The future costs of renewable electricity generation technologies in Lebanon : what projections for 2030 ?

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Abstract— **This paper presents the findings of our study on forecasting the levelized cost of electricity of different electricity generation technologies including renewable energy (solar PV, hydropower, biomass and wind) until 2030. Usually, the cost of electrical generation from renewable and conventional sources are compared by using the LCOE method (Levelized Cost Of Energy). In general, the LCOE is calculated based on the assumptions for each technology. In this paper, we evaluate the LCOE of the various electricity generation techniques for the case of Lebanon. The study predicts future evolution of these costs in Lebanon until 2030 according to specic assumptions related to each technology and taking into account the triple aspects : technical, economic and environmental. The generation costs don't depend only on investment, maintenance and fuel costs, but also on the cost of carbon emitted by each technology per unit of the electricity produced. We focus our analysis on these assumptions and the impact of their variability on the cost by using sensitivity analysis. Our study shows that by 2030, renewable generation technologies will remain more expensive than fossil-fueled technologies. However, within certain measures taken by the State, as integration of a carbon price, renewable energy resources could emerge strongly in the electricity generation investment planning and become much competitive.**

Key-words

Electricity of Lebanon, Renewable Energy Market, Levelized Cost Of Electricity, Cost Analysis

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. Despite rapid technological development, renewable generation technologies account now for only 5% of total electricity generation, including hydropower and small photovoltaic installations. The electricity generation depends essentially on fossil fuels (95% of total production comes from thermal power plants). 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). In addition, carbon emissions due to the electricity sector have increased considerably from 18% in 1995 to 57.2% in 2014 (ALMEE, 2014).

These are the reasons that made Lebanon aims to shift towards renewable energies by increasing their share in the electrical mix till 20% until 2030 (Bassil, 2010). Indeed, the issue of costs is fundamental. Unlike the prices of fossil fuels, which tend to increase, the LCOE of renewable energy technologies has decreased over time. This decrease is partly due to rapid technological progress, more efficient production processes, increasing awareness of the scarcity of resources, the need to ensure a certain degree of energy independency and the environmental aspects (global warming, carbon emissions...). As a result, the competitiveness of renewable energy sources has increased from one year to another.

Many stakeholders, governments, and private companies, are interested in monitoring these developments and in studies that compare the production costs between different technologies. Lebanese planners and policymakers need more studies to make the best decisions in terms of investment choices for the future energy infrastructure. One of the most commonly methods used to compare the costs per unit of electricity produced is the LCOE cost method, which is applied in many studies (OECD, NEA/IEA, 2015 ; Wiser and al., 2009 ; Singh and Singh, 2010 ; IRENA, 2012a, 2012b ; Roth and Ambs, 2004). In Lebanon, many studies have been done to demonstrate the problems in the electricity sector (Bouri and El Asaad, 2016 ; Fardoun, and al., 2012 ; Hamdan and al., 2013 ; Kinab and El-Khoury, 2012). However, to our knowledge, there are no studies that estimate the LCOE for renewable energies in Lebanon. This paper fills this research gap. Based on our findings, we propose policy recommendations for decision makers to define the convenient strategy for developing electricity generation. Achieving better decision-making to improve the electricity sector is a real challenge for Lebanon. The objective of this study is to forecast the possible future cost in terms of the LCOE for different technologies until 2030.

After the introduction, the paper proceeds as follows.

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Section 2 describes methodology. Section 3 presents the results of costs for different technologies. Section 4 discusses the results of the sensitivity analysis. Finally, conclusions and possible avenues for further research are drawn.

II. Methodology

A. Notion of LCOE (levelized cost of electricity)

In order to calculate the average cost of electricity generation for each adopted technology in Lebanon, we apply the methodology of levelized cost of electricity LCOE's [1] calculation. It is defined as the constant real wholesale price such that debt lenders and electric utilities are compensated their required rate of return, i.e., the LCOE is based on corporate finance's central concept of zero economic profit. The main objective is to analyze the key aspects of electricity generation during planning and to assess the cost-effectiveness of different power generation technologies. Based on the literature review, many authors propose to apply the methodology based on a set of parameters specific to each technology. It has been used to determine the appropriate investment choices in electricity sector. LCOE is defined as the price of electricity production by a power plant during its lifetime. According to the International Energy Agency, the discounted cost of generating electricity is defined as the average price consumers pay to repay the capital, in addition to the operating and maintenance costs of the investor, with a rate of return equal to the discount rate (IEA, 2010). In other words, it corresponds to the electricity production price over the lifetime of the plant that produces it. Discounting is an indispensable tool for comparing the technologies cost, as it reflects the return on investment in the absence of specific market and technological risks.

