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Research article

Comparative effectiveness of environmental regulation instruments: Case of the Moroccan electricity mix

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Abstract: Fossil fuels dominate the electricity mix of Morocco, the country is placing renewable energy at the heart of its energy strategy, to improve the security of supply and ensure environmental sustainability. However, the penetration of renewable energy technologies (RET) in the Moroccan electricity mix remains low due to an excess of investment in conventional energy technologies. This study first explores the characteristics of the Moroccan electricity mix before studying the dynamic effects of environmental regulatory instruments, in particular the carbon tax and the emission standards. To do so, we analyzed scenarios using a bottom-up linear and dynamic optimization model «OSeMOSYS». We will therefore assess the impact of the carbon tax and the emission standards on RET adoption in the Moroccan electricity mix, over a period from 2015 to 2040. Our results suggest that environmental regulation in the electricity sector will lead to a large diversification of the Moroccan electricity mix with a large penetration of RET thus reducing the overall production of conventional energy technologies. Therefore, it follows that the carbon tax encourages the adoption of RET in the Moroccan electricity mix with significant reductions on fuel costs and operating & maintenance (O&M) costs of conventional energy technologies compared to emission standards.

Keywords: environmental regulation; electricity mix; energy transition; OSeMOSYS; optimisation

1. Introduction

In a national context of environmental preservation, the Moroccan electricity sector is concerned by this challenge and must take into account the need to reduce its greenhouse gas (GHG) emissions to achieve a sustainable electricity mix. The Moroccan electricity generation mix is very dependent on conventional energy technologies, with a 79.83% share in 2019 [1]. This increases energy bills in the future and represents a significant environmental cost in the form of (GHG) emissions, to which electricity production contributes the most due to its excessive dependence on conventional energy. Moreover, the emissions generated by fossil fuels in Morocco in 2019 were 68.9 kton (CO_2) of which 52% was oil, 45% was coal, and 3% was natural gas [2].

The Moroccan energy mix is slowly moving to renewable energy sources. However, the environmental impacts associated with the use of conventional energy technologies have made it necessary to deploy renewable energy production technologies. Adding to that, the volatility of fuel prices in international markets leads to shocks in the country's trade balance. Morocco has a diverse potential of renewable energy sources, which can be exploited to satisfy its energy needs. In this respect, the penetration of RET in electricity generation allows Morocco to follow a sustainable development path. The high investment costs of RET constrains their large-scale development. In this perspective, the consideration of GHG emissions in the evaluation of energy policy is an important issue for the planning of future energy investments.

The evaluation of sustainable energy strategies uses different outcome analysis. Bottom-up optimization models have an explicit and detailed description of the technology mix. The objective is to determine the least-cost energy mix under a set of technical and environmental constraints to meet an exogenously defined demand [3]. However, when assessing the impact of future impact of an energy strategy, the total costs of energy production technologies serve as a relevant indicator [4]. Various studies have focused on the issue of energy policy evaluation, and this through the emergence of the OSeMOSYS (Open-Source Energy Modeling System) model. This modeling tool has had numerous applications in different contexts [5,8]. Indeed, there is only one empirical study to our knowledge that has modeled the Moroccan power system [9], but the analysis of technology choices with emission reduction constraints has not been studied.

OSeMOSYS model has been applied by [10] to analyze the current strategy of electricity generation expansion in Morocco and to propose alternative approaches, highlighting the cost of each policy scenario. Indeed, the change in the structure of electricity production is necessary to face the challenges of climate change. Electricity production in Morocco contributes the most in GHG emissions with a share of 38.7% in 2016 [11]. This share is mainly linked to the combustion of fossil fuels, which are imported from abroad. Despite the progress of mitigation measures, the conventional energy technologies share in the Moroccan electricity generation is still high.

Mitigation measures relating to electricity production in Morocco include programs to develop wind, solar and hydraulic energy. However, the initial target of a 42% share of renewables in the electricity mix by 2020 (14% solar, 14% wind, and 14% hydro) has not been achieved and this delay is due to their planning process [12]. The removal of fossil fuel subsidies is also an important element for the development of renewable energy. However, this removal has not provided an incentive for energy producers to adopt renewable energy. In this perspective, a carbon tax or an emission standard in the electricity production market can be a real mitigation instrument accelerating the adoption of renewable energies in the electricity production system, and reducing emissions.

This paper aims to evaluate the impact of a carbon tax and an emission standard on the penetration of RET in the Moroccan electricity mix using a bottom-up modeling framework for optimization. By using an economic analysis of the results obtained, we show that a carbon tax provides a greater incentive to invest in renewable energy than the standard.

The rest of the paper is organized as follows: section 2 presents a literature review on the effectiveness of the carbon tax and the emission standard in incentivizing the adoption of clean technologies. Section 3 presents the data and methodological framework of the OSeMOSYS. Section 4 depicts our main results, and finally, Section 5 concludes the paper and provides some policy implications.

2. Litterature review and theoretical framework

2.1. Environmental regulation: the neo-classical approach

The theoretical framework of our research hypothesis originates in the field of environmental economics, which fundamentally raises and explores major issues related to externalities. This field, combined with other theories, constitutes, among others, one of the theoretical corpuses of the effectiveness of economic and regulatory instruments for pollution [13]. Thus, incentive theory, externalities theory, and public goods theory can explain some aspects of environmental cost internalization and justify its theoretical and empirical foundation.

