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Research Article

Modelling the Optimal Electricity Mix for Togo by 2050 Using OSeMOSYS

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Abstract. This work uses bottom-up modeling to explore the future evolution trajectories of the electricity mix in Togo by 2050. The objective is to investigate the evolution of the mix and the future investments needed to achieve the sustainable energy and climate change goals. Three scenarios were developed using OSeMOSYS. The reference scenario, named Business As Usual, closely reflects the evolution of the Togolese electricity sector under a business-as-usual assumption and planned capacity increases up to 2030. The second scenario, Net Zero by 2050, is based on the first scenario while ensuring that CO_2 emissions cancel out in 2050 by following the Weibull law. The third scenario called Emission Penalty aims not only at the integration of renewable energies like the second one but also at the least cost electricity mix if emission penalties are applied. The results of the cost optimization indicate that photovoltaic and importation are the optimal choices ahead of gas and hydropower. The renewable energy aspect of the electricity mix is more highlighted in the last scenario. At the same time, the model shows that greater energy independence is achievable at the cost of a transitory increase in the cost of the electricity system. A tenfold investment effort is needed in 2030 to ensure either continuity of the status quo or a shift in strategy.

Keywords: Bottom-up modeling, renewable energy, emission penalties, optimization, Togo.

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1. Introduction

Electricity being a key sector for development, it is nowadays one of the major concerns and an indispensable parameter for developing countries in achieving the Sustainable Development Goals (SDGs) (International Energy Agency *et al.* 2022). It contributes to the reduction of poverty by improving economic development, health, food security, education and environmental protection (Swain & Karimu 2020; Anwar & Elfaki 2021; Syromyatnikov *et al.* 2021; Souza *et al.* 2022; Nguyen *et al.* 2022). The SDGs adopted by the United Nations in 2015, are a global call to action to eliminate poverty, protect the planet and ensure peace and prosperity for all people by 2030 (United Nations 2021). Among the seventeen goals, SDG7 aims to ensure access to affordable, reliable, sustainable and modern energy for all. This target is critical to the achievement of many other goals. Fuso Nerini et al. established in 2018 that there is an interaction between SDG7 and at least 85% of the other SDGs and their sub-goals (Fuso Nerini *et al.* 2018). All countries must therefore make universal electricity access a priority.

In Togo, the electricity access rate increased from 30.8% to 54% between 2010 and 2020 (World Bank 2022). However, the accelerating population growth in a context of energy transition leads to an increase in the demand of sustainable electrical energy. It is therefore necessary to invest in renewable energies and improve energy efficiency to achieve the SDG7. The ambition of Togo is to achieve universal access to all Togolese by 2030, passing by 75% in 2025. To achieve this, Togo intends to focus on the rural electrification rate, which is expected to rise from 7% in 2017 to 40% in 2022. This growth in the rural electrification rate is mainly linked to the CiZo rural electrification project implemented since 2017 (African Development Bank 2019). This involves the distribution of individual solar kits at an affordable cost to more than 2 million citizens (i.e. about 300,000 households). The social component of the project includes equipping 800 health centers and 3,000 small farms with individual solar kits or water systems. Also Togolese government has launched in 2019 a tender for providing 317 mini-grids financed by the West African Development Bank and the Energy Development Fund (Antonanzas-Torres *et al.* 2021). This project is composed of five lots divided into three phases of 11 MW and 480 km of distribution lines. This shows the country's willingness to capitalize on renewable energy to overcome its electricity deficit.

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The main renewable energy sources available in Togo are: wind energy, solar energy and hydropower. The wind speed in Lomé is low with a monthly average value generally under 4 m/s. However, for small-scale applications, and in the long term as wind turbine technology develops, the use of wind energy may be foreseeable (Salami *et al.* 2016; Guenoukpati *et al.* 2020). The solar energy flux received daily is generally higher than 1700 kWh/m2 /year. The solar radiation is constant throughout the year with a level of irradiation varying between 5.01 kWh/m²/d in the southern part and 5.55 kWh/m²/d in the northern part (Amou *et al.* 2010; Ministère de l'environnement, du développement durable et de la protection de la nature *et al.* 2020; Patchali *et al.* 2022). Concerning the hydropower potential, about 40 sites have been identified on the rivers MONO and OTI, of which about half of them have a potential higher than 2 MW. The expected productivity of all the sites is estimated at about 850 000 MWh for an installed capacity of about 224 MW.

In 2020, the total domestic electricity production in Togo was 533.4 GWh against a demand of 1545.68 GWh (Autorité de Règlementation du Secteur de l'Electricité 2022). The remaining energy needed is imported from neighboring countries such as Ghana and Nigeria. Togo's generating fleet consists mainly of a 20 MW gas turbine, a 65 MW hydroelectric power plant, a 65 MW thermal power plant, a 50 MW solar power plant, a 100 MW group power plant and several diesel generators with a total capacity of 36.3 MW. In addition, the country has a potential for renewable energy resources such as solar, wind and hydro (Ministère des Mines et de l'Energie *et al.* 2015).