B. Calculation of LCOE

This paper is essentially concerned with calculating the levelized cost of electricity (LCOE) of the possible electricity generation technologies in Lebanon (thermal, hydropower, solar photovoltaic, wind onshore and biomass). The LCOE calculation includes the expenditures incurred over the lifetime of the power plant (capital, operational, fuel). It is expressed by a constant unit cost per MWh ($/MWh). The calculation is then based on the initial investment and several cost categories spread over a long period (Cormio and al., 2003) as mentioned in the cost functions below :

— Fixed investment cost (I)

$$I = \sum_{t=0}^{T} \frac{1}{(1+a)^t} \quad I_t Cap_t \tag{1}$$

— Operational & Maintenance cost (OM)

$$OM = \sum_{t=0}^{T} \frac{1}{(1+a)^t} \; OM_t CC_t \tau \tag{2}$$

— Fuel cost (F)

$$F = \sum_{t=0}^{T} \frac{1}{(1+a)^t} \; F_t CC_t \tau \tag{3}$$

— Carbon emissions cost ($CO2$)

$$CO2 = \sum_{t=0}^{T} \frac{1}{(1+a)^t} \; CCO2_t CC_t \tau Em \tag{4}$$

Then, the LCOE is expressed by the following equation :

$$LCOE = \frac{\sum_{t=0}^{T} \frac{1}{(1+a)^t} \; (I_t Cap_t + \tau CC_t (OM_t + F_t + CCO_{2t} Em))}{\sum_{t=0}^{T} \frac{1}{(1+a)^t} \; E_t} \tag{5}$$

where $LCOE$: Levelized cost of electricity ($/MWh) ; I_t : Investment cost in year t ($) ; OM_t : Operational & Maintenance cost in year t ($) ; F_t : Fuel cost in year t ($) ; $CCO2_t$: Carbon emissions cost in year t ($) ; Cap_t : Installed capacity in year t (MW) ; CC_t : Cumulative installed capacity in year t (MW) ; τ : Load factor of the power plant (%) ; E_m : Carbon emissions (ton CO2/MWh) ; E_t : Produced electricity in year t (MWh) ; a : Discount rate (%) ; T : Operational lifetime (in years) ; and t : Individual year of lifetime.

III. Data inputs

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 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*

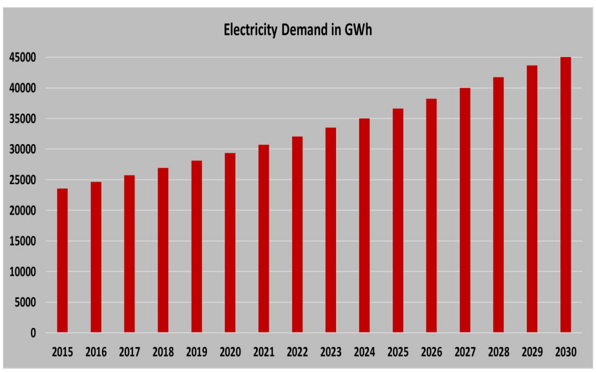
The reference year in our study is 2015. A cost model only accepts one year to start planning. We estimate the costs by covering the period between 2015 and 2030. We have also chosen 5-year periods due to the Lebanese government who develops the energy policies of the country every five years.

1. For more details on the calculation method of LCOE, see : Sathaye and Phadke (2004), Feretic and Tomsic (2005), Marrero and Ramos-Real (2010).

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).

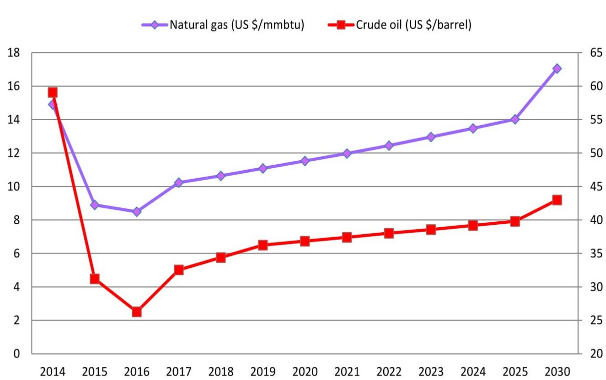
Fig. 1: Forecast of the electricity demand (in GWh) up to 2030 with a growth rate of 4.5% per year (source : own calculations)



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).

Fig. 2: Projections of oil and natural gas prices 2030 (constant US $ 2005) (source : IEA, 2015)



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 and 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 I.

