Optimization of Lebanon's power generation scenarios to meet the electricity demand by 2030

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Abstract

Presently, Lebanon provides 95% of the primary energy electricity power generation by using fuel-oil used in thermal power plants. To meet the population needs, private generators are also used in all the country and they represent the third of total electricity production. The challenges over the future development of the Lebanese electric sector are economic and environmental. This is why currently, the energy policy makers aim to diversify the national electricity generation mix in the energy planning strategy and to introduce low-carbon technologies. The complexity of these challenges in the particular Lebanese context has motivated our study which aims to recommend policies to develop the optimal electricity generation scenario by 2030. This paper presents a methodology to evaluate different scenarios reflecting different combinations of technologies by 2030. This is achieved by using an excel tool “Excel Solver Optimization Calculator” which makes possible the interaction of various inputs to produce a least-cost generation mix. The main results focus on the least-cost electricity generation portfolio, total investment required to generate electricity, level of energy independence and carbon emissions. Many policy choices could be feasible and very advantageous for Lebanon if renewable energies are deployed massively. However, this requires policies that support the massive use of renewable energy technologies in the mix.

Key-words
Lebanon, Optimization model, Power generation mix, Renewable energy, Electricity Scenarios.

JEL Classification Codes : Q2 ; Q4 ; C1.

I. Introduction

Lebanon is a small developing country, located on the Eastern edge of the Mediterranean Sea. Currently, it is a strongly dependent on suppliers in terms of energy. 98% of the total primary energy supply is imported to satisfy the energy needs (ALMEE, 2014). Over the last fifteen years, the generation of electricity by EDL (Électricité Du Liban) didn't increase, when the demand increases by 7% in some years. This is why a large market of private generators has been developed since 1997 and today, they represent 33% of the total electricity generation. In terms of source of production, 95% of total production comes from thermal power plants. The contribution of renewable energies including hydropower in the electricity mix in 2015 was only 5% (BlomInvest Bank, 2015). Lebanon is also one of the largest carbon dioxide (CO2) emitters in Middle East, ranked the first before Jordan, Tunisia, Egypt, Morocco, Syria and Yemen. It is also the 67th largest global carbon emitter in the world rankings (WRI, 2009). In 2013, the CO2 emission marked a tremendous increase to 24,34 MtCO2e compared to 7,39 MtCO2e in 1990. Furthermore, in 2015 power sector alone contributed 57.8% of total CO2 emissions (World
of which 25.2% come from private generators. The electricity demand has grown steadily, while the current generation was and continue to be far from being sufficient for the needs of the population. It covers only 63% of electricity needs (EDL, 2014). In addition, production costs are excessively high and were about 220 US c$/MWh (EDL, 2014), of which 67% accounts fuel costs, while electricity generation and distribution constitute the remaining costs (Bassil, 2010). Thus there is a need to explore other long term sustainable options for power generation. This is why Lebanon aims to shift towards renewable energies by increasing their share in the electrical mix till 20% until 2030 (Bassil, 2010).

Thus there is a need to explore other long term sustainable options for power generation in Lebanon. This type of long term studies are still lacking in Lebanon and optimization models are known to be able to provide an objective evaluation of future generation technologies and fuel mix portfolios. They are applied in many studies (Haiges et al., 2017; Bernhard and Missaoui, 2014; Vidal-Amaro et al., 2015; Sithole et al., 2016). For the lebanese case, most of the studies have treated the aspects of demand for electricity (Houri and Korfali, 2005, Saab et al., 2001, Abosedra et al., 2009, etc.). However, to our knowledge, very few studies have addressed the issue of electricity supply. The scenarios analysis is one of the methods used to compare different possible combinations of technologies in order to meet a policy's targeted objective. The objective of this study is to forecast the possible future scenarios in Lebanon, according to many possible policy choices by 2030. In this sense, several questions emerge: How to model the problem of electricity generation in Lebanon? What is the appropriate model that incorporates the different available energy sources? How to choose the best combinations for the production mix, taking into account the different economic and environmental constraints? And what role can renewable energy (low-carbon) play in the Lebanese electricity sector?

After the introduction, the paper proceeds as follows. Section 2 describes the analytical framework of modeling. Section 3 presents the constructed scenarios. Section 4 discusses the results. The electricity demand projection, capacity levels, electricity generation by technology, the CO2 emission profile, as well as the average system cost for all scenarios will be presented. Finally, conclusions and possible avenues for further research are drawn.