In line with the Paris agreement, which aims to limit global warming to below two degrees Celsius compared to pre-industrial levels (Horowitz 2016), Togo has set a target of 50% renewable energy in the national energy mix including 10% solar PV by 2030. This will considerably reduce the level of greenhouse gas emissions in the country.

Given the dual context of accelerating development and increasing use of green energies, it is necessary to investigate the future evolution of Togo's electricity mix beyond 2030. This study addresses the following research questions: (i) What will the national electricity mix look like after 2030 in the context of economic development and the current trajectory of the electricity strategy? (ii) What are the options for Togo to definitively remove direct greenhouse gas emissions from the electricity sector?

The objective of this research was to explore the policy decisions and investments needed to achieve national and international targets related to sustainable energy and climate change.

2. Literature review

Electricity mix, (similar to the energy mix which outlines the share of each primary commodities in the final energy consumption of a given area) indicates the fraction of the total electricity produced by each source in a given region, country, continent or in the world. Modelling the future electricity mix is important to assess the impact of economic, environmental and political decisions. It provides the best guidance to governments and industry on the most economically and environmentally viable approach to electricity generation, while ensuring a secure supply of electricity in both quantity and quality (Foley *et al.* 2010). Models can be divided into short, medium, and long-term models. In all three cases, constraints related to the availability of potential, dynamics of demand, market prices, policy regulation, technological evolution of the network and environmental concerns are taken into account (Quevedo & Moya 2022; Kansongue *et al.* 2022).

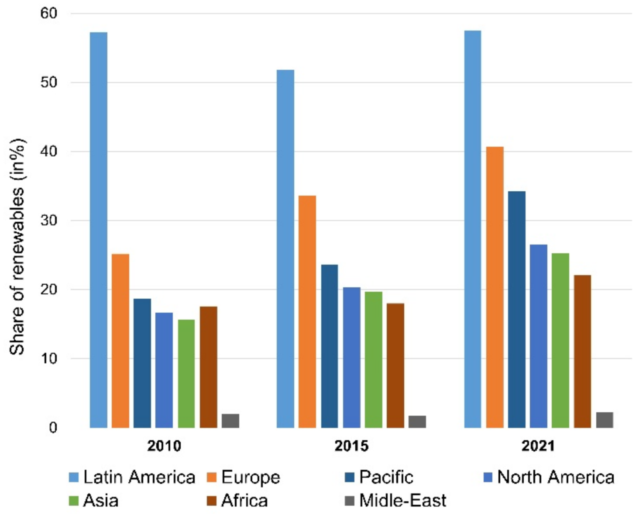

Fig. 1 Share of renewables in electricity generation in the world's regions.

These constraints differ from region to region depending on the degree of development and natural conditions. Figure 1 shows the ratio of electricity generation from renewables (hydro, wind, geothermal and solar) to total electricity generation across the regions of the world from 2010 to 2021. In 2021, the global electricity mix was composed of 28.1% renewables and 71.9% non-renewables.

In general, the share of renewables in the electricity mix is particularly high in countries with large hydroelectric resources such as Brazil, Canada, Sweden or Norway (Stefanelli *et al.* 2019; Lima *et al.* 2020; Zhong *et al.* 2021; Skjærseth & Rosendal 2022). However, this share has increased recently, as ambitious renewable energy policies and the continued decline in the costs of solar and wind technologies have contributed to a sharp increase in renewable electricity generation in Europe (notably in the UK, Greece, Germany and the Netherlands), China, USA, Australia, South Korea and South Africa (Ntanos *et al.* 2018; Swain & Karimu 2020; Kyriakopoulos *et al.* 2018).

2.1 International context

The worldwide energy context is mainly characterized by a global awareness of its effects on the climate. There is a growing international concern about the climate change caused by greenhouse gas (GHG) emissions, almost 89% of which are generated by the energy sector (Herbert *et al.* 2016; IEA 2022). According to the International Energy Agency, the largest growth in CO2 emissions by sector in 2021 occurred in electricity and heat production. It accounts for 46% of the global increase in emissions (IEA 2022). To address this situation, countries have pledged to commit to the energy transition. Several elements such as the increasing contribution of renewable energy and the promotion of energy efficiency can be highlighted.

The European Union's Renewable Energy Directive has established a clear common framework for the development of renewable energy (RE) in the EU and has set a binding target of 32% for the overall RE share of the EU's gross final energy consumption by 2030 (Anna Zygierewicz & Lucia Salvador Sanz 2021). In 2020, Chammas et al. carried out the modelling and optimization of the French and European electricity mix for the period 2020 - 2060 on behalf of French Environment and Energy Management Agency (Agence de l'environnement et de la maîtrise de l'énergie) ADEME (Chammas *et al.* 2022). They have investigated four scenarios, the main characteristics of which are summarized in Table 1. Up to 2030, the development of RE at the same time as the extension of the existing nuclear fleet leads to an increase in production in all scenarios. After 2030, the differences become more pronounced, showing divergences in both the demand scenarios and the mix orientations. Under all trajectories, regardless of demand volumes and mix orientations, the penetration rate of RE will exceed 50% by 2040.