In the neoclassical theory, the presence of externalities is considered a market failure, as the price does not determine the total costs/benefits generated. This situation leads to a non pareto optimal market equilibrium since there is a difference between the costs or benefits of the market parties and society in general. Indeed, the evolution of a firm's costs and profits differ according to the nature of the externality. In the case of a negative externality, the overall costs are underestimated and the benefits are overestimated, and vice versa in the positive externality [14].

Therefore, regulation through economic and environmental instruments aims to correct these external effects by internalizing them [15]. This consists simply of introducing external costs into the economic calculation of agents and putting the costs/benefits system back into the market price formation. Indeed, external effects such as greenhouse gases generated by the production of electricity now constitute an obstacle to the success of a clean energy transition on the one hand and lead to a decrease in social welfare on the other hand. As a result, taking emissions into account by investors becomes an important element for the growth of renewable energies as well as sidestepping critical and irreversible thresholds relating to environmental issues.

In the same order of ideas, a carbon tax regulation is more efficient economically than the emission standard because it allows the environmental objectives to be achieved at a lower variable cost [16]. If we reason in terms of the total cost of the policy, the standard becomes economic compared to the tax because it imposes only the cost of depollution necessary to comply with regulatory requirements. In contrast to the standard, the tax leads agents to pay a price in addition to the same clean-up cost, which is proportional to their total remaining emissions. However, the total social welfare is the same in the case of a tax or a standard, but it is not distributed in the same way among the agents. The yield of the tax is usually redistributed in a lump sum to taxpayers.

However, the dynamic efficiency (i.e., the incentive to adopt clean technologies) of the carbon tax and the emission standard are not identical [17]. For example, when applying an emission standard, agents will not have a continuous incentive to adopt clean technologies because agents cannot exceed their emission reductions at the level imposed by the emission standard and, therefore, will not have an incentive to reduce emissions beyond the threshold. The comparative advantage of a carbon tax is the continuous presence of the incentive due to its price mechanism.

Furthermore, it should be pointed that the neoclassical paradigm is based on the assumption of agents' rationality and on the conflicting links between the economy and the environment, in so far as environmental constraints are considered costs to be minimized. To this end, environmental regulation leads to a reduction in productivity. This is obvious since the firm suffers from the additional burden of reducing emissions. But it should be mentioned that this reduction in productivity is linked to the regulator objectives, i.e., to continue to pollute and to live with the environmental damage or to reduce pollution and follow the path of innovation.

In this work, we assume that the Moroccan regulator plans to implement a mitigation policy based on the emission standard and a carbon tax in the electricity sector to stimulate the adoption of renewable energy technologies and the reduction of GHG emissions. Therefore, a graphical analysis of the effectiveness of these two instruments based on the costs of depollution is of great necessity.

2.2. Dynamic efficiency of the carbon tax: graphical analysis

Incentives for the adoption of innovative technologies have been strongly discussed in recent decades. It is an important criterion to consider when implementing environmental policies [18]. Thus, some studies [19,21], show that market instruments provide different incentives for the adoption of clean technologies. In a framework where firms are competing in such a way that they cannot influence the price of their product and where the regulator is myopic, Requate and Unold show that the tax is a greater incentive to innovation than the emission standards [22], but this result needs to be argued and qualified.

In this case, we study the incentive to stimulate technological change in the electricity mix provided by the tax and the standard using a graphical analysis based on a static model proposed by Afif [23]. We show from this graphical analysis that the tax achieves significant emission reductions and cost savings compared to the emission standards. Figure 1 shows the incentive to adopt a clean electricity mix when emissions are regulated by a tax and emission standards. We assume that the electricity generation market is in pure and perfect competition. The curves $C_x^0(x)$ and $C_x^1(x)$ represent the marginal cost of depollution of an electricity mix based on conventional energy technologies and the marginal cost of depollution of an electricity mix based on clean technologies. We use the term clean to mean any energy technology that can reduce emissions more than conventional energy technologies.