TABLE I: Environmental characteristics of technologies (carbon emissions in gCO2/KWh) (source : Edenhofer and al., 2012

Technology	**Carbon emissions (gCO2/KWh)**
Oil plants	840
Natural gas plants	469
Solar	48
Biomass	18
Wind	12
Hydroelectric	4

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. Results

The outcome of this study are mainly the electricity generation costs projections for technologies in Lebanon until 2030 and the effects they undergo when changing technical, economic and environmental input parameters.

A. Reference scenario

1) Thermal power plants: Currently, there are three main types of thermal power plants in Lebanon : Combined Cycle Gas Turbines, Open Cycle Gas Turbines and Steam Turbines. Natural gas has been replaced for years by heavy fuel oil for the operation of these plants, since its supply was not assured in energy imports. The use of fuel oil is not just more expensive but also more polluting (IEA, 2017). The reason why we have compared the levelized cost of production for existing plants depending on the type of fuel, knowing that they require rehabilitation. We have also estimated this cost for new thermal plants. In both cases, the cost of fuel constitutes between 60 and 75% of the total cost of production. The investment costs and the maintenance costs combined do not exceed 30 to 40% of the total cost.

For existing plants, the production of the EDL has fluctuated between 1500 and 1900 MW between 2010 and 2015. If rehabilitated, they could produce a capacity of 2038 MW. At a 5% discount rate, we estimate an average cost that can range from 39.4 to 54.29 $/MWh in the case of using natural gas as fuel. On the other hand, it is almost three to four times more when using fuel oil, where the average cost vary from 184.02 to 214.33 $/MWh.

On the other side, new thermal power plants require higher capital costs. Assuming a load factor of 85%, the unit cost of these plants is between 61.1 and 75.9 $/MWh if the fuel used is natural gas. In contrast, it is much higher when the fuel oil is used instead, lying between 204.4 and 234.57 $/MWh until 2030 taking into consideration the technological development and the decreasing of investments costs within years. At this stage of the study, we do not take into account the carbon emissions costs for the technologies. Later, beyond the reference scenario, we will analyze the impact of integration of a carbon price on the electricity production costs of Lebanon.

2) Hydroelectric power plants: Over the years 2013-2015, the percentage of hydroelectric generation represented 4.76 % of the total production of EDL (40 MW in 2015, with a load factor of about 50%). The rehabilitation of existing plants, including replacement of old turbines with new ones, would increase production by at least 15% over current production (LCEC, 2012b). The load factor of hydraulic plants in Lebanon varies between 25% and 68%, depending on the site and the average annual flow of water (LCEC, 2012). According to a study conducted by the MEW in collaboration with the consultant Sogreah-Artelia, several sites in which there is a significant hydroelectric potential have been identified. The study mapped these sites and declared the possibility of installing an additional capacity of 205 MW, under the condition of taking into account the environmental effects of the construction of these plants. Therefore, we have developed the producing electricity costs of hydropower plants by considering the size and the lifetime (to be constructed) or already existing (to be rehabilitated). Generally, construction costs constitute 96% of the production costs. Despite the high initial cost, hydropower is considered one of the cheapest and cleanest sources of electricity (IEA, 2010). They do not require a lot of maintenance or fuels to operate. In our calculations, we have taken the hypothesis of technological development and the evolution of investment costs between 2015 and 2030.

To rehabilitate hydroelectric plants, the required investment cost is approximately 204.75 million dollars. Our calculations show that electricity generated from existing hydropower costs 19.37 $/MWh, much cheaper than that produced by EDL from thermal power plants, ie 220 $/MWh in 2014 (LCEC, 2016). For new hydroelectric plants, the investment costs are between 1050 and 7650 $/kW installed. Thus, to install a capacity of 205 MW, the minimal required investment cost 215 millions $ and can reach 1.5 billion $. In our study, we suppose the investment cost declared by the Ministry of Energy, ie 4 millions $/kW installed for a large hydroelectric dam. Thus, we assume the reduction of investment expenses in 2025. Our results show also that the unit cost of production would decrease from 103.3 $/MWh in 2020 to 51.65 $/MWh in 2025, making it competitive compared to gas turbines.

3) Biomass (municipal solid waste power plants): In Lebanon, the forests covered up to 35% of Lebanese land in 1965. Today, they present only 3.5% of the total area. Thus, it is not advisable by the government to use wood for electricity production, as the available potential is limited and very protected in law (Abi Said, 2005). However, another important biomass resource exists : municipal solid waste (MSW). This waste can be divided into two categories : residential waste estimated at about 4200 ton per day, and non-residential mainly commercial and industrial waste, estimated at about 600 ton per day (SWEEPNET, 2010). Till now, Lebanon does not currently benefit from these important resources. Nevertheless, many studies have shown that municipal solid waste can easily provide up to 30% of Lebanese electricity needs (Kinab and Elkhoury, 2012). In its national energy strategy developed in 2010, the MEW adopted a potential of at least 107 MW, considering a rate of electricity production of 600 kWh/t (IEA, 2007). This potential can be much more important especially after the waste crisis that began in June 2015. The garbage disposal difficulties accumulated after the closure of the largest dump in Lebanon. This led to a great interest in using this waste to produce electricity. For this type of power plant, construction costs are decisive for calculating the LCOE. We assume these costs based on data from the IEA taking into account technological developments in 2025 as well as the maintenance costs which represents less than 10% of the overall investment cost throughout the duration plant life.