II. Methodology
A. Scenarios analysis

The scenario method used in this study allows involves various possible political choices to develop the electric mix. We have based our study on models that were used in the literature review to formalize issues related to energy issues. They are based on the technical and economic data provided by the different countries and according to the contexts in which they are located. The tables in the appendix A summarize some existing models that we have used to construct our model. Table 1 shows the developer and the software used to run each of them. Table 2 presents the characteristics of each model according to their purpose, the methodological approach and technique used, as well as the time horizon and geographical area of its application. We can deduce that almost all models use the bottom-up approach and have the objective of optimizing investment choices and developing different energy scenarios over the long term (2030 or 2050). Some of them are applied at a regional level (TEMOA), others at a global level (MESSAGE) et al. at regional and global levels (TIMES). In these models, several variables related to the conventional and renewable production technologies are used (capital, maintenance and fuel costs). They are also used to make simulations to study the effect of taxes or subsidies on the composition of the optimal mix. Table 3 shows some economic and technical
In our approach, we develop a linear optimization model, which minimizes the cost of electricity production, taking into account the characteristics of technologies, the constraints to which they are subjected as well as the possible political choices. We use the Excel solver tool that allows us to conduct our simulations. Thus, our research methodology can be summarized by the following steps:

- Define the framework of modelling: the purpose of the model and the constraints to which it is subjected.
- Acquire data and assumptions needed for demand forecasting and characterization of adopted production technologies.
- Establish the reference scenario and simulate different policy choices to address the challenges that Lebanon faces in developing its power generation.
- Find the optimal production mix in each scenario.
- Evaluate and compare the economic and environmental consequences of the studied scenarios.

B. Construction of the optimization model

1) Objective function

The model\(^1\) aims to minimize the average cost of electricity production of the mix. This cost represents the objective function, denoted \(F_{mix}\) and corresponds to the production level of each technology.

2) Constraints of the model

The optimal investment choice policy for the future electricity mix is often linked to constraints, determined by a set of variables and parameters associated with the model. In our model, we have identified technical and political constraints.

2.1 Maximal feasible potential

Renewable energy systems (hydropower, wind, solar and biomass) can not be productive infinitely (Kim et al., 2012). The technical potential represents the theoretical upper limit of the amount of generated electricity from a specific source of energy.

2.2 Satisfaction of the demand

A power generation mix should be able to meet the demand. Then, the level of production should, at any time, be greater or equal to the demand of electricity.

2.3 Policies constraints

The policies constraints reflect the objectives to be achieved, such as the target of renewable energies in the mix or the targets related to the protection of the environment.

III. Data inputs and hypothesis

To calculate the cost of electricity produced by each technology, we used technical and economic assumptions, based on data taken from various studies and reports published by different establishments (World Bank WB, International Energy Agency IEA, Ministry of

\(^1\) The constructed model is detailed in the appendix B. It summarizes the equations of the objective function and the constraints of the model.
Energy in Lebanon MEW, Électricité Du Liban EDL, AZOROM International Electricity Power Engineering Consultants, etc.). The comparison between the different electricity generation technologies based on calculating the levelized cost of energy (LCOE) is a fundamental instrument for companies and policy makers to take investment decisions in energy infrastructures. However, it is not a perfect tool. It presents some limits, which the energy literature has repeatedly pointed. LCOE depends on many a range of input parameters and is then highly sensitive to their variations. This is why we have defined in our study a reference scenario to compare different scenarios. Based on this scenario, we have executed sensitivity analysis to conclude the main parameters that should be taken into consideration when taking decision regarding the investment choices in the electricity generation plants.

A. Long-term cost forecasting

   The reference year in our study is 2015. A cost model only accepts one year to start planning. We estimate the costs by covering the period between 2015 and 2030. We have also chosen 5-year periods due to the Lebanese government who develops the energy policies of the country every five years.

B. Economic growth dynamics and demand forecasting

   The cost of electricity depends on both supply and demand profiles. Estimating future demand is a fundamental step in predicting the supply. Most studies are based on factors that determine this demand, such as population growth and economic growth (Abosedra, 2009). This method is often adopted in developing countries where data are often incomplete and inaccurate. In our study, we have adopted the same approach. We have assumed the future demand evolution with an annual growth rate of 4.5%, according to the base scenario set by the Ministry of Energy (Fig. 1).

Fig. 1: Forecast of the electricity demand (in GWh) up to 2030 with a growth rate of 4.5% per year (source : own calculations).
C. Fuel prices

Based on historic oil and natural gas prices, the International Energy Agency forecasts the long-term projections for these prices each year. We adopt these projections to estimate the cost of each thermal technology in 2020 and 2025 (Fig. 2).

