AMERICAN UNIVERSITY OF BEIRUT

ECONOMIC FEASIBILITY OF MITIGATION STRATEGIES TO LIMIT CO_2 EMISSIONS FROM THE POWER SECTOR IN LEBANON

by
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AN ABSTRACT OF THE THESIS OF

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Based on the latest communication report submitted, in November of 2016, to the United Nations Framework Convention on Climate Change (UNFCCC), Lebanon has emitted Greenhouse Gases (GHG) equivalent to 26,333 Gg (Gigagrams) of CO_2 in 2012 – excluding removals by sinks – where 13,980 Gg were emitted only from the power sector. Compared to the base year of 1994 – the year during which the first GHG inventory was recorded – where total emissions were estimated at 13,947 Gg CO_2eq, the number has increased by 89% which is considered to be a very alarming rate. Out of the emitted rate in 2012, 53% of the emissions came from the power sector, making it the highest emitting sector in Lebanon. This high emission rate allows the power sector to have priority in terms of mitigation strategies, especially after Lebanon's unconditional pledge to reduce CO_2 emissions by 15% by 2030. Moreover, Lebanon suffers from a deficiency in capacity, where power demand is never met by adequate power supply, leading to frequent load shedding, estimated at an average of 14 hours per day in 2019.

This thesis aims at evaluating the power generation sector in Lebanon from a generation expansion, environmental and economic perspective, via a medium-term approach. In the 10-year time span from 2020 until 2030, four scenarios are modelled using LEAP – a tool that allows the study of a power system from both an environmental and economic standpoint – and these scenarios are then compared to a business as usual scenario that is adopted according to past and current trends. The first scenario assumes that existing units start using natural gas (NG) instead of heavy fuel oil (HFO) and diesel oil (DO), given that existing technologies permit the usage of NG as fuel. It also assumes that capacity expansion occurs through the addition of new combined cycle gas turbines (CCGT) that operate on NG. The second scenario is based on the penetration of renewable energy (RE) sources, where newly added capacity pertains to solar photovoltaics and wind farms. The third scenario is a hybrid of the first two, where it is assumed that both CCGT and RE sources are added to meet the needed power requirements. The fourth and final scenario adopts the ministry of energy and water (MoEW) updated policy paper expansion plan.

The environmental and economic feasibility of the four scenarios is then investigated as compared to the business as usual scenario. Moreover, a sensitivity analysis is conducted in order to account for variations in key cost factors such as market interest rates and fuel prices.

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CHAPTER I

INTRODUCTION

As the world entered 2020 several months ago, the biggest challenge still facing humanity – besides the COVID 19 pandemic – is climate change. There is currently a global consensus amongst all scientists and decision makers that human activities have been, and still are, the main cause of global warming [1]. The issue with human activities is that they emit Greenhouse Gases (GHG), which are key factors in raising the temperature of the atmosphere [2]. This occurs because GHG's atomic composition allows them to trap heat in the atmosphere and then transfer it back to the earth, thus raising its temperature through what is known as the Greenhouse Effect [3]. This effect is actually a very serious phenomenon, as estimates predict that the temperature of the atmosphere would rise by as much as 3.7°C by 2090, compared to 1995 [4]. To be able to understand the severity of the situation, Fig.1 depicts the annual CO_2 emissions as they change throughout the years. It can be seen that a huge increase in emissions is recorded in our recent era.

The concern on climate change is of big interest for the major players worldwide. For instance, EU countries have reached an agreement to cut their emissions by 80% by 2050. Concerning CO_2 levels, the agreement stated that they should be kept below 450 ppm (parts per million) in order to help control global warming and keep it below 2°C [7]. Moreover, and on a worldwide scale, an Intergovernmental Panel on Climate Change (IPCC) was created in 1988 by the World Meteorological Organization and the United Nations Environmental Program in order to oversee all scientific research carried on climate change in order to suggest appropriate action to policy makers.