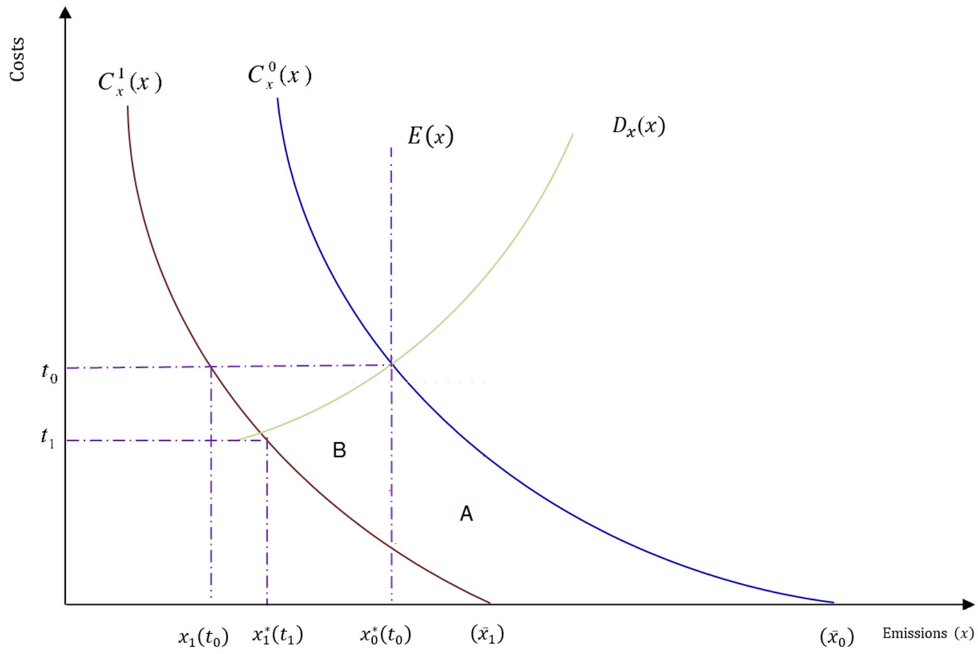

Figure 1. Incentives for innovation through a carbon tax or environmental standard in a perfect market.

Without any regulations, the emission level is $\bar{x}_0$. The regulator is fully aware of the cleanup cost of the power mix based on conventional energy technologies. We also assume that the regulator is myopic, this assumption can be justified in practice by the length and complexity of the legislative process.

Thus, in the application of the regulatory policy, the regulator announces a tax t_0 *and* $E(x)$ to implement the optimal emission level x_0^*. In the following, we will note $x_0^*(t_0)$ *and* $E(x)$: the optimal emission level of the conventional electricity mix when the emission price is t_0 and the emission quantity is $E(x)$. This level is a Pareto optimum because it equals the marginal social cost $C_x^0\,(x)$ to the marginal social damage $D_x(x)$. The regulator wants the electricity mix to depollute the quantity $\left(\bar{x}_0 - x_0^*(t_0)\right)$ and $(\bar{x}_0 - E(x))$.

The integration of renewables into the electricity mix, with the unchanged quantity of emissions, is followed by the decrease of the marginal cost of depollution which becomes $C_x^1\,(x)$. This decrease is reflected in a horizontal shift of the curve towards the origin, which decreases the maximum depollution level and the socially optimal depollution level, which become $\bar{x}_1$ *and* $x_1^*(t_1)$ respectively. We know that the level of depollution imposed on the electricity mix does not change because the regulator is assumed to be myopic.

Indeed, using an emission tax, the clean electricity mix has the effect of simultaneously allowing two savings. The first is a saving in the cost of depollution resulting from the reduction of emissions independently of the regulation policy. The second is a saving in the price of depollution resulting from the decrease in the marginal cost of depollution, which in turn depends on the regulatory instrument put in place. Following the adoption of renewables energy technologies, the electricity mix achieves two savings equivalents to the A + B zone. However, the standard allows for only one saving represented by the A zone, this saving translates into a quantity maximum of emission that will not be voluntarily crossed by the electricity mix.

3. Materials and method

3.1. OSeMOSYS optimization model

To assess the impact of the carbon tax and the emission standard on the evolution trajectory of the Moroccan electricity mix, we adopt a linear dynamic partial equilibrium optimization model named OSeMOSYS. This model provides a disaggregated technological representation with a set of block equations that describe the objective function, costs, GHG emissions, capacity adequacy, energy balance, constraints, and storage as can be seen in (Figure 2). The model equations are derived from optimization programs, in which power producers are assumed to be price takers in a competitive market [24]. The main assumptions of the model are:

-The electricity market operates in an environment of pure and perfect competition where generators optimize their production functions under specific constraints, hence equilibrium is achieved by the intersection of the supply and demand curve.

-Electricity demand is defined exogenously.

-Electricity production is defined endogenously.

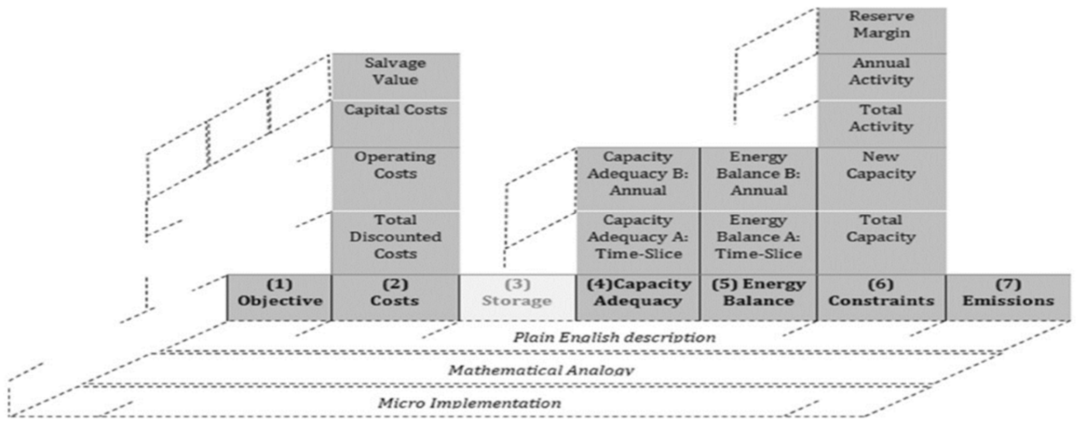

Figure 2. The modular structure of the OSeMOSYS model.