Based on our results, we deduce that by 2020, the LCOE is estimated at 93.22 $/MWh, which means that this technology is not very competitive with natural gas plants, but more competitive with the oil-fired plants. By 2025, the LCOE decreases from 101.82 to 84.01 $/MWh in 2025, which is less than the LCOE of natural gas power plants. On the other hand, if the waste plants are expected to use fuel oil to operate, the average cost of generating electricity will be at least two to three times higher, lying between 232.4 and 268.8 $/MWh. In this case, they are not privileged by comparison with thermal plants.

4) Wind onshore: In Lebanon, there is still no wind farms set up. Small wind projects have been developed modestly. The UNDP-CEDRO project has published the National Wind Atlas in Lebanon and offered an overview of wind generation potential in Lebanon in all regions in Lebanon. They produced a map for wind speeds at altitudes of 50 m and 80 m (Hassan, 2011). Hassan (2011) indicates that by studying the most pessimistic scenario that assumes a reduction of 10% of all average speeds, the potential capacity of onshore wind generation in Lebanon will be reduced to 1.5 GW. Therefore, the wind potential can reach high levels of production capacity of 12139 GWh/year, which is equal to 71.32% of electricity production by EDL in 2015. Indeed, the absence of wind farms in Lebanon makes it impossible to rely with certainty on a reference case in terms of costs for inputs as well as for the quantity of electricity produced. For the capacity to be installed, we have assumed that it can reach a maximum of 500 MW, the potential expected to be achievable under the LCEC until 2030. The main other factors that contribute to calculate the LCOE of wind turbines are the investment costs (cost of construction and equipment), operating and maintenance costs (material and repair costs). We have made assumptions by referring to the publications of the International Energy Agency (IEA, 2010) and the International Renewable Energy Agency (IRENA, 2012). Investment expenses vary between 1095 and 1950 $/MW installed. As for operating and maintenance costs, according to Tegen et al. (2012), these costs are between 10 to 15% of the LCOE during the first years of the life cycle of a turbine, then increase from 20 to 35% at the end of its life.

Based on our results, the costs of generating electricity from wind farms in Lebanon are lower than the electric generation by EDL. Considering a load factor of 34% (Abi Said, 2005) in our reference scenario, we concluded that the LCOE of wind farms is approximately 137.5 $/MWh, which is more expensive than production from natural gas plants (61.1 $/MWh) but less expensive than those running on fuel oil (204.4 $/MWh) in 2015. While, until 2020, the LCOE decreases to reach 102.9 $/MWh and be less competitive than thermal plants functioning on natural gas. Starting from 2025, the wind technology becomes competitive, with a cost around of 77.2 $/MWh.

5) Solar photovoltaïc: In Lebanon, solar energy is an important source of energy, with 300 days of sunshine a year (8 to 9 hours of sun per day) (CEDRO, 2016). However, the only photovoltaic solar farm currently existent is the demonstration project of the Beirut River Solar Snake BRSS project of 1 MW. Then, we cannot consider a small project such as the BRSS as a reference case in terms of inputs to estimate the cost of producing electricity from PV solar technology. Therefore, we rely on estimates of investment costs and maintenance costs issued from International Energy Agency publications. In general, large centralized photovoltaic systems with a capacity of 1 MW or more take into account economies of scale in the installation of a large number of PV modules and associated equipment. The lifetime of photovoltaic modules is assumed to 30-years (IEA, 2017). Given the high development potential of solar PV in Lebanon, NREAP assumes that 150 MW can be feasible until 2030 (LCEC, 2016b). According to the feasibility study report for China's photovoltaic plants, we assume that the cost of operating and maintaining a solar power plant represents 0.2% of the total construction cost in the first five years, increases to 0.5% in the next seven years and reaches 1% in the last 13 years. Based on the above assumptions, the operational and maintenance cost represent 10-12% of the LCOE of solar PV, based on IEA, NEA, OECD (2015) data. According to Pierre El-Khoury, the on-grid PV system varies between 1300 and 2000 $/kW so that the price was around 3800 $/kW in 2010 (MEW, 2016).