D. Carbon emissions

Many studies have estimated the carbon emissions by different power generation technologies, as an environmental indicator, expressed in grams of CO2/kWh. In our study, we base our assumptions on the publications of the International Energy Agency (World Energy Outlook, 2017) as well as a meta-analysis that has been carried out on more than 50 publications (Edenhofer et al., 2012). We denote that these values are regularly revised according to technological developments. In the reference scenario, we will not consider the price of CO2. Later, in the sensitivity analysis, we will include it to test its impact on the LCOE of technologies. To our knowledge, there has been no study that estimates the LCOE of technologies in Lebanon by simulating a carbon pricing. This is one of this paper’s contribution to encourage the least-carbon emissions policies in the country. The carbon emissions by each technology are indicated in the following table 4.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Carbon emissions (g CO2/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil plants</td>
<td>840</td>
</tr>
<tr>
<td>Natural gas plants</td>
<td>469</td>
</tr>
<tr>
<td>Solar</td>
<td>48</td>
</tr>
<tr>
<td>Biomass</td>
<td>18</td>
</tr>
<tr>
<td>Wind</td>
<td>12</td>
</tr>
<tr>
<td>Hydroelectric</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 4 : Environmental characteristics of technologies (carbon emissions in gCO2/KWh) (source : Edenhofer et al., 2012).

E. Discount rate

The discount rate is an important key aspect in any power generation project evaluation
in order to make the convenient choices of the least cost technologies (Khatib, 2010). In fact, renewable technologies are capital-intensive projects and they accumulate revenues over a long period of time. That’s why the choice of a suitable discount rate is fundamental and may be largely different between technologies. Yet, most of the studies use fixed discount rates, which are often 5%, 8% and 10%, in order to make the results comparable. In our study, we use the same discount rate of 5% by ignoring the market risks. This may be one of our study’s weaknesses, as every study using the traditional LCOE method to compare the electricity generation technologies.

F. Load factor
For the various energy sources, the number of hours of operation of the power stations varies between 2628 and 4380 hours/year for hydraulic plants (30-50%), from 876 to 2190 hours/year for solar photovoltaic (10-25%), from 1314 to 3504 hours/year for wind energy (20-40%) and from 3504 to 7884 hours/year for thermal power stations operating with fossil sources (40-90%). Given the specificity of each country and each site, we have chosen in our study and referring to the Ministry of Energy in Lebanon, we have chosen specific load factors for Lebanon: 85% for thermal power plants, 68% for waste plants, 50% for hydraulic, 34% for wind turbines and 21% for solar photovoltaic plants.

G. Lifetime and period of construction
In our assumptions, we have adopted the lifetime and the duration of construction for each type of the power plants according to the final energy strategy submitted by the Ministry of Energy in 2010.

H. Other assumptions
- Seasonal and daily load fluctuations were not taken into account. We assumed a demand level known in advance with certainty.
- All the plants will be connected to the centralized national network. However, we do not take into account the costs of distribution and grid connection in our model.
- Lebanon uses the US dollar and the national currency Lebanese Pounds (LP). We have used the US dollar to compute the costs to compare our results with other international ones.
- We assumed that there are no constraints on the availability of funds to invest in new energy infrastructure.
- We assumed the existence of a public will to encourage global policies for renewable energies development (regulatory framework, sufficient public awareness of the benefits of renewable energies).

More detailed information regarding the origin of parameters and the assumptions for the different power plant types can be looked up in the appendixes.

IV. Construction of Scenarios
The evaluated scenarios are defined as follows.

A. Reference scenario REF
The reference scenario, also known as BaU (Business as Usual), supposes to remain on the current energy policies. It provides an important basis for the development and evaluation of
many policy choices that can be taken into account. Thus, its comparison with other scenarios will allow us to discover the possible investment trajectories to meet future electricity needs. This comparison could provide interesting information that guides the decision-making process. Indeed, the obtained results from the reference scenario reflect the economic and environmental impacts in case of absence of new energy policies.

B. Carbon scenario CAR

The utilization of low carbon energy technologies has become a very important factor in energy planning. This has led to fix renewable energy targets in national energy systems (Østergaard, 2015). In addition of that, environmental issues are very present in Lebanon today. However, the absence of climate targets for reduction of CO2 emissions is due to the absence of Lebanese studies. While, most of the existing energy models in the literature have studied the impact of a decarbonization policy by adding a carbon tax. We adopt the same approach, in the carbon scenario, by associating a carbon price with the production cost.

The carbon scenario will allow us 1) to analyze the impact of the application of a carbon price on the optimal electricity mix and 2) to evaluate the tax from which renewable energy sources would emerge considerably in the mix.