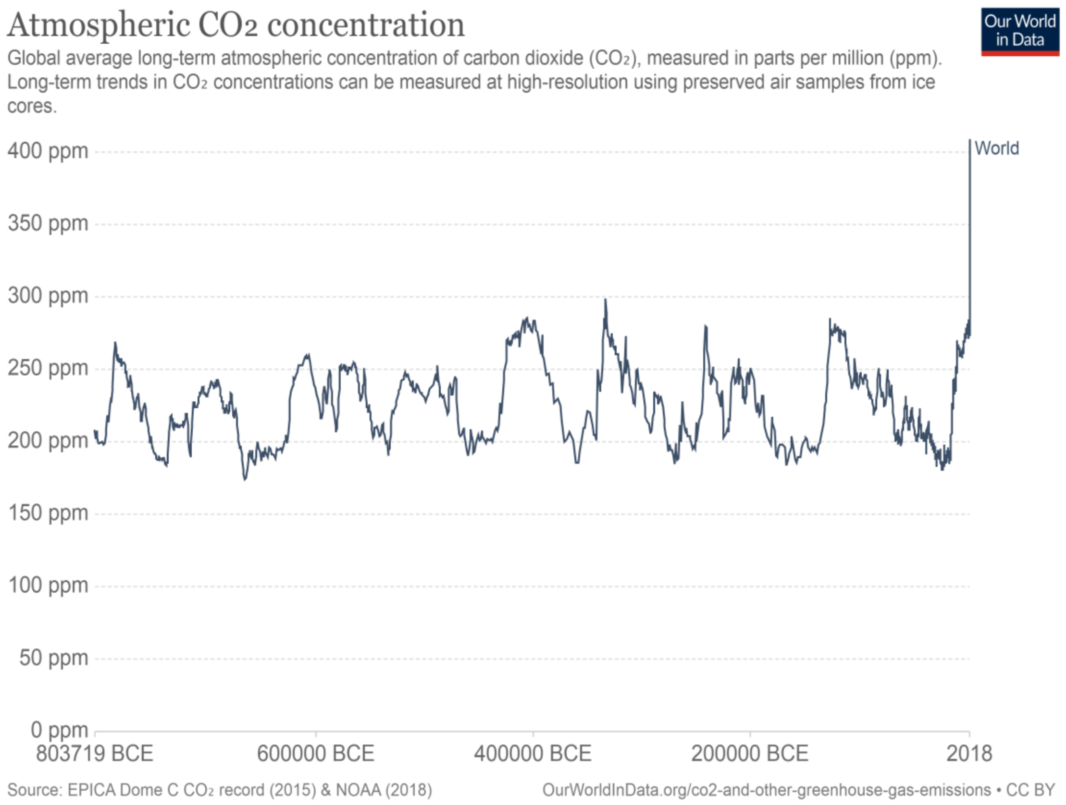

Figure 1: Long-term CO_2 Emissions **[5]**, **[6]**

Afterwards, an international environmental treaty, known as the United Nations Framework Convention on Climate Change (UNFCCC), was adopted in 1992 after multiple countries ratified the convention. The purpose behind it was clear: "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" [8]. Five years later, in 1997 the UNFCCC aims were readdressed through the Kyoto Protocol, and all participating countries were introduced to the concept of common but differentiated responsibilities, where each country possesses different capabilities in the battle against climate change [9].

In addition to that, a conference took place in 2009 known as the United Nations Climate Change Conference in Copenhagen. The aim behind the conference was to enforce the Kyoto protocol of 1997 and strengthen international cooperation between governments in the fight against global warming and climate change [10]. However, it has been agreed that the Copenhagen conference was a failure, mainly due to the reason that it did not emphasize the process of GHG mitigation and climate change fight, rather than just stating those targets. After increased international pressure, and under the auspices of the UNFCCC, an agreement took place in The Paris Conference on the 12th of December 2015 that involved 196 parties - including Lebanon - that ratified the UNFCCC. This time, the agreement was legally binding, having terms that stated that the involved countries shall submit nationally determined contributions every five years [11], [12]. This was made in hope that the fight against global warming would be taken more seriously and in a more effective way by applying the changes needed in real life.

A. The Lebanese Perspective on Climate Change

Back in 1975 and until 1989, Lebanon suffered a devastating civil war that impacted the Lebanese infrastructure drastically. All sectors, from electricity and transport, to agriculture and industry, were badly affected and were held back without proper maintenance and development [13], [14]. This decline in all major sectors' infrastructure influenced the environment negatively, as Lebanon failed to stay in touch with international efforts to stabilize the global warming effect.