However, for a large solar farm, we assume the investment costs declared by the MEW, which were around of 5,000 $/kW installed in 2015. Based on our results, the competitiveness of large PV solar farms remains far from all other fossil and renewable technologies. Our calculations show that the average unit cost of production of the solar farm is around of 346.9 \$/MWh, 260.18 \$/MWh and 256.12 \$/MWh respectively in 2015, 2020 and 2025. In fact, decentralized PV solar energy can develop in a less complicated way in Lebanon, since it does not require a large space as the large solar farms. Small solar PV plants are not far from the progress made in the solar sector in the country. Since 2010, the total capacity of photovoltaic installations installed in Lebanon has begun to increase, particularly after the introduction of the National Energy Efficiency and Renewable Energy (NEEREA) program in 2012, in the framework of which Banque Du Liban (BDL) has set up provides a mechanism for businesses and individuals to benefit from low interest rate loans of approximately 0.6% to finance solar PV projects (MEW, 2016). Installed capacity reached 9.45 MW in 2015, which is about 0.47% of the country's total electricity capacity (Amine and Rizk, 2016). According to the GHI, PV solar potential was estimated to more than 87.6 GW with an effective capacity equal to 146.9 MWh, which is approximatively nine times more than the amount of electricity demand in Lebanon in 2010. Our results show that the small solar installations cost between 47 and 160.65 \$/MWh taking into account the technological development and consequently the decrease of the investment costs. While, compared to the electricity produced by the EDL, whose cost reached 220 \$/MWh in 2014 (BlomInvest Bank, 2015), the small solar power plants could be more competitive. The highest contribution to EDL's cost of production comes mainly from the imported fuel fossil invoice (Bassil, 2010). Therefore, the use of solar energy using small photovoltaic projects to produce electricity would generate huge savings. However, it seems that it is not the case for the large solar farms. The development of LCOE until 2030 for the different generation technologies is shown in figure 3. The figure 4 summarizes the results of our LCOE's calculation by 2030.

Fig. 3: Forecast of the LCOE of renewable energy technologies as well as conventional power plants in Lebanon by 2030 (\$/MWh)

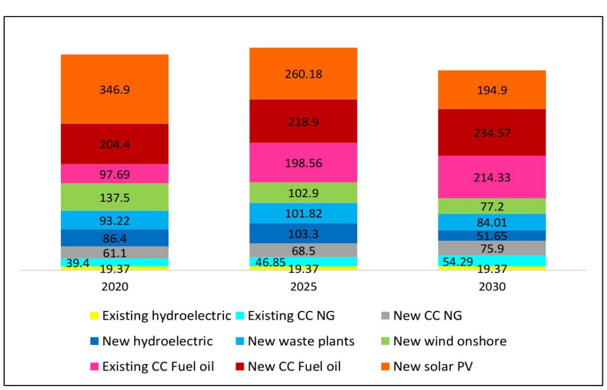
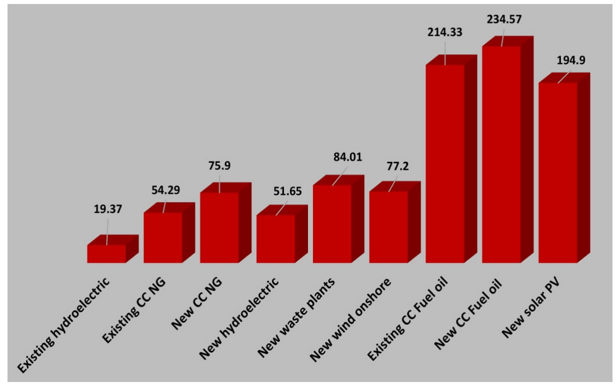


Fig. 4: Results of LCOE of electricity generation technologies in Lebanon by 2030 (\$/MWh)