C. Subsidies scenario SUB

We know that the the high investment cost is the main obstacle usually considered for the development of renewable energies. This would automatically lead to an increase in the cost of electricity production and therefore its price to consumers. In order to ensure the transition from a mix dominated by fossil fuels to a diversified mix, the SUB scenario involves subsidizing renewable technologies (Carley, 2011; Hedegaard et al., 2012; Senkpiel et al., 2016).

From this scenario, we will be able to deduce the level of support needed to promote the integration of low-carbon technologies. In this context, the development of expertise in renewable energies field, the knowledge of the technical aspects of these technologies and the connection of the produced electricity to the national grid are indispensable elements.

D. Independence scenario IND

The energy independence scenario is based on the same assumptions used in the reference scenario. In addition, it assumes that the policymakers' priority is to better improve the security of energy supply. Therefore, we are conducting the optimization by adding a tax on energy imports, applied on the fuel cost.

This scenario will highlight the contribution of a tax associated with imported fossil fuels. It allows to 1) analyze the impact of this tax on the optimal electrical mix and 2) to identify the tax from which the different sources of renewable energies emerge more considerably in the mix.

V. Results and discussions

The results of the assessment will be presented in the following section. First, we will present the optimal mix and the electricity generation by technology in each of the scenarios REF, CAR, SUB and IND. Then, we will discuss the consequences of each scenario in this order: the necessary investment cost, the system cost estimates, the level of energy imports and the CO2 emission profiles.

A. Optimal composition of the mix
1) Reference scenario REF

The reference scenario is not necessarily the best mix, but it makes possible the comparison between different scenarios, based on a base case, in order to study the consequences of maintaining, or not, the current policy to develop the electrical system. According to the last energy policy in 2010, we have run the model under constraint to achieve a target of 12% of renewable energies in the mix, by 2030, without taking into account other constraints. The generation capacity for all optimized least cost scenarios is expected to increase from 2658 MW in 2015 to 5886 MW by 2030 subject to each scenario. In the reference scenario, our calculations have shown that among renewable production techniques, hydropower will increase. As for fossil fuels, gas-fired generation will be preferred over oil-fired power plants (Fig. 3).

In 2030, the optimal electricity mix will consist of a thermal production of 1028 MW (fuel oil) and 2543 MW (natural gas). The rest comes from renewable energies. Hydroelectric production increased from 2% in 2015 to 9.18% in 2030 (478 MW). The share of wind generation remains very low, around of 0.45% (26 MW). Photovoltaic solar generation increases from 0.5 to 2.31% (120 MW). However, waste power plants and large solar farms do not emerge in this mix. They stay non-competitive compared to the other technologies (Fig. 4).
Then, we have executed the model by considering a more ambitious goal of renewable energy, with a target of 20% in 2030. Our results show that there is not a big change in the power capacity to be installed (Fig. 5).

![Fig. 5: Evolution of the capacities of production 2015-2030](image)

By 2030, the total capacity of the power system will reach about 5205 MW, of which 80% comes from thermal generation, 9% from hydropower and 11% for renewable energy (4% wind and 7% solar PV). Large solar parks and waste power plants will obviously remain non competitive (Fig. 6).

![Fig. 6: Optimal mix in Reference Scenario (20% of RE)](image)

2) Carbon scenario CAR

The value of the carbon cost is not a constant measure. It can vary according to the countries and their contexts. In our study, we simulate an internationally applied range of values (10, 20 and 30 $/tCO2), in order to find the carbon tax from which renewable energies could emerge in the mix. The implementation of a decarbonization policy, through this carbon tax,
allowed us to detect different evolution from those observed in the reference scenario. The application of a carbon tax would privilege renewable technologies. Gas and oil turbines emit respectively 469 and 840 g CO2/kWh, compared with only 4, 12, 18 and 48 g CO2/kWh for hydropower, wind turbines, waste plants and solar farms. The effect of rising carbon prices, between 10 and 30 $/MWh, is almost negligible on the variable cost of production from renewable technologies, except the waste power plants. Our results show that by applying a price of 30 $/tCO2, the cost of fossil fuel plants increases by at least 25%. Despite this trend, natural gas fired power plants will remain the most competitive. However, beginning 2025, they become less competitive than wind power, which is not the case in the reference scenario. For renewable technologies, the carbon tax increases the cost of waste plants only, and they emerge in the mix starting from a carbon tax of about 84 $/tCO2, becoming more competitive than thermal plants (Fig. 7).