The objective function of the OSeMOSYS model is to determine the optimal production mix to meet the demand while minimizing the total discounted cost:

$$\left[Minimise \sum_{y} \sum_{t} \sum_{r} TC_{y,t,r} = OC_{y,t,r} + CC_{y,t,r} + EP_{y,t,r} - SV_{y,t,r}, \forall y, t, r \right] \quad (1)$$

where $TC_{y,t,r}, OC_{y,t,r}, CC_{y,t,r}, EP_{y,t,r}, SV_{y,t,r}$ represents the total discounted cost, the operating cost, the investment cost, the technology emission penalty, and the salvage value respectively. y, t, r, are the year, technology, and region indices respectively. A full description of the OSeMOSYS methodology is presented in the work of [25]. The modeling is used through the MoManI interface which is an open-source available to all researchers. In addition, the OSeMOSYS model uses the GNU MathProg linear programming language solved by the GLPK solver.

3.2. Description of scenarios

The baseline scenario (BC) is the optimal power generation mix that continues the trend of the existing energy strategy. OSeMOSYS has developed the model according to the type and size of technologies and the timing of the dispatch. The carbon tax and emission standard scenarios are similar to the baseline scenario. The only difference is the introduction of the carbon tax and emission standard constraint.

The carbon tax (CT) scenario assumes the introduction of a tax of \$30/tonne CO_2 in 2020, rising to \$60/tonne CO_2 in 2040. The emissions target (ET) scenario assumes the introduction of a 25% emissions reduction target relative to the baseline scenario. Both scenarios are in line with Morocco's new energy strategy which emphasizes the need to reduce emissions by introducing mitigation actions.

3.3. Data for the OSeMOSYS Model

The Moroccan OSeMOSYS model was designed with 2015 as the base year, to analyze the evolution of the Moroccan power generation technology system until 2040. The base year was chosen to make explicit the implementation of the national energy strategy which favors the integration of renewable energies in the Moroccan electricity mix.

The OSeMOSYS Bottom-Up methodology was adopted to model the future electricity mix. Morocco's electricity demand in 2015 was 34.4 TWh and is expected to increase fourfold in the future according to [26]. The installed capacity of Morocco in 2010 was 8158 MW, composed of conventional energies with a total capacity of 5431 MW, the rest coming from renewable energies. To model, Morocco's optimal generation mix, different electricity generation technologies were considered. Installed capacity and participation in Morocco's electricity supply were determined by annual reports published by ONEE [27]. The Moroccan renewable energy potential was determined using the renewables ninja database [28]. A discount rate of 5% was assumed.

The technology cost data was adopted from the European Commission on the assessment of energy technology benchmarks [29]. The capital cost of future years of conventional energy technologies in Morocco (coal-fired, CCGT, and oil-fired) was assumed to be constant throughout the study, while that of renewable technologies was assumed to decrease according to the projections presented in [30]. Fossil fuel prices are largely unpredictable due to their huge fluctuations in the global market. The reference fuel price projection in [31] is considered the most reliable assumption and is therefore taken in this study.

4. Results and discussion

4.1. Results

The optimization results of the OSeMOSYS prospective modeling give the electricity mix, the power generation mix, the costs, and the emission level. Based on these indicators, we will attempt to analyze the technological changes realized under the two CO_2 emission reduction constraints.

4.1.1. *Electricity mix*

The electricity mix is the installed capacity of electricity generation technologies. As shown in Figure 3, the scenarios integrate largely RET. In 2040, the share of installed capacity of RET reaches 44%, 57% and 65% in the BC, ET, and CT scenarios respectively. This is due to the lower investment costs at this horizon, which makes them more competitive.