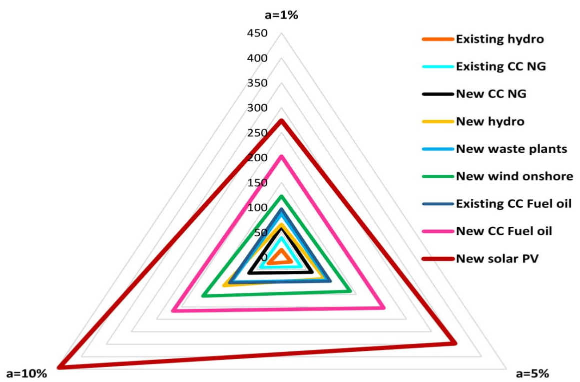


B. Sensitivity Analysis

1) Objectives: As presented before, a range of variables is used to make the LCOE's calculation. However, the future faces many uncertainties, particularly with regard to technological development, fuel prices variations, capital investment, maintenance costs, as well as policy dynamics related to electricity supply which takes into account the environmental effects. These uncertainties are a reality for the energy markets. In addition, all these parameters vary greatly between different countries, and can also vary in the country itself. For example, in Lebanon, given the high topographic and climatic diversity, a wind power plant with a nominal capacity of 100 MW can produce a quantity of electricity in the south that is different from that which could be produced by the same plant in the north. In order to show the impact of the variability of these parameters on the LCOE and the consequences of certain assumptions, we have conducted in the following sensitivity analysis tests by simulating a range of alternative assumptions on discount rate, load factor, technological development, fuel prices, maintenance costs and carbon price. While, knowing that we must be aware of the risk we can take if we consider a large number of scenarios. It is not advisable to have a wide range of choices as this can interfere with the decision-making process (Hansen and Percebois, 2010).

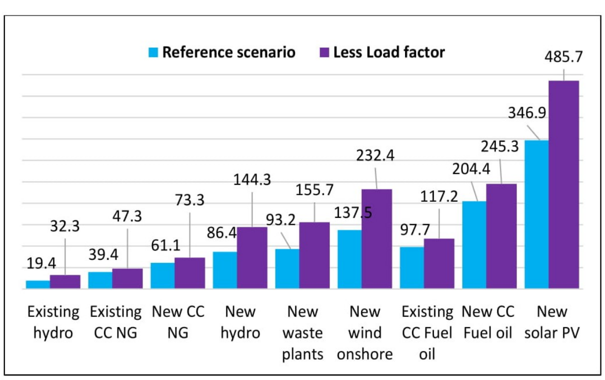
2) Sensitivity Analysis Results: Our results show that the **discount rate** is an essential factor especially for wind, solar photovoltaic and hydroelectric power plants, which represent very high investment costs. By increasing the discount rate to 10%, their LCOE increased by 14%, 28%, and 33% respectively compared to the reference scenario, and decreased by 11%, 21%, and 24% for a discount rate of 1%. On the other hand, this parameter has less effect on the waste plants. Their LCOE varies from 7 to 8% by varying the discount rate. This is because their cost of production is partly a fuel cost, which implies that they are less sensitive to the change in the discount rate. For thermal power plants, variable costs are the main determinant of the cost of electricity production, so they are very sensitive to changes in fuel costs. The LCOE of thermal power plants varied very slightly. It decreases of 1% for a discount rate of 1% and increases of 6% for a discount rate of 10% for fossil power plants (Fig. 5).

Fig. 5: Impact of discount rate variations on LCOE



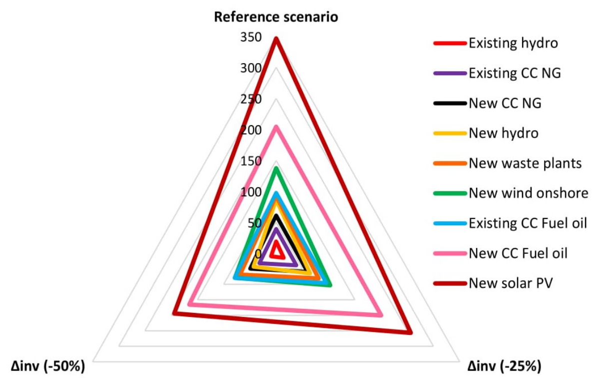
The results show that by varying the load factor from 50% (the actual load factor of some existing thermal power plants in Lebanon) to 90%, the LCOE decreases by 20%. For the new thermal plants, which are supposed to function with a load factor of 85%, their LCOE decreases by only 5%. On the other hand, it could be shown that changes in capacity factor have a significant impact on the LCOE of the renewable energy technologies. Actually, based on the range of possible load factor for every technology, the sensitivity analysis shows that a load factor reduction from 50 to 30% leads to a increase of the LCOE for the hydropower plants by about 66.7%. A reduction from 68% to 40% increases the total LCOE by about 69% for waste power plants. The LCOE of wind farms increases by the same percentage (69%) if the load factor decreases from 34% to 20%. Concerning the solar photovoltaic power plants, a load factor reduction from 21% to 15% increases the LCOE by 40% (Fig. 6). Therefore, we can conclude that renewable energy technologies, which needs higher investment cost, are much more sensitive to load factor variations than fossil fuel technologies.