Fig. 7: Evolution of the capacities of production 2015-2030

In this scenario, the application of a carbon tax increases the renewable generation in the optimal mix by about 14% compared to the BaU scenario. Combined-cycle gas-fired and oil-fired power plants experience a capacity decrease to 53% and 20% respectively in 2030. Renewable energy capacity increases from 2.45% in the base year to 27% in 2030, divided into 10% of wind plants, 8% of solar photovoltaic and 9% of hydropower (Fig. 8).
3) Subsidies Scenario SUB

The electricity generation by fuel type in the subsidies scenario by 2030 is delivered from 9% hydropower plants (2333 GWh), 19% solar (1834 GWh), 10% wind (1489 GWh) and 2% waste (637 GWh), as presented in the Fig. 9. The fossil fuel plants produce 60% of the total electricity generation, distributed between 7654 GWh for fuel oil and 16075 GWh for natural gas (Fig. 10).
It should be noted that public subsidies could encourage the development of renewable projects and improve their competitiveness, especially solar PV and wind. The more the government sets targets for these energies in the power mix, the more support will be required. The partnership between the public and the private sector is also an important option to consider in this type of projects.

4) Independence Scenario IND

The scenario of energy independence pushes the government to highlight Lebanon's security of electricity supply and to reduce the high level of energy imports. Our results show that a tax on these imports increases the production cost of thermal and waste power plants, as they include the cost of imported fuel. On the other hand, it does not affect that of renewable energies. By introducing this tax, the gas-fired power plants become less competitive, while renewable energies will occupy most of the electrical capacity to be installed. However, the renewable potential is limited. Hence the fact that thermal production can not be neglected in the mix. Gas and oil-fired power plants play an essential role in completing the necessary electricity production to meet the needs by 2030 (Fig. 11).
In this scenario, it is observed that by 2030, the production share of thermal power plants would constitute 53% of the optimal electricity mix. Photovoltaic solar will dominate, in a remarkable way, with a share of 26%. The generation mix comprises also of 10% wind, 2% biomass and 9% hydro (Fig. 12).

In summary, the composition of the optimal mix changes significantly in the different scenarios. The share of renewable energies is much higher in the scenarios of political choices than in the reference scenario. It reached 27%, 40% and 38% respectively in CAR, SUB and IND, against 12 to 20% in REF. Hydropower constitutes between 22.9% and 76.5% of renewable energies' share. Waste power plants could not constitute, according to our results, more than 5.1% in the mix. Solar production represents at least 19.2% and a maximum of 47.8% of the share of renewable in the mix. Wind energy represents between 4.16% and 36.11% depending on the scenarios. In all scenarios, the share of oil-fired power plants is minimal since they are very expensive compared to the high prices for fuel oil. These results are confirmed, even more so, taking into account environmental aspects. The carbon tax increases their cost of
production. If we assume that these power plants can disappear or be replaced by the use of natural gas, this will have positive effects on the energy imports bill and also on the environment. In this case, fuel oil-fired plants should be replaced until 2025. As for natural gas-fired plants, their share in the reference scenario is lower than that in the other scenarios. The thermal plants constitute at least 40.25% of the total electricity production.

**B. Economic and Environmental Effects**

There is not one scenario, in itself, better than the other. Hence the interest of our analysis examining different policy choices for investing in electricity production. This provides a basis for decision makers by evaluating the economic and environmental consequences of each of these choices. In the following, we compare the investment cost required for the capacity to be installed, the average cost of production, the carbon emissions and the level of energy imports for each studied scenarios.

1) **Investment Cost**

Comparison of the total system investment cost across all scenarios is presented in Fig. 13, the model assigned the existing technology scenario with the lowest system cost of 4.2 billion of $ if the natural gas-fired power plants are used. An increase till 5.2 and 5.4 billion of $ in system cost was observed respectively in the scenarios SUB and CAR. The higher cost in the independence scenario IND is due to the highest share of renewable energies in the mix. An interesting finding is that the system cost for all scenarios much lesser than the current electricity mix in Lebanon. It is important to note that the reference scenario could constitute the highest system cost out of all the scenarios if the government remains on the current energy policy of using oil-fired power plants instead of natural gas.