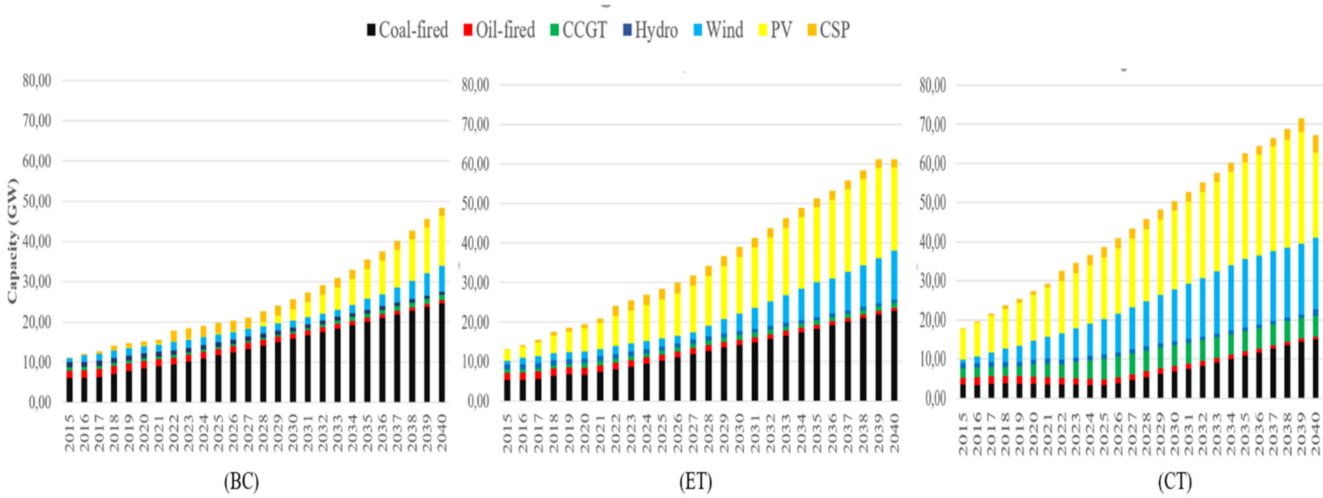

Figure 3. Installed capacity by plant type in BC, ET, and CT scenarios during the period 2015–2040.

Of these investments, the BC scenario is characterized by a high capacity of coal fired technologies exceeding the installed capacity of RET (hydro, PV, CSP and wind), while the ET and CT scenarios are characterized by a high installed capacity of RET, particularly wind and photovoltaics (PV). In the CT and ET scenarios, concentrated solar power (CSP) technologies were not considered a more economical alternative compared to wind and PV due to their high capital costs. In addition, compared to the BC and ET scenarios, the introduction of the carbon tax favors the integration of CCGT into the electricity mix due to their low emission rates.

The comparison between the BC, ET, and CT scenarios highlights the diversification of the mix targeted by the emissions constraints. For the year 2040, the BC scenario, given by the cost optimization, proposes a total installed capacity of 48.4 GW. It is dominated by coal fired technologies with a 50.8% share, followed by PV technology with 25.5%, and wind technology with 13.5%, while other technologies make up the remaining 10.2%. This technological distribution constitutes an unfavorable situation for Morocco in the long term, as it is expected that the country will reduce the use of coal and intensify the use of other energy technologies such as CCGT (less polluting) and RET (PV, wind, and CSP).

Nevertheless, the CT and ET scenarios propose higher installed capacities than the BC scenario. This is due to the negative externality of renewables intermittency. This result is in line with [32], who propose that higher capacities of RET are needed to satisfy the same energy demand of conventional energy technologies due to lower capacity factors. It is also worth mentioning that the introduced capacity of renewables in the CT scenario is higher than in the ET scenario. This shows the importance of the carbon tax instrument in the adoption of RET.

4.1.2. *Electricity generation*

Figure 4 illustrates the amount of electrical energy supplied by electricity generation technologies between 2015 and 2040 for the scenarios. Certainly, the electricity supply in the BC scenario highly depends on coal fired technologies, which account for 70% in 2040, while the share of oil-fired technologies in the generation mix is almost zero, which is explained by their low investment shares in terms of installed capacity. The share of RET, while dominated by PV and wind, it realizes important electricity supply. This is explained by the absence of variable costs making their use competitive with coal-fired technologies.

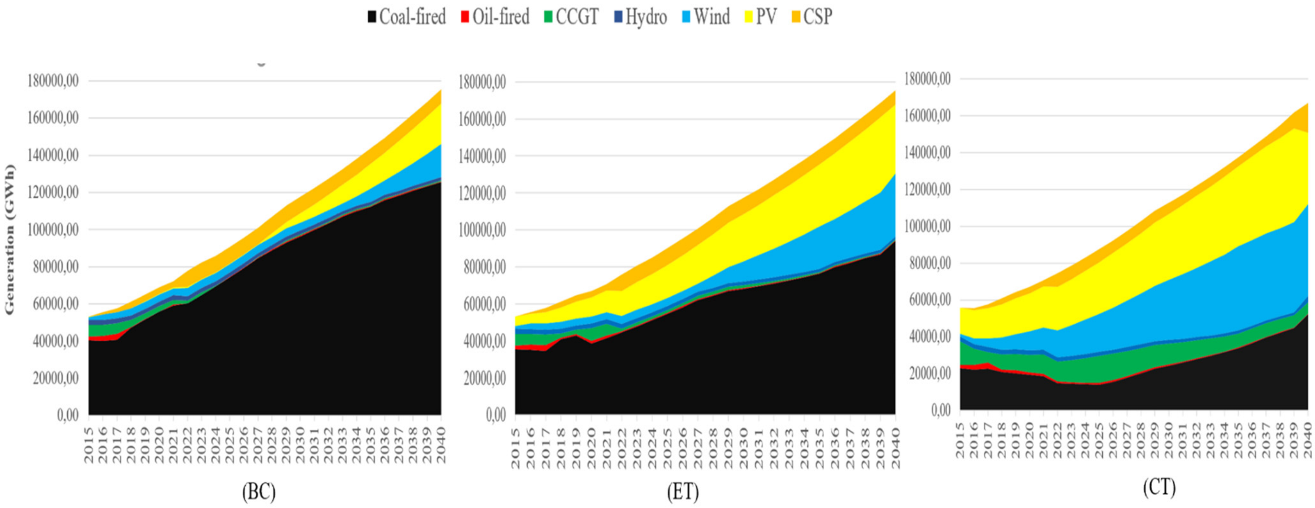

Figure 4. Electricity generation by plant type in BC, ET, and CT scenarios during the period 2015–2040.