In Germany, the energy policy is shaped by the law concerning the promotion of renewable energies in the electricity sector introduced in 2000 and the abandonment of nuclear power in 2002 (Sovacool 2008; Lipp 2007; Wüstenhagen & Bilharz 2006). In 2010, The Federal Government adopted a comprehensive energy concept (Energiekonzept), which sets out the main directions of the energy transition up to 2050 with the aim of reducing greenhouse gas emissions (Prognos *et al.* 2010; Becker 2010). Since January 2022, Germany has set a target of 80% renewable energy for electricity generation by 2030 and almost 100% by 2035. Hansen et al. proposed a feasible transition strategy to reach 100% renewable energy, taking into account all energy sectors (Hansen *et al.* 2019). To achieve this high share of renewable energy, there are some crucial measures, such as the use of electric vehicles to replace internal combustion engine vehicles (Salkuti 2021). This allows more electrical storage to be added to the energy system and greatly increases the energy efficiency of the transport sector by using renewable energy sources. It has been found that energy efficiency is essential to be able to stay within the sustainable resource potential for renewable electricity. In particular within the heating sector, there is significant potential for energy savings, while complementary savings are also possible in the industry and electricity sectors. Furthermore, technologies such as electric vehicles, mini-grids, heat pumps and electrolysers improve the efficiency of the energy system while increasing its flexibility and allowing the integration of more renewable electricity (Kyriakopoulos & Arabatzis 2016; Hansen *et al.* 2019; Salkuti 2021). Also in the Latin America, the electricity mix of countries has been changing significantly in the last few years. In the Dominican Republic, the renewable energy generation fleet in 2020 was composed of 187.46 MW of solar power (3.81% of total installed capacity) and 370.25 MW of wind power (7.52% of installed capacity), increasing the share of renewable energy from 12% in 2019 to 15% in 2020 (Quevedo & Moya 2022).

Table 1
Scenarios for modelling the French electricity mix (Chammas *et al. 2022)*

Scenarios	Description
S1	• 100% RE by 2050 • Rooftop PV in the residential sector • Distribution of production plants throughout the territory
S2	• Small increase in demand 2020 - 2050 • Highest production of the 4 scenarios • Development of RE with cost minimization
S3	• Significantly increases demand • Variant 1: development of an EPR (European Pressurized Reactor) program • Variant 2: significant development of floating offshore wind
S4	• The biggest increase in demand with little energy efficiency and little development of demand flexibility • All production technologies are taken into account, to ensure volumes exceeding 800 TWh in 2050

The country aims to produce 25% of its electricity from renewable energy sources by 2025. In an optimistic perspective, the share of renewables in installed electricity generation capacity could reach 59% by 2030. In general, the share of renewables in electricity generation in the region is not uniform. It shows significant differences between countries. These differences have become more pronounced in recent years as several countries have started to invest in technologies such as solar and wind power. Paraguay stands out with 99.9% and is the country with the cleanest electricity production in the world (Washburn & Pablo-Romero 2019; IRENA 2021). This trend is due to several measures to promote the use of renewable energy for electricity generation. These include the feed-in tariff system, net metering, tax incentives and the public auction system (Washburn & Pablo-Romero 2019).

Achieving 100% renewable sources in the electricity mix is a challenge for the United States of America (Denholm *et al.* 2021). The U.S. Energy Information Administration estimates that about 61% of the electricity generation comes from fossil fuels such as coal, natural gas and oil. About 19% comes from nuclear power, and about 20% from renewable energy sources. The US was one of the first countries to integrate energy policy into its economic system, but in 2009 it became the second largest emitter of carbon dioxide (CO_2) in the world (after China). Nowadays, several regulations are in place to promote the use of renewable energy. The Energy Independence and Security Act and the Energy Policy Act are promoting both energy efficiency and renewable energy applications. (Lu *et al.* 2020).

In Asia, it has been shown that both China and India have implemented an attractive five-year energy plan, while Pakistan has failed to implement its energy plans due to economic, political and security problems. However, the friendly relations between China and Pakistan under the China-Pakistan Economic Corridor and the significant investments in the Pakistani energy sector are promising (Ahmed *et al.* 2016; Thapar *et al.* 2016; Kyriakopoulos *et al.* 2018). China's non-renewable energy resources are likely to be exhausted within 20 to 50 years. Coal accounts for over 60% of primary energy consumption in China (Baležentis & Štreimikienė 2019).

At different levels, countries are making efforts to comply with international agreements on both climate change and electricity generation. The measures range from energy efficiency to overall transformation of the generation mix as well as technological innovation.