Fig. 6: Impact of load factor variations on LCOE



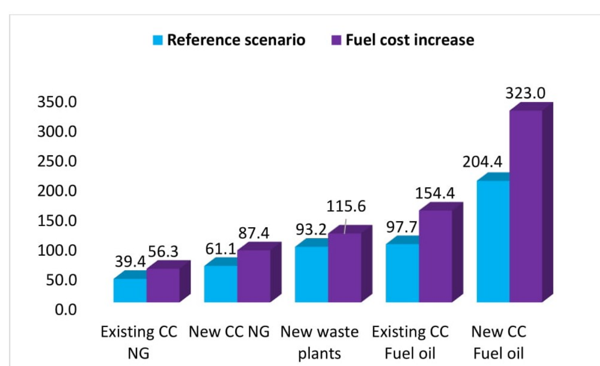
As a result of technological development, and based on International Energy Agency data, the **investment costs** tend to decrease. It is shown in our results on table IV that the LCOE is reduced by at the most 20% for thermal plants, but the effect on the total LCOE was with 27% for waste plants, 44% for solar, 50% for hydro and 44% for wind (Fig. 7). This major effect on the levelized cost of electricity for renewable energies is based on the high percentage of the capital costs in their LCOE. Our study confirms the fact of that the predicted technical innovations may affect strongly the LCOE, especially regarding the renewable energy technologies.

Fig. 7: Impact of investment cost variations on LCOE



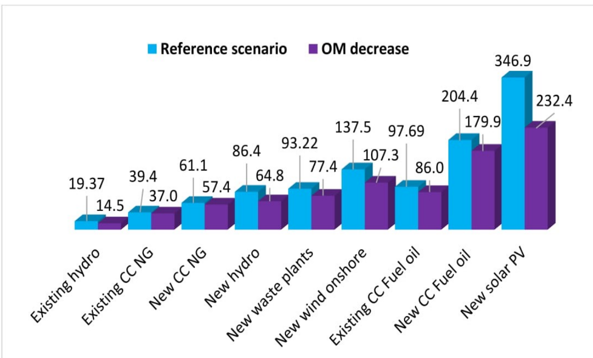
The **fuel cost** doesn't constitute a part of the total cost of generating electricity for renewable technologies except biomass. Only thermal and waste power plants are affected by the fuel price fluctuations. The results show that the LCOE increases by 58% for fuel oil plants and by 43% for natural gas plants. There is a lighter increase for waste plants, where LCOE increases between by 24% compared to the reference scenario (Fig. 8).

Fig. 8: Impact of fuel cost variations on LCOE



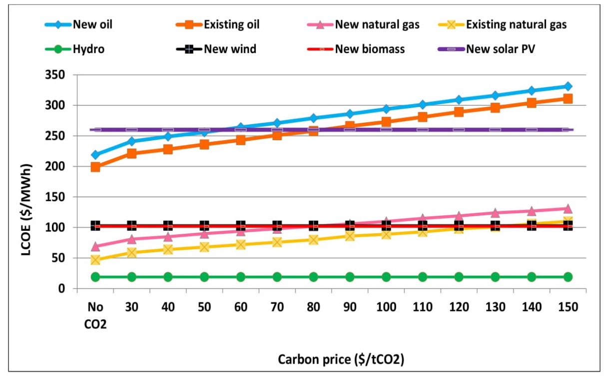
We have tested the sensitivity of LCOE to changes in **operational and maintenance costs**. The results show that these variations have a low impact on the LCOE of thermal power plants : their LCOE decreases by 6% and 12%. For non-fossil technologies, the impact is greater. Waste stations and hydroelectric dams comes in second position where LCOE decreases respectively by 17% and 25%. On the other hand, the impact is greater for solar power plants and wind turbines. Their LCOE decreases by 22% and 33% respectively (Fig. 9).

Fig. 9: Impact of OM variations on LCOE



As mentioned before, we didn't consider a **carbon price** in the reference scenario. In developing countries as Lebanon, the integration of a carbon pricing in energy planning and economic evaluation is rarely included. Therefore, we have executed many simulations to conclude the proper carbon pricing which allows renewable technologies to be more competitive in the energy market. However,carbon pricing could be very significant in generation costing and calculating LCOE, since it favors zero carbon emissions technologies (renewable energy). We have conducted sensitivity analysis by adding a price of carbon starting from 30$ per ton of CO2, equal to that considered in international studies (IEA, OECD, NEA). As shown in the figure 10, without a carbon price, the hydroelectric seems to be the least-cost technology, followed respectively by the natural gas turbines power plants, wind, biomass, fuel oil turbines and finally the solar PV. While, after the application of a price of 30$/tCO2, our results show that the application of a carbon price equal to 30$/MWh increases the production cost of thermal power plants by at least 25% but doesn't modify the merit-order of technologies. Our simulations show that starting from a carbon price equal to 90$/MWh, thermal plants functioning on natural gas become less competitive than wind, biomass and new hydroelectric power plants. They stay more competitive than only fuel oil plants which have more competitive production cost than solar PV plants. However, the application of a carbon price of 60$/MWh allow the solar farms to become more competitive, where LCOE of fuel oil plants increases to become the less competitive against all renewable technologies.