For the ET and CT scenarios, it can be seen that the diversification of the electricity mix is reflected in the electricity supply. Indeed, with the renewable energy potential of Morocco, the capacity factors of renewables allow them to be more present in electricity generation [33]. In the CT scenario, in 2040, wind, CSP, PV, and hydro participate at 30%, 10%, 23%, and 2% respectively, to satisfy electricity demand. In addition to the contribution of coal fired technologies which reaches a share of 31%. While in the ET scenario, the share of coal-based technologies in the generation mix reaches 53.6%. Similarly, for the RET, our results suggest lower shares than those obtained in the CT scenario, i.e., 0.9%, 19.4%, 21.3%, and 4.4% for hydro, wind, PV, and CSP respectively.

These results show that the carbon tax directly affects the production costs of conventional energy technologies and makes RET more suitable economically. These results are consistent with [34], who adopted the LEAP model to analyze the low emission scenarios and their impacts on the electricity sector in Lebanon. In addition, we notice a significant reduction in electricity generation under the carbon tax scenario compared to the other scenarios. This is due to the increase in the production costs of conventional energy technologies which now leads to a decrease in electricity production.

This result has not been discussed yet in the analysis of the evolutionary trajectory of the electricity mix [34,36], the researchers thus focus on the analysis of alternative scenarios for the deployment of RET without paying attention to the productive aspect. Indeed, the implication of the carbon tax is obviously reversed on the consumers by increasing the price of the final product (electricity). In this sense, the energy transition and more particularly the decarbonization process does not only involve the energy industries but also the consumers because they are also concerned by the problem of GHG emissions which takes the character of the environmental damages.

4.1.3. *CO_2 Emissions*

As illustrated in Figure 5 the emissions trend in scenarios is similar, with peaks higher in the BC scenario. CO_2 emissions depend on the use of conventional energy technologies. In the first period, through 2021, emissions increase due to existing coal-fired and oil-fired technologies capacity. In the 2021–2024 period, the decrease is due to the retirement of oil-fired technologies. From 2024 onward, the slope of CO_2 emissions increases sharply, due to the high investment in coal-fired technologies and the continued use of combined cycle gas turbine (CCGT) technologies. In the last two years, emissions start to decrease due to the penetration of renewable energy technologies in the optimal power generation system. The CT and ET scenarios avoided 1087.4 and 545 thousand tons of cumulative CO_2, respectively, over the time horizon below the baseline scenario. Based on the agreements that the Moroccan government signed at COP 21, the carbon tax and emission standard instruments will contribute significantly to reaching the carbon reduction target.

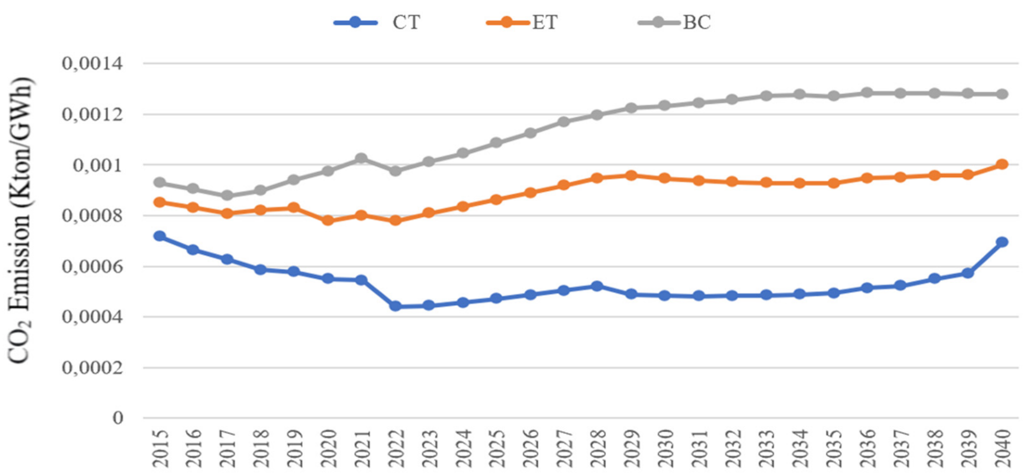

Figure 5. Emissions evolution in BC, ET, and CT scenarios during the period 2015–2040.

4.1.3. *Costs*

According to Figure 6, the total discounted cost of electricity generation in the CT scenario is higher than in the ET and BC scenarios. This is due to the internalization of the external cost of emissions, which becomes an incentive to invest in renewable energy technologies. Moreover, the total cost of electricity production in the ET scenario is lower than in the CT scenario. This allows us to validate the «win-win» hypothesis according to which environmental regulation has a positive impact on the deployment of innovative technologies such as RET with a relatively low production cost compared to scenario CT [37]. In other terms, and still in the power generation technologies, the emission standard is intended to position conventional power producers and not to constrain competitiveness.