2.2 African context

Regarding the future direction of electricity generation in Africa, there is a little scientific convergence in the literature. The estimated future capacity, even for the relatively near horizon of 2030, ranges from about 315 to 620 GW. Energy planning analyses show that Africa has the potential to move to a low-carbon growth trajectory over the next decade by adopting clean energy technologies and skipping the carbon-intensive development stage (Alova *et al.* 2021). Africa has a clear potential to leverage solar, wind, hydro, natural gas and energy efficiency. The continent's estimated renewable energy generation potential from existing technologies is 1,000 times greater than its projected electricity demand in 2040, meaning that the Africa has enough capacity to meet its future demand (KFW *et al.* 2020). The most abundant energy resource is solar. Currently, the total installed power capacity in Africa is estimated at 236.2 GW, with renewable capacity of approximately 49.5 GW.

Speaking of emissions, the African continent accounted for 4% of global energy-related CO_2 emissions in 2018. North Africa accounted for the largest share of the continent's energy-related emissions, with 40%, followed by South Africa with 35%. In general, access to electricity is low in Africa, but the electricity sector is the most emitting sector, followed by transport and manufacturing (Chambile *et al.* 2021).

In South Africa for example, there has been a trade-off between green electricity production and production costs. It has always been cheaper to build new coal-fired power plants, given the country's large coal resources. But this has changed in recent years. In 2011, the country embarked on a large-scale auction process for renewable energy, known as the Renewable Energy Independent Power Producer Procurement Program (REIPPPP), which significantly reduced the tariffs offered by developers (Wright *et al.* 2019). The country's electricity mix is currently dominated by coal. 86% of the electricity supplied in 2021 comes from this fuel. The remainder is mainly composed of 6% nuclear, 4% wind and 3% solar. Both hydro and natural gas account for less than 1% of the mix (Ritchie *et al.* 2022).

Several studies have been done regarding the energy mix and the greenhouse gas emissions reduction in Togo. The assessment of renewable energy potential takes a particular place in these studies (Salami *et al.* 2022; Kitegi *et al.* 2022). Kansongue et al proposed an assessment of the development of renewable energy in Togo's energy mix (Kansongue *et al.* 2022). It was concluded that increasing the share of renewable energy, namely solar PV and hydropower, could significantly improve the energy balance in Togo. This could be done through the construction and development of small-scale solar and hydro power plants. For their part, Agbossou et al. developed the assessment of climate change and air pollution mitigation in Togo (Agbossou *et al.* 2022). They provide an approach by which Togo can optimize its contribution to climate change while at the same time achieving local benefits by 2030.

So far, to our knowledge, all these studies focused on the 2030 horizon and there is no study on the modelling of the electricity mix taking into account the current orientation of Togolese energy policy in order to make a projection up to 2050. This work aims to introduce the discussion on the issue by investigating, with clear assumptions, the future evolution of Togo's electricity mix. It explores the policy decisions and investments needed to achieve national and international objectives related to sustainable energy and climate change. The modeling tool used for this purpose is based on the bottom-up modeling approach.

3. Methodology

Bottom-up modeling of energy systems involves several disciplines such as applied mathematics, economics, accounting, computer science, environmental and social sciences, etc. Several specialized software tools have been developed to help with this modeling but they are mostly commercial and intended for a limited number of specialists. OSeMOSYS (Open Source energy MOdelling SYStem) as its name suggests, is an open source energy system modeling tool. It is a complete system optimization model for long term energy planning. Compared to classical models such as TIMES, MESSAGE or PRIMES, the OSeMOSYS system requires a significantly lower learning curve and commitment time for its construction and exploitation. This is possible thanks to a simple open source code and a modular structure that allows more sophisticated model elements to be added. Moreover, since it doesn't use proprietary software, commercial programming languages or solvers, it doesn't require an initial financial investment.

3.1 The OSeMOSYS model

OSeMOSYS is a bottom-up modeling and optimization framework used primarily for the analysis and long-term planning of energy systems. The first code was made available to the public in 2008 and it has been continuously developed since then. It is built in modules so that it can be adapted by users (Howells *et al.* 2011). It has had several applications. Recently, it has been used to study options for stabilizing renewable energy sources in long-term energy systems (Gardumi *et al.* 2019), modeling energy systems to evaluate alternative scenarios (Quevedo & Moya 2022), and modeling solutions for energy security in the electricity sector (Yeganyan 2021) among others.

The mathematical formulation of the OSeMOSYS model was first presented by (Howells *et al.* 2011). It is a partial equilibrium model based on a linear optimization problem. Its objective is to minimize the total effective cost of the energy system to satisfy a specific energy demand in a given territory, over a given period and under specific constraints. In the end, the solution of the problem gives the configuration of the energy system with the lowest total cost. The objective function to be minimized is therefore obtained by summing up all the costs involved in the system. This is the sum of the operating cost, investment cost and emission penalty of the technology minus the cost of the remaining capacity available before the modelling period. The summation is done according to the technology, the period of time and the region of interest. The model can be forced to take into account a large number of specific constraints such as the minimum amount of renewable energy production, the greenhouse gas emission limitation, etc. (Ezzahid & Icharmouhene 2021). The problem formulation is as follows:

$$Minimize\ \sum_y \sum_t \sum_r TDC_{y,t,r}\ ;\ \forall\ y,t,r \quad (1)$$

$$under\ constraint\ g_i \leq 0, with\ i = 1,2,3,\ldots,k \quad (2)$$

$$\sum_y \sum_t \sum_r TDC_{y,t,r} = OC_{y,t,r} + IC_{y,t,r} + EP_{y,t,r} - RV_{y,t,r} \quad (3)$$

Where TDC, OC, IC, EP, RV, y, t et r respectively stand for total discounted cost, operating cost, investment cost, technology emission penalty, residual values, year, technology and region. The constraints gi can be either of equality or inequality. A full description of OSeMOSYS is presented in the paper of (Howells *et al.* 2011).