Fig. 10: Impact of CO2 pricing on LCOE



To conclude on the LCOE forecast and the sensitivity analyses for conventional and renewable technologies, we can see that renewable technologies (except large solar PV farms) and fuel fossil power plants functioning on natural gas show high competitive costs compared to the current electricity generation alternatives in Lebanon. By supposing strong cost reductions as a result of technological innovations, our calculations show that production from hydroelectric power plants is the least expensive renewable technology, followed by the production of electricity from wind turbines and waste power plants. However, their LCOE is very sensitive to changes in several parameters as the load factor and investment cost. This can make huge difference. For thermal power plants, our simulations have shown their high sensitivity against fuel cost. By supposing the predicted increase of fuel prices in the future, producing electricity from fuel oil plants will become much more inefficient, because of its high price and also its high carbon emissions level. Investing in natural gas turbines is more advantageous for Lebanon in terms of cost and of environment protection.

V. Conclusions and policy implications

Lebanon is a major oil importer country despite the evidence for the existence of oil and natural gas resources, as well as of signicant renewable energy potentials. However, renewable energy is still modestly used in the field of electricity generation. The current electrical generation is very expensive and polluting. To overcome this problem, we adopt in this paper the LCOE calculation as a tool to analyze and compare the economic feasibility of different electricity generation technologies until 2030, based on technical and economic parameters specific for each technology. This type of studies is useful for policy makers since it allows them to know what technologies should be used to invest in electricity generation. In addition, it provides the influence of changes in economic, technical and environmental parameters on electricity generation cost of each technology. The study focuses on the existing fuel fossil CCGT (Combined Cycle Gas Turbines), ST (Steam Turbines), hydroelectric power plants ; and the new power plants that could be constructed (thermal, hydro, wind onshore, biomass, solar PV).

Our results indicate that in 2030, at a discount rate of 5%, the LCOE of natural gas turbines (ranged from 54 to 76 $/MWh) and hydropower plants (ranged from 19 to 52 $/MWh) are the least-cost technologies, followed by waste power plants (84 $/MWh) and wind onshore plants (77 $/MWh). The higher-cost technologies are the solar PV farms (195 $/MWh) and fuel oil plants (ranged from 214 to 234 $/MWh). The cost model results under reference scenario conditions prove that new and existing fossil fuel power plants should use natural gas instead of fuel oil. This is the best option economically and environmentally to generate electricity from fossil fuel technologies.

However, the sensitivity analysis tests illustrate that the change of the technical and economic parameters, such as fuel prices, investment cost, maintenance cost, discount rate, load factor as well as the environmental cost associated with this type of production, can affect considerably the cost of electricity production of each technology. Even small parameter variations can be decisive and have a huge impact on the total LCOE.

For renewable technologies, which necessitates intensive capital, it could be demonstrated that load factor and capital cost have very significant impact on the LCOE. Then, energy planners should especially focus their attention on selecting the best sites for installing renewable power plants especially wind farms, in selecting sites with a high average wind speed, and photovoltaic farms with selecting sites with convenient solar irradiation.

The effect of fuel prices variations on fuel fossil technologies is currently a very important debate in the energy prospective. The cost of fuel in thermal plants is a major influencing factor in their LCOE since it presents at least 65-70% of the total operating cost of the power plant. According to our study for the Lebanese case, we have illustrated that the impact of these changes is much higher for the LCOE of fuel oil plants than natural gas turbines. The impact of maintenance cost reduction on the LCOE of thermal power plants is much lower compared to renewable electricity generation technologies.

In addition, the calculation of LCOE including a carbon cost have been included based on a carbon price of 30$/tCO2, which is used in international studies. Results indicate that by applying a carbon price of 60$/tCO2, solar PV technology become more competitive than fuel oil power plants which becomes the less competitive technology against all others. Without a carbon price, the large solar farms could remain very expensive until 2030. The small solar PV projects could be a better alternative since they were rapidly developed between 2010 and 2015, and strongly encouraged by the investors in Lebanon. Moreover, starting from a carbon price of 80$/tCO2, wind, biomass and new hydroelectric power plants become more competitive than natural gas turbines.

Our concluded costs in this study are very convincing compared with the actual very expensive cost of electricity for the current Lebanese electricity sector, which is around of 220 $/MWh (MEW, 2014). Therefore, energy policy for the development of new power plants - in particular renewable technologies - should be seriously targeted in Lebanon.

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