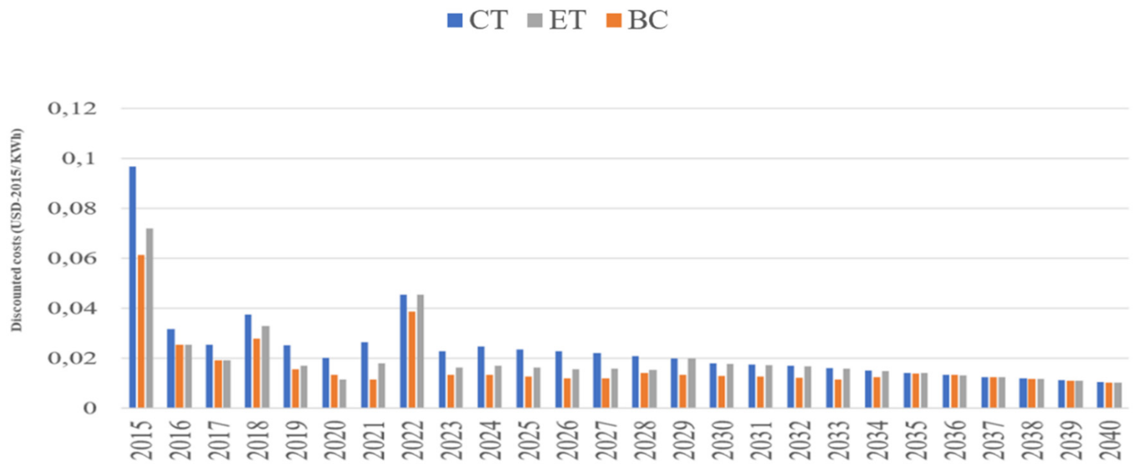

Figure 6. Comparison of LCOE for BC, ET, and CT scenarios during the period 2015–2040.

In terms of the cost structure, the CT scenario is characterized by high capital and low fuel costs, and lower O&M a cost of the technologies (fixed and variable costs) (see Figure 7). In the ET scenario, O&M costs increase the total annual cost of electricity generation, which explains the lack of investment in RET compared to the CT scenario. In the BC scenario, more than 40% of the expenses come from fossil fuel costs, indicating the increasing share of fossil fuels in the electricity mix. In addition, the additional investments in the CT scenario are almost entirely offset by the savings in fuel costs.

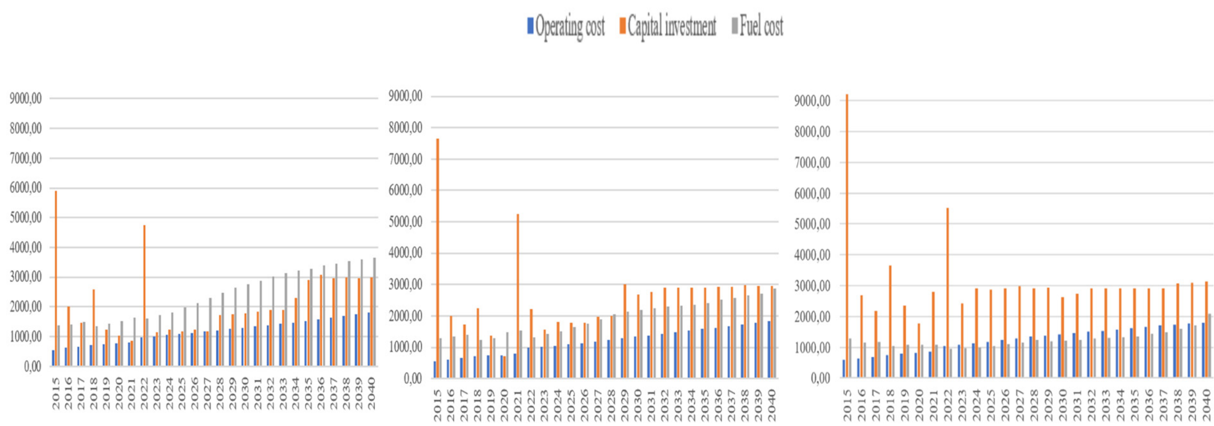

Figure 7. Costs evolution in BC, ET, and CT scenarios during the period 2015–2040.

The objective of the OseMOSYS optimization is to determine the least-cost power system mix. A static economic analysis technique was adopted for the evaluation of the effectiveness of the scenarios of RET. Economic analysis is an analytical tool used to determine the benefits of alternative scenarios.

In this study, a comparison of fuel costs, conventional technology O&M costs and RET investment costs was used to show which scenario favors RET investments at lower costs, and simultaneously reduce emissions.

Table 1 presents the results provided by the OseMOSYS model. It is observed that the CT scenario leads to higher investment costs of RET compared to the ET and BC scenarios. This is due to the internalization of emission costs which leads to an additional investment cost in RET. Thus, the CT scenario achieves significant reductions, i.e., a 34.44% reduction in fossil fuel costs and a 48.34% reduction in O&M costs of conventional energy technologies compared to the BC scenario. These reductions are much higher than in the ET scenario. This clearly shows that the tax provides a greater incentive for the deployment of RET in Morocco's optimal production system at a lower cost.

Another advantage of the carbon tax is that it keeps conventional energy technologies at lower emissions over time. This temporal continuity is called dynamic efficiency. The tax stimulates the model to maintain research in technologies that would allow them to decrease their marginal reduction costs. The standard that unilaterally imposes a reduction in emissions would not allow this motivation over time, because once the model has achieved its goals, it will not seek to further improve the electricity mix.