After the war ended, Lebanon started to compensate for the lost time. It was in 1992, when Lebanon first acted towards combating climate change after signing the UNFCCC in Rio De Janeiro. Two years later, Lebanon ratified the Convention and thus became a Non-Annex 1 party, belonging to the nations that are considered developing. In 1996, and in accordance with the decision taken in the Geneva Convention, Lebanon was requested to start presenting National Communication reports concerning its GHG emissions and inventory [15].

To date, Lebanon has submitted 3 National Communication reports in 1999, 2011 and 2016, where the data in the reports aim at describing the GHG inventory in Lebanon for the years of 1994, 2000 and 2012, respectively. From a more general perspective, the three reports aim at describing the reality of the Lebanese environment's well-being, and to show if Lebanon is controlling its emissions and is doing its part in the battle against climate change. Moreover, the MoE submitted five independent sectoral reports as part of the third communication to highlight in detail the mitigation strategies (implemented and proposed) in order to limit future emissions. These reports were submitted one year prior to the third communication report and their data handle years ranging from 1994 up until 2011.

In 2015, the major players worldwide aimed at creating a new international climate agreement at the Paris UNFCCC conference of parties [12]. It was then that Lebanon pledged to reduce GHG emissions by 15% or 30% in 2030, see Fig.2, based on unconditional and conditional pledges, respectively, compared to the business as usual scenario, where the government of Lebanon explicitly states that it will require international support to achieve its conditional mitigation target through capacity building, technology transfer, in addition to financial support. This pledge came in Lebanon's "Intended Nationally Determined Contribution" (INDC) as a post-2020 action and shall be achieved through various mitigation approaches [16]. To further probe around the difference between the conditional and unconditional pledge, it is essential to highlight the targets and milestones to be achieved through Lebanon's INDC, as depicted in table 1.

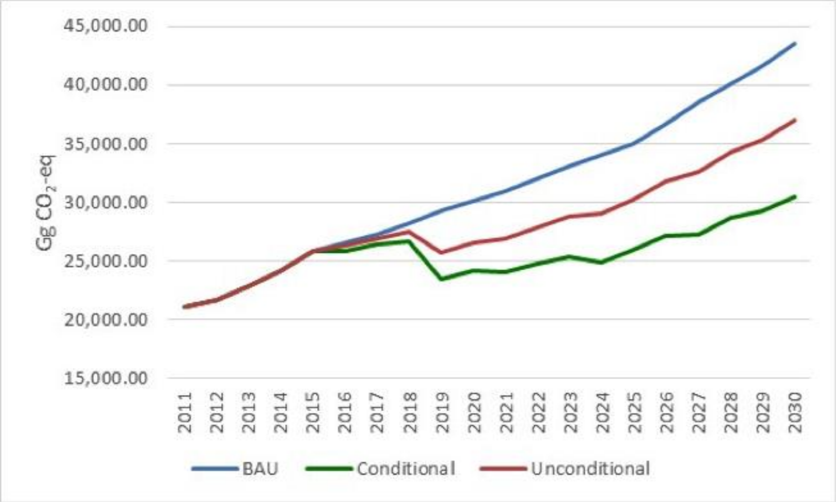

Figure 2: Lebanon’s Overall CO_2 Reduction Potential **[16]**

Table 1: Conditional vs. Unconditional Targets of Lebanon's INDC **[16]**

Unconditional Target	Conditional Target
1. Reduce GHG emissions by 15% in 2030 compared with the B.A.U scenario.	1. Reduce GHG emissions by 30% in 2030 compared with the B.A.U scenario.
2. The power sector supplies 15% of its energy from renewable energy sources in 2030.	2. The power sector supplies 20% of its energy from renewable energy sources in 2030.
3. Reduce power demand by 3% in 2030 using energy-efficient measures.	3. Reduce power demand by 10% in 2030 using energy-efficient measures.