![Fig. 13: Investment cost of power plants during 2015-2030 (billion of $)](image)

2) **Average cost of electricity production**

The values of the average leveled cost of electricity are shown in Figure 14 for each scenario. The strong decline in prices for the renewable power plant investments has a substantial influence on the development of these technologies. Our results show that in the reference scenario, the cost of electricity generation is supposed to decrease up to 97-98 $/MWh, in case of the use of natural gas in the thermal power plants. This cost increases by 2.6% in the SUB scenario and becomes 100.6 $/MWh, compared to a 14.7% increase in the CAR scenario.
(112.5 $/MWh). However, the scenario of energy independence IND records the highest cost (200.4 $/MWh). This is twice that of the reference scenario. However, we remind that the cost of production today is at an average of 220 $/MWh and risks to increases if the fuel oil will not be replaced by the natural gas. Despite this, taxing imports can be considered an important avenue to consider in developing the electric sector.

3) Level of energy imports

Fossil thermal installations represent between 80 and 88% of the mix in the reference scenario. While, in the other scenarios, the political choices could increase the level of independence by 12 to 40% (Figure 15).

4) Carbon emissions
The environmental consequences of electricity production depend on the type of technology. According to our estimates, carbon emissions will be multiplied at least by 5 to 6 times compared to the reference scenario, if Lebanon continues the massive use of private generators to produce its electricity. While emissions will decrease significantly until 2030 mix if some policies are highlighted. They will decrease by 15-27% in the other scenarios (Fig. 16 and 17).

![Fig. 16: Total carbon emissions by 2030 (kton)](image1)

Lebanon, as previously mentioned, has a much higher carbon intensity than its neighboring countries. It is therefore essential to produce its electricity in a way that is more respectful of the environment. For that, it should undergo a significant change in its types of production and government should be aware of these consequences in order to determine the priorities in the development of energy policies.

VI. Conclusions and policy implications

The electricity scenarios' evaluation presented in this paper could be considered to support the complex decision making process that is currently ongoing concerning Lebanon's
future energy policies. Our study does not propose a single scenario. In addition to the reference scenario, we subjected three different electricity scenarios which involves various policy choices. The analysis consists of a cost minimizing electricity model to identify an optimal energy mix. The economic and environmental consequences for each policy are also presented.

The results of this study indicate that from an economic side, the reference scenario provides electricity generation at an average cost of 97 $/MWh but should be more than 220 $/MWh is the fuel oil is not replaced by the natural gas. While the other scenarios have a maximum cost of 200 $/MWh. They include a greater share of renewable energy in the mix. In addition to that, we must not ignore the bill of imported oil in Lebanon. In the REF scenario, the level of energy dependency remains very high. A much lower bill would be supported in the other scenarios.

Besides the economic cost, the environment is the another issue currently a hot topic in the energy planning. The carbon emissions caused by the different mix were compared. The REF scenario emits the highest rate of these emissions, about 513 gCO2/kWh. The CAR scenario has lower emissions. These become much lower in the SUB and IND scenarios, which have higher shares of renewable energy. It has to be mentioned that in the REF scenario, emissions could be even greater if power plants continued to operate with oil-fired fuel.

To conclude, the author believe that this study could be very beneficial for the Lebanese energy policy-makers and the technique presented could offer a useful computational tool to provide many alternative options for Lebanon’s future power generation, where the base load can be sourced from hydropower, solar photovoltaic, wind and waste potential. It must be noted that our analysis is a purely national approach. During this study, it could be shown that renewable technologies are still little exploited. However, Lebanon could achieve a less expensive electricity mix, cleaner and more secure, to meet the demand by 2030 by substituting fossil fuels with renewable resources.

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## APPENDIX A

<table>
<thead>
<tr>
<th>Model</th>
<th>Model Name</th>
<th>Developer</th>
<th>Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEM-E3²</td>
<td>General Equilibrium Model for Economy-Energy-Environment</td>
<td>European Commission Funded Multinational Collaboration</td>
<td>GAMS</td>
</tr>
<tr>
<td>LEAP³</td>
<td>Long-range Energy Alternatives Planning</td>
<td>Stockholm Environment Institute</td>
<td>SA</td>
</tr>
<tr>
<td>LIMES-EU⁴</td>
<td>Long-term Investment Model for the Electricity Sector</td>
<td>Potsdam Institute for Climate Research - Paul Nahmacher</td>
<td>GAMS/CPLEX</td>
</tr>
<tr>
<td>MARKAL⁵</td>
<td>MARKet ALlocation model</td>
<td>IEA-ETSAP</td>
<td>GAMS + Excel solver</td>
</tr>
<tr>
<td>MESSAGE⁶</td>
<td>Model for Energy Supply Strategy Alternatives and their General Environmental Impact</td>
<td>IIASA</td>
<td>GAMS</td>
</tr>
<tr>
<td>POLES⁷</td>
<td>Prospective Outlook on Long-term Energy Systems</td>
<td>CNRS (GAEL Energy), Enerdata, JRC-IPTS</td>
<td>Excel solver</td>
</tr>
<tr>
<td>PowerGAMA⁸</td>
<td>Power Grid and Market Analysis</td>
<td>SINTEF Energy Research - Harald G. Svendsen</td>
<td>Python</td>
</tr>
<tr>
<td>Primes⁹</td>
<td>Price-Induced Market Equilibrium System</td>
<td>E3MLab/ICCS at the Technical University of Athens</td>
<td>-</td>
</tr>
<tr>
<td>TIMES¹¹</td>
<td>The Integrated MARKAL-EFOM System</td>
<td>IEA-ETSAP</td>
<td>GAMS + Excel solver</td>
</tr>
</tbody>
</table>