The ET scenario is also an important measure as it reduces emissions and it maintains competitiveness between renewable and conventional technologies. Thus, the investment cost of RET is estimated at 37.7 billion USD with significant savings compared to the baseline scenario. However, the high reductions suggest the need for the country to adopt carbon minimization strategies to reduce emissions and also to diversify the electricity mix.

Table 1. Costs in BC, ET, and CT scenarios.

	Costs (Billion US$)		
Scenarios	O&M of conventional energy technologies	Fuel Costs	Capital investment in renewable energy technologies
BC: (High carbon electricity mix)	20.56	62.83	23.42
ET: (Intermediate carbon electricity mix)	18.1	50.47	37,7
CT: (Low carbon electricity mix)	13.48	32.46	44.88
	Percentage change		
BC: (High carbon electricity mix)	0	0	0
ET: (Intermediate carbon electricity mix)	−11.96	−19.67	60.97
CT: (Low carbon electricity mix)	−34.44	−48.34	91.63

4.2. Discussion of results

The results show that the alternative scenarios have a positive impact on the diversification of the Moroccan electricity mix. This can be explained by the fact that emission constraints are taken into account when planning future investments. Moreover, the negative effect of the carbon tax on the cost of electricity production is expected as the tax helps to restraint competitiveness between technologies and to adopt a low carbon electricity mix. In Morocco, tax regulation is far from existing because the country is still in the first stages of regulation which consist in regulating the monopoly of electricity transmission. Certainly, the problem of energy dependence is a major constraint to the development of large-scale RET in Morocco. The results of the alternative scenarios show significant reductions in fuel costs, which can be achieved at the expense of investment costs in RET. Given the importance of RET and their necessity for the security of energy supply, the ET scenario shows a high penetration of RET in the Moroccan electricity mix compared to the BC scenario. This diversification of the electricity mix is achieved with a total cost of electricity production lower than that obtained in CT scenarios. This allows us to assume that the ET scenario is adequate for the Moroccan context because it allows for a proportional reduction in emissions without hampering the competitiveness between technologies. The results of this study also reveal that an incentive for the adoption of RET with a minimum cost can be obtained with the CT scenario.

The results also suggest that regulatory instruments could be key factors in limiting the need for coal, which remains the most used energy source for electricity generation in Morocco. This is consistent with the existing literature on decarbonization of optimal electricity mixes [38,40]. Moreover, even if Morocco is making renewable energy a major vector for sustainable development, the mechanisms used in the electricity generation market remain major obstacles to GHG emissions mitigation [41]. In this sense, [42] suggest a new conception of the Moroccan electricity production market, by proposing the implementation of transparent rules applicable to create an open and competitive market between renewable and conventional energies, the goal is to have a market that combines in an optimal way the allocation of energy resources.

5. Conclusion and policy implications

This paper investigates policy choices that can be employed to meet Morocco growing electricity requirement based on the available energy resources and generation technologies. Total electricity generation will need to be multiplied more than fourfold between 2015 and 2040 to be able to meet future electricity demand. Therefore, Morocco is facing a number of challenges in balancing environmental implications and social costs, as well as in diversifying the electricity mix.

The results show that an adaptation of the ET scenario, which is one of the cheapest options in terms of the average cost of electricity generation compared to the CT scenario, will result in cumulative benefits in terms of incremental benefits over the baseline scenario, due to fuel costs and conventional energy technology O&M costs savings over the studied period. However, these savings will be sufficient to offset the high capital investment of RET. A long-term perspective of energy planning is therefore necessary and suggests that the application of emission standards can be cost-effective when considered over a long-term horizon. The significant increase in the average cost of electricity generation is the main obstacle to the implementation of the CT scenario. However, the results show that the tax incentivizes the deployment of RET in the generation system in a direct way unlike the emission standards. But its feasibility implies a fully liberalized electricity market not yet available in Morocco.

Diversification of the generation mix with RET will reduce the overall output of conventional energy technologies which is characterized by less reliable fuel supply as well as price fluctuations. The results show that the CT scenario significantly reduces greenhouse gas emissions compared to the

BC and ET scenarios. These results suggest that if the country could afford to upgrade its generation system with a high deployment of renewable energy technologies, additional benefits in the form of carbon trading under the Kyoto protocol could be obtained. This will have important consequences for future RET investments. Therefore, we claim that the problem of moving from an energy system based on conventional energy to an energy system based on the use of renewable energy in Morocco faces two difficulties: the absence of market incentive mechanisms for the development of these new technologies and the absence of a well-defined local industrial policy for the manufacture of the necessary capital equipment that allows to decrease the high cost of RET.

The OSeMOSYS model has allowed us to evaluate the long-term impacts of the carbon tax and emission standard scenarios on the optimal Moroccan electricity mix, the short-term impact is not considered in our study which creates a first limitation of our work. The same is true for the analytical framework, which relies on a linear approach to explore the link between emissions constraints and the electricity mix. However, the application of the stochastic OSeMOSYS approach is highly desirable to explore the impact of a carbon tax and an emission standard on the electricity mix in a non-perfect market situation.

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Conflict of interest

All authors declare no conflicts of interest in this paper.

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