3.2 Period and time slices

The simulation period considered here is from 2022 to 2050. The notion of time slice refers to the temporal division of each year of the model; it is considered as the temporal resolution of the model. Four climatic seasons have been considered during each year: the long dry season (LD), the long rain season (LR), the short dry season (SD) and the short rain season (SR). Each day is divided in two periods: the day and the night. From this configuration, we have eight time slices. The slices were considered to have balanced coefficients (the sum of each coefficient in a year must be equal to 1). Table 2 shows this more clearly.

3.3 Reference electrical system of Togo

Togo's reference electricity system is shown in Figure 2, which is a schematic representation of the country's electricity supply chain from primary sources to consumption by sectors. In this study we consider secondary sources and energy potentials presented by the national energy regulator in its report (Autorité de Règlementation du Secteur de l'Electricité 2022).

Table 2
Year Split.

No	Time Slices	2022	2023	…	2050
1	LD-DAY	0.125	0.125	0.125	0.125
2	LD-NIGHT	0.125	0.125	0.125	0.125
3	LR-DAY	0.125	0.125	0.125	0.125
4	LR-NIGHT	0.125	0.125	0.125	0.125
5	SD-DAY	0.125	0.125	0.125	0.125
6	SD-NIGHT	0.125	0.125	0.125	0.125
7	SR-DAY	0.125	0.125	0.125	0.125
8	SR-NIGHT	0.125	0.125	0.125	0.125

Table 3
Participation factors of each consumption group

No	Time Slices	RES	IND	COM
1	LD-DAY	0.122	0.122	0.122
2	LD-NIGHT	0.126	0.126	0.126
3	LR-DAY	0.124	0.124	0.124
4	LR-NIGHT	0.128	0.128	0.128
5	SD-DAY	0.123	0.123	0.123
6	SD-NIGHT	0.126	0.126	0.126
7	SR-DAY	0.124	0.124	0.124
8	SR-NIGHT	0.126	0.126	0.126

3.4 Electricity demand

The electricity demand profile used in this study is based on the data selected for the modeling of Togo's energy system (Allington *et al.* 2021). The total demand is the joint sum of the demands in the residential (RES), industrial (IND) and commercial (COM) sectors. Figure 3 shows the annual evolution of the national demand. To stratify the demand for electricity in the different sectors or consumption groups, the participation factors of the electricity demand shown in Table 3 were determined. These factors reflect the annual fraction of electricity demand that is required in each time slice for each consumption group. We assume a uniform distribution of demands from each group.

3.5 Production systems

Table 4 shows the status of the minimum installed capacity considered by technology. The national production uses solar (PWRSOL), hydroelectric (PWRHYD) and thermal (PWRNGS) sources (Ministère des Mines et de l'Energie *et al.* 2015). Due to the uncertainties related to the other sources, only the Namgbéto hydroelectric plant, the Blitta solar plant, the Kékéli thermal plant and the Contour Global group power plant are considered to set the minimum production. In 2022, the minimum available capacity is therefore set at 165MW for thermal sources, 50MW for solar sources and 65MW for hydroelectric sources. Taking into account the lifetime of the systems, the Namgbeto hydroelectric plant is considered non-productive from 2037 and the solar plant from 2045. From these dates, the minimum capacity is therefore set to zero. The model will estimate the necessary capacity to be installed and importations if necessary. Tables 5 and 6 show the Capital Cost and Fixed Cost considered in the model, respectively. The Variable Cost is set equal to 0.0001 Million $/PJ for all technologies.

3.6 Definition of the scenarios

Three scenarios were investigated:

- **Scenario 1:** Business As Usual (BAU)

The first scenario represents the current situation of the Togolese electricity sector with the status quo and the planned increases in production capacity up to 2030. The model is constrained to ensure 50% renewable energy in the electricity mix by 2025; to ensure universal access by 2030 and to have a maximum hydroelectric capacity of 224 MW given the country's hydroelectric potential (Ministère des Mines et de l'Energie *et al.* 2015). The renewable energy sources considered are solar, wind and hydroelectric. The evaluation of the electrical system is done by optimizing the total costs.

- **Scenario 2:** Net zero by 2050 (NZ2050)

The second scenario is based on the first one. The difference is that the model is constrained to progressively reduce greenhouse gas emissions from 2030 to zero in 2050 following a decrease according to the Weibull law. This law is characterized by the following function:

$$f(x,k,\lambda) = \frac{k}{\lambda}\left(\frac{k}{\lambda}\right)^{k-1} exp\left(\left(-\frac{x}{\lambda}\right)^{k}\right) \quad (4)$$

Where k > 0 is the shape parameter and λ > 0 is the scale parameter. Only the CO2 emissions as shown in Table 7 are considered in this study.