B. The Lebanese Power Sector

Not only does it emit the highest share of GHGs in Lebanon, the power sector in Lebanon remains plagued by its poor infrastructure and deficiency in supply. Although many plans were proposed to rehabilitate the sector, sectarianism and political instability stood in the way of reformation. The Lebanese power sector is controlled by Electricite Du Liban (EDL), a national utility that was established in 1964 to oversee and manage all aspects of generation, transmission and distribution of electricity in Lebanon. EDL is under the supervision of the Ministry of Energy and Water. Currently, Lebanon's electricity production comes from several entities:

1. ***Electricite Du Liban (EDL)****:* EDL is a public utility with a commercial and industrial vocation under the control of the Ministry of Energy and Water (MoEW) [17]. EDL produces around 75% of the Lebanese electricity (excluding IPPs and imports), where the generating units owned by EDL are summarized in Table 2.
2. ***Independent Power Producers (IPP)****:* IPPs are separate entities that produce electric energy and sell it to EDL. These entities are mainly hydropower plants that constitute the Litani River Authority, Kadisha Hydro, Bared Hydro and Nahr Ibrahim Hydro [18] [19]. In addition to that, Lebanon started buying electricity from two Turkish Power Barges in 2013. The IPPs are summarized in Table 3.
3. ***Imports***: Lebanon imports electricity from both Syria and Egypt through power purchases [18]. Currently, only Syria is providing Lebanon with electricity. In 2017, Lebanon imported 543 GWh of electricity from Syria.
4. ***Solar PV***: The solar PV market in Lebanon has been growing drastically since 2010 at a rate of 100% per year [20]. Based on the latest report of the LCEC [21], the PV capacity in Lebanon reached 56.37 MW_p in 2018 and PV output in 2017 was estimated at 53 GWh.
5. ***Private Generation***: Overall, EDL produced 14,954 GWh of electric energy in 2017. 14,358 GWh were produced by EDL's thermal units and IPPs, 543 GWh were imported from Syria and 53 GWh were obtained from solar PV. During that year, demand was estimated at 19,650 GWh [22]. This comprises a deficit of 4,696 GWh. This deficit is supplied from private generation. This means that the capacity of private generators is approximated – using eq. (1) and (2) - at 765 MW (load

availability of 70%), without accounting for technical losses on the grid (technical losses are estimated at 12%, which means that out of the 14,985 GWh generated, 1,798 GWh are lost).

$$Cap_{peak}(MW) = \frac{Cap_{avg}(MW)}{load\ factor(\%)} \times 100 \qquad (1)$$

$$Cap_{avg}(MW) = \frac{E(GWh) \times 1000}{24 \times 365} \qquad (2)$$

Table 2: Generating Units Owned by EDL **[19] [23]**

Power Plant	Type	Year Put in Service	Installed Capacity in 2018 (MW)	Effective Capacity in 2018 (MW)	Production in 2017 (GWh)
Zouk 1	Thermal	1984-1987	607	440	2,018
Zouk 2	ICE	2017	198	157	1,225
Jieh 1	Thermal	1970-1981	343	180	774
Jieh 2	ICE	2017	78	63	495
Zahrani	CCGT	1998-2001	469	420	2,618
Deir Amar	CCGT	1998-2002	464	430	3,207
Baalbeck	OCGT	1996	64	57	170
Tyre	OCGT	1996	72	56	250
Richmaya	Hydro	1932-1956	13	3	10
Naameh	Waste-to-energy	/	7	7	41
Total	/	/	2,305	1,813	10,808

Table 3: Generating Units of IPPs

IPP	Type	Year Put in Service	Installed Capacity in 2018 (MW)	Effective Capacity in 2018 (MW)	Production in 2017 (GWh)
Litani	Hydro	1962-1981	199	47	242
Nahr Ibrahim	Hydro	1951-1961	32	17	72
Bared	Hydro	1936	17	6	33
Kadisha	Hydro	1924-1961	21	15	131
Barges	Thermal	2012	390	390	3,072
Total	/	/	659	475	3,550

At this stage, it is evident that the Lebanese power sector suffers from serious deficiencies in supply and is the highest emitter in the country in terms of GHGs. Figure 3 gives a proper insight regarding the contribution of the power sector to the overall emissions in Lebanon, where it is clear that the sector emits more than half of total GHGs in the country.