Table 1: General characteristics of some energy models
<table>
<thead>
<tr>
<th>Model</th>
<th>Objective</th>
<th>Type of model</th>
<th>Approach</th>
<th>Horizon</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>EnergyPlan</td>
<td>Inv, Sc</td>
<td>bottom-up</td>
<td>simulation</td>
<td>1 an</td>
<td>local, global</td>
</tr>
<tr>
<td>GEM-E3</td>
<td>Sc</td>
<td>top-down</td>
<td>equilibrium model</td>
<td>2030 et 2050</td>
<td>global (38 countries)</td>
</tr>
<tr>
<td>LEAP</td>
<td>Sc</td>
<td>hybrid</td>
<td>simulation, optimization, LP</td>
<td>20-50 years</td>
<td>local, global</td>
</tr>
<tr>
<td>LIMES-EU</td>
<td>Inv, Sc, Op</td>
<td>hybrid</td>
<td>optimization, LP</td>
<td>2050</td>
<td>Europe</td>
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<tr>
<td>MARKAL</td>
<td>Sc</td>
<td>bottom-up</td>
<td>optimization, MIP</td>
<td>long term DM</td>
<td>local, regional</td>
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<tr>
<td>MESSAGE</td>
<td>Sc, Inv</td>
<td>hybrid</td>
<td>optimization, LP</td>
<td>long term (50-100 years)</td>
<td>11 regions</td>
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<tr>
<td>POLES</td>
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<td>hybrid</td>
<td>simulation</td>
<td>2050-2100</td>
<td>66 regions</td>
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<td>bottom-up</td>
<td>simulation, optimization, LP</td>
<td>1 year</td>
<td>local, regional</td>
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<tr>
<td>Primes</td>
<td>Sc, Inv</td>
<td>hybrid</td>
<td>simulation, optimization, LP</td>
<td>long term DM</td>
<td>Europe</td>
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<tr>
<td>Temoa</td>
<td>Sc</td>
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<td>simulation, optimization, LP</td>
<td>DM</td>
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<tr>
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<td>hybrid</td>
<td>optimization, MIP</td>
<td>long term DM</td>
<td>local, global</td>
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</tbody>
</table>


The abbreviations used in the table:
Inv – investment decision; Sc – method of scenarios; Op – exploitation decision; LP – linear programmation; MIP – mixed integer programmation; DM – defined by the modeller.

Table 2 : Objective, approach, horizon and location of some energy models
<table>
<thead>
<tr>
<th>Model</th>
<th>Technologies</th>
<th>Elasticity of demand/GDP</th>
<th>Variables (cost categories)</th>
<th>Emissions</th>
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<tbody>
<tr>
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<td>I, M, F, CO2, T</td>
<td>CO2</td>
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<td>elastic</td>
<td>I, M, F</td>
<td>any pollutant</td>
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<td>elastic</td>
<td>I, M, F</td>
<td>any pollutant</td>
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<td>non-elastic</td>
<td>I, M, F, CO2</td>
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<td>I, M, F, CO2, T</td>
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<td>I, M, F, CO2, T</td>
<td>every pollutant</td>
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<td>I, M, F, CO2, T</td>
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<td>elastic</td>
<td>I, M, F, CO2, T</td>
<td>any pollutant</td>
</tr>
</tbody>
</table>


The abbreviations used in the table : Fossil – fossil energy technologies ; Ren – renewable energy technologies ; I – investment cost ; M – maintenance cost ; F – fuel cost ; CO2 – carbon price ; T – tax (carbon tax, imported fuel tax) ; GES – greenhouse gas.

Table 3 : Economic and technical data, hypothesis and simulations of some energy models
APPENDIX B

1. Methodology of calculation of levelized cost of energy (LCOE)

The LCOE is calculated by using the following equations.