- **Scenario 3:** Emission Penalty (EP)

In the third scenario, the evolution of the electricity mix is assessed if an emissions penalty is applied for each ton of greenhouse gases emitted in the process of electricity production. The carbon price is set at 40 USD/t between 2031 and 2040 and at 65 USD/t between 2041 and 2050, in line with the level of carbon pricing recommended to reach the Paris Agreement targets. This scenario is based on the first two.

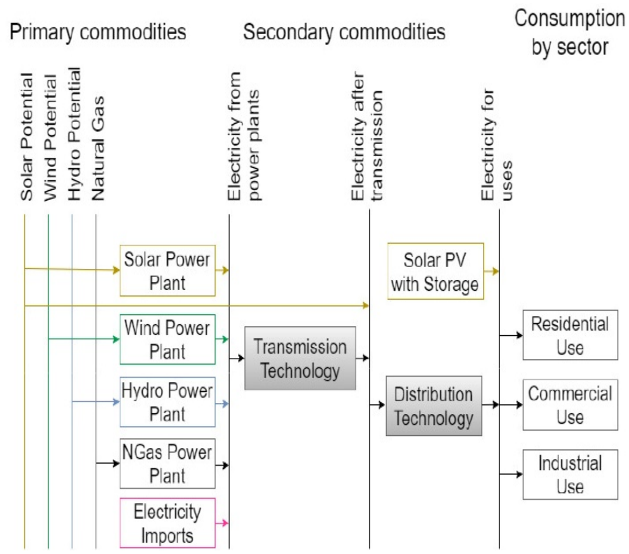

Fig. 2 Reference electrical system of Togo

Table 4
National minimum production capacity by technology (MW)

Technology	2022	…	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
PWRNGS	165	165	165	165	165	165	165	165	165	165	165	65	65	65	65	65
PWRSOL	50	50	50	50	50	50	50	50	50	50	50	0	0	0	0	0
PWRHYD	65	65	65	0	0	0	0	0	0	0	0	0	0	0	0	0
PWRWND	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5
Capital cost by technology (Million $/GW)

Technology	2022	2023	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044	2046	2048	2050
PWRNGS	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200
PWRSOL	1220	1142	1063	964	925	886	852	817	785	754	723	723	723	723	723	723
PWRHYD	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
PWRWND	1370	1310	1251	1170	1129	1087	1025	964	933	933	933	933	933	933	933	933

Table 6
Fixed cost by technology (Million $/GW)

Technology	2022	2023	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044	2046	2048	2050
PWRNGS	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
PWRSOL	15.9	14.8	13.8	12.5	12.0	11.5	11.1	10.6	10.2	9.8	9.4	9.4	9.4	9.4	9.4	9.4
PWRHYD	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0
PWRWND	54.8	52.4	50.0	46.8	45.1	43.5	41.0	38.6	37.3	37.3	37.3	37.3	37.3	37.3	37.3	37.3

Table 7
Annual CO2 emission limit (Mton)

Years	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044	2046	2048	2050
Emissions	35500	35495	35407	34745	32251	26850	19284	11748	6023	2556	859	206	27	1	0

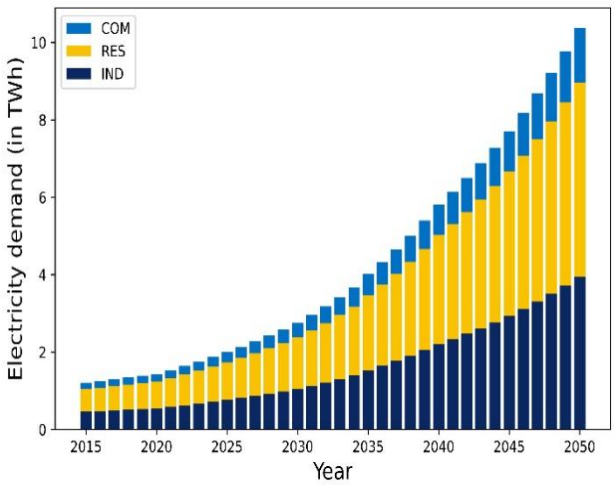

Fig. 3 Electricity demand in Togo (in TWh)

4. Results

Figure 4 shows the progression of the electricity mix in each of the three developed scenarios. In 2020, Togo's electricity mix was composed of 44.44% thermal, 44.29% importation and 11.27% renewable sources (Autorité de Règlementation du Secteur de l'Electricité 2022). This proportion is reflected in the business as usual model in 2022.

The comparison between the three scenarios shows that solar PV is a major component of the electricity mix in Togo. To reach universal access in 2030 in the first scenario, the model estimates a total available power of 15.4 GW. This mix is dominated by solar at 61%. Importation comes in second place with 25%. The third place is occupied by thermal sources with 10%. Hydroelectricity and wind power are respectively in fourth and fifth place with 2% and 1%. These last two will no longer be cost-effective by 2050.

