Contributes to fiscal sustainability
	20%	Social	Reduces social inequalities by considering the most vulnerable groups
			Improves health
			Preserves the cultural heritage
			Reduces external dependence on energy sources
			Diversifies available resources
			Generates local employment
			Promotes availability and access to services resulting from
			Contributes to local development
			Promotes gender equality
			Is replicable
	20%	Political and institutional	Contributes to political stability
			Improve governance
	20%	Climatic	Reduces GHG emissions
			Promotes GHG removal / sequestration
			Increases resilience to climate change (win win)
	20%	Environmental	Protects natural resources (in quality and stocks)
			Protects biodiversity
			Promotes soil protection (does not cause erosion)
			Promotes air quality (does not increase pollution)
			Promotes quality water resources (does not increase pollution)
			Promotes soil quality (does not increase pollution)

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