- Fixed Investment Cost (I) : $I = \sum_{t=0}^{T} \frac{1}{(1+a)^t} I_t \ Cap_t$ \hspace{1cm} (1)

- Operational and Maintenance Cost (OM) : $OM = \sum_{t=0}^{T} \frac{1}{(1+a)^t} OM_t \ CC_t \ \tau$ \hspace{1cm} (2)

- Fuel Cost (F) : $F = \sum_{t=0}^{T} \frac{1}{(1+a)^t} F_t \ CC_t \ \tau$ \hspace{1cm} (3)

- Carbon emissions Cost (CO$_2$) : $CO_2 = \sum_{t=0}^{T} \frac{1}{(1+a)^t} CC02_t \ CC_t \ \tau \ E_t$ \hspace{1cm} (4)

Then, the LCOE is expressed by the following equation :

$$LCOE = \frac{\sum_{t=0}^{T} \frac{1}{(1+a)^t} (I_t \ Cap_t + OM_t + F_t + CO2_t \ E_t))}{\sum_{t=0}^{T} \frac{1}{(1+a)^t} E_t}$$ \hspace{1cm} (5)

where $LCOE$ : Levelized cost of electricity ($/MWh$) ; $I_t$ : Investment cost in year $t$ ($$) ; $OM_t$ : Operational & Maintenance cost in year $t$ ($) ; $F_t$ : Fuel cost in year $t$ ($) ; $CC02_t$ : Carbon emissions cost in year $t$ ($) ; $Cap_t$ : Installed capacity in year $t$ (MW) ; $CC_t$ : Cumulative installed capacity in year $t$ (MW) ; $\tau$ : Load factor of the power plant (%) ; $E_t$ : Produced electricity in year $t$ (MWh) ; $a$ : Discount rate (%) ; $T$ : Operational lifetime (in years) ; and $t$ : Individual year of lifetime.

2. Optimization energy model

The optimization model aims to minimize the average cost of electricity production of the mix. This cost represents the objective function, denoted $F_{mix}$, and corresponds to the production level of each technology "e", designated by $x_e$. This function is expressed in $$/MWh and is given by:

$$\text{Min } F_{mix} = \sum_{e=1}^{E} x_e \ LCOE_e$$ \hspace{1cm} (6)

where :

LCOE : Levelized cost of electricity ($$/MWh) and $x_e$ : Optimal production of technology $e$ (MWh).

The optimal investment choice policy for the future electricity mix is often subjected to constraints, determined by a set of variables and parameters associated with the model. In our model, we have identified technical and political constraints.
1) Maximal feasible potential

Renewable energy systems (hydropower, wind, solar and biomass) can not be productive infinitely (Kim et al., 2012). The technical potential represents the theoretical upper limit of the amount of generated electricity from a specific source of energy. It is represented by:

$$\sum_{t=0}^{ET} x_{e,t} + x_{e,0} \leq PR_{e,t}$$ (7)

where $PR_e$: the feasible potential for each technology (MW) ; $x_e$: the existing potential at t=0 (MW).

2) Satisfaction of the demand

A power generation mix should be able to meet the demand. Then, the level of production should, at any time, be greater or equal to the demand of electricity. This constraint is represented by:

$$\sum_{e=1}^{E} x_{e,t} \geq (1 + g)^n \cdot D_t$$ (8)

where $g$: the average growth rate of the demand (%) ; n: the number of years in planification period (years) ; $D_t$: the initial demand of electricity (MWh).

3) Policies constraints

The policies constraints reflect the objectives to be achieved, such as the target of renewable energies in the mix or the targets related to the protection of the environment. This constraint is expressed by:

$$\sum_{e=ER}^{E} x_{e,t} \geq TER_t \cdot \sum_{e=1}^{E} x_e \quad \forall \quad t = \{1, 2, 3\}$$ (9)

where $TER_t$: the target goal of renewable energies in year t.

3. Taxes or subsidies associated to the model

The carbon $tax_{CO2}$ ($/tCO_2$) is associated to the model in the scenario CAR. It is expressed by:

$$CO_2 = \sum_{t=0}^{T} CC_t \frac{t_t \cdot Em}{(1 + a)t} \cdot tax_{CO2}$$

The subsidies applied on the investment cost (designed by sub) in the model in the scenario SUB are expressed by:

$$I = \sum_{t=0}^{T} I_t Cap_t \frac{Cap}{(1 + a)t} \cdot sub$$

The tax on the energy imports (designed by imp), applied on the fuel cost, in the model in the
scenario IND is expressed by:

\[ F = \sum_{t=0}^{T} \frac{F_t \cdot CC_t \cdot \tau_t}{(1 + a)^t} \cdot \text{imp} \]