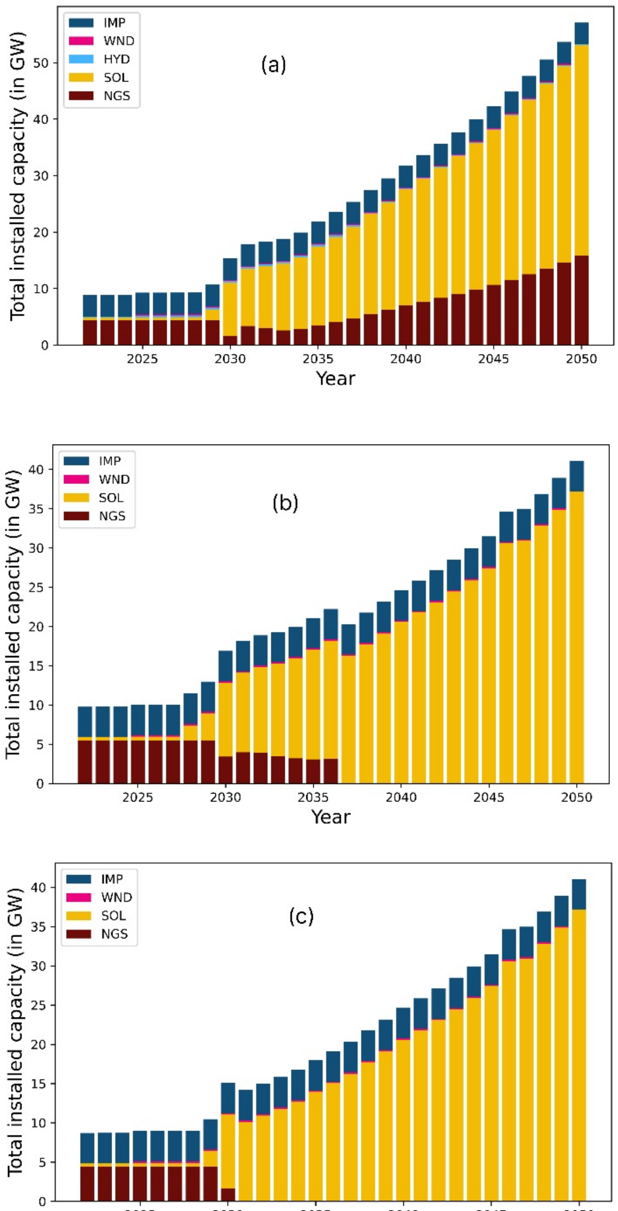

Fig. 4 Evolution of the mix in the (a) BAU scenario, (b) NZ2050 scenario, (c) EP scenario

The economic optimization shows that by 2050, the electricity mix will still be dominated by solar power (65%) out of a total installed capacity of 57.1 GW. The remaining capacity is shared between thermal sources (28%) and imports (7%). Nevertheless, this scenario is the most diversified of the three. Indeed, the constraints of emissions and production applied to the model have led to a low diversity of the mix in scenarios 2 and 3.

In the second scenario, the electricity mix by 2030 is composed of 56% solar, 23% imported, 20% thermal and 1% wind power out of a total installed capacity of 16.9 GW. In this situation, the share of thermal sources considered as pollutants is following a decreasing trend and will be cancelled out by 2037. The wind potential (Autorité de Règlementation du Secteur de l'Electricité 2022) of Togo does not guarantee a techno-economic efficiency. For this reason, the cost optimization of the system by 2050 proposes solar power at 91% and importations at 9% for a total available capacity of 41 GW. The importations are therefore the most economical option to solve the problem related to the intermittency of solar power and the large power calls. It is clear that this mix is unlikely to be realistic. It would require renewable technologies with significant levels of inertia, such as hydroelectricity or electricity storage. This would require additional investment. The model projects the same mix by 2050 in the third scenario taking into account the emission penalties.

In the third scenario, despite the fact that the introduction of the emission penalty is done in two steps, the model has completely downgraded the thermal sources from 2031. The projected electricity mix by 2030 consists of 62% solar, 26% imported, 11% thermal and 1% wind for a total installed capacity of 14.2 GW. This capacity is lower than in the business-as-usual scenario.

Figures 5 and 6 respectively shows the comparison of the annual CO_2 emission and the total discounted annual cost for the three scenarios. The maximum investment over the modeling period will be recorded in 2030. This is approximately 801 million US dollars for the BAU scenario, 636 million US dollars for the NZ2050 scenario and 788 million US dollars for the PE scenario. The current pathway is the most challenging economically, and the investment required in each of the three scenarios between 2028 and 2032 is more than ten times the total investment required by 2025.

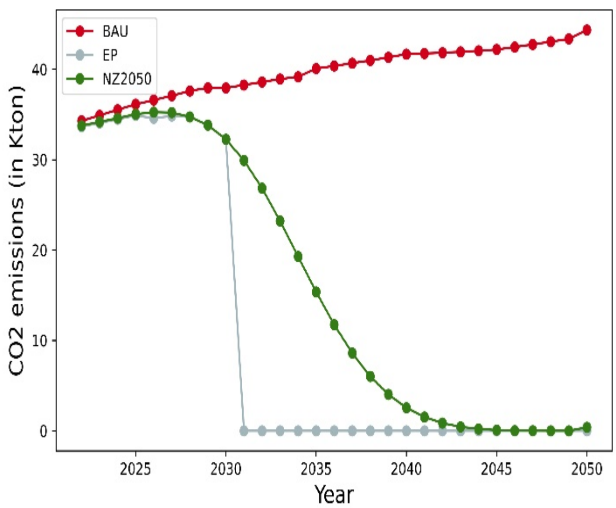

Fig. 5 Annual CO_2 emission

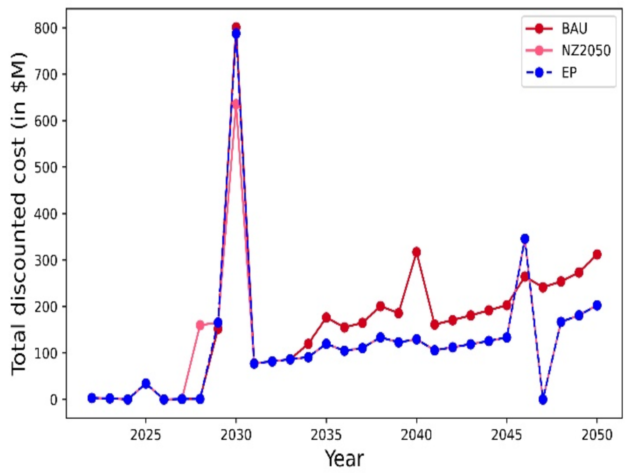

Fig. 6 Total discounted cost

5. Discussion

This paper presents the results obtained by modelling the electricity system of Togo using OSeMOSYS. The main objective is to determine, on a scientific basis, what the country's electricity mix will look like after 2030 in the context of economic development and the current trajectory of the national electricity strategy. It highlights options available to permanently remove direct greenhouse gas emissions from the electricity sector. For this purpose, it is important to use reliable tools based on application experiences in similar contexts with scientifically supported results, and it is preferable that they are open source. The tool used should enable the participation of the institutions responsible for energy development planning in the country and facilitate contributions from the academic and scientific community, which represents a significant potential for finding sustainable solutions (Quevedo & Moya 2022).

In this case study, a business as usual scenario was initially modelled in order to reflect the current orientations of the electricity system. The results found for the year 2020 are in accordance with the report of the National Authority for the Regulation of the Electricity Sector published in 2022 (Autorité de Règlementation du Secteur de l'Electricité 2022). Based on the current baseline scenario, greenhouse gas monitoring shows that Togo can achieve a carbon neutrally operating power sector by 2050. But the energy transition must be accelerated from now in order to have a transition in the best conditions. The number of countries committed to achieving net zero emissions by mid-century or a little later continues to grow, but the global emissions of greenhouse gases continue to grow as well.

For Togo, the key will be solar energy. One of the challenges resulting from the widespread adoption of solar energy is the low dispatching capacity due to the lack of inertia of this particular source. In the context of this research, scenarios including storage systems to improve the dispatching capacity of solar power plants will be modelled (Battula *et al.* 2021).

The economic aspect should not be relegated to the background. It is a key factor for developing economies like Togo. Indeed, the readiness to adopt renewable energy can be correlated to the long-term economic growth of countries (Ntanos *et al.* 2018). Countries with low GDP would be less likely to develop their economy based on renewable energy.

The results obtained so far should not be taken as absolute and time-invariant in a highly dynamic environment, although they provide guidance for the design of energy policies that contribute to the sustainable development of Togo. The evolution and diversity observed in the technologies used to provide energy services and manage demand indicate that energy system modelling is an essential support for agile, accurate and scientifically based decision-making.

6. Conclusion

The purpose of this study is to open the debate on the future of the electricity mix in Togo beyond 2030. It is to highlight the possible trajectory of the electricity mix by 2050 taking into account the energy transition context. The reference electricity system of Togo shows that Togo has solar, wind, rivers and natural gas as potential sources of electricity. The target of the country is to ensure universal access to electricity by 2030 and to have 50% of renewable energy in the mix by 2025. Nevertheless, most of the electricity used in Togo is imported from neighboring countries. Three key aspects were addressed in this work: (i) the issues of the business-as-usual pathway, (ii) the goal of reaching zero emissions by 2050, and (iii) the perspective of introducing an emissions penalty. The economic optimization of the models identifies solar PV as a key component of the electricity mix. Its share varies between 56% and 62% in 2030 and between 65% and 91% in 2050. The financial estimation reveals that a tenfold investment effort is needed in 2030 to ensure either the continuity of the status quo or a shift in strategy. At the same time, this work highlights the necessity of undertaking a study on the flexibility of the electric system in the long term.

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