The cause behind this high emission contribution is the fact that power plants in Lebanon have a high emission rates compared to worldwide average rates for the same technologies. Table 4 presents some data on seven main power plants in Lebanon and their contribution in terms of CO_2 emissions. The average emission rate is calculated to be 717.97 g/kWh. To indulge further, an article written by de Gouw et al. [24] calculates an average emission rate in the U.S for the period spanning from 1997 until 2012. The authors found out that the emission rate varies depending on the technology being used. For instance, coal has an emission rate of 915 g/kWh, 549.4 g/kWh for natural gas, 436 g/kWh for natural gas with combined cycle technology and 784 g/kWh for other fuels [24].

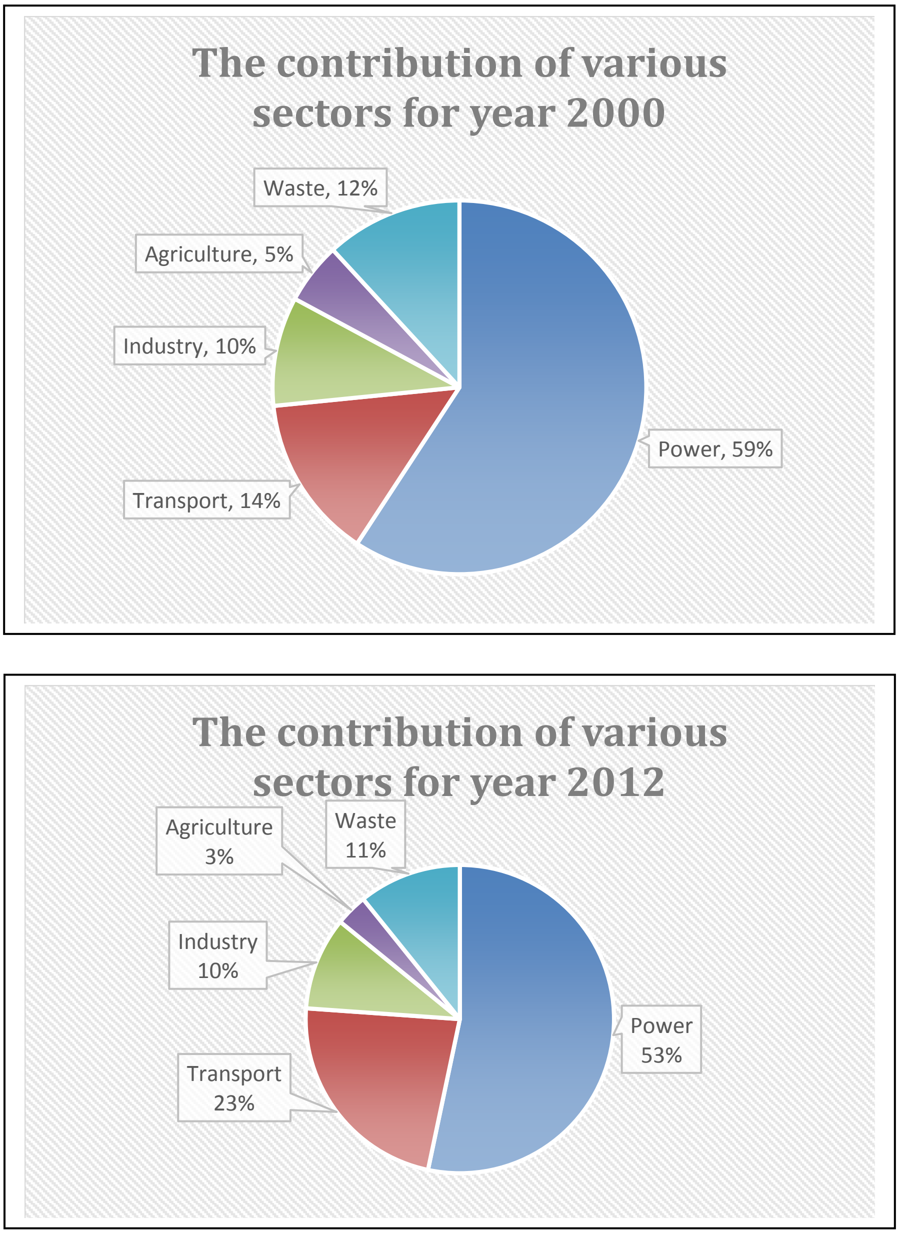

Figure 3: The contribution of various sectors to the Lebanese GHG Emissions

Another journal article written by Krauter and Ruther describes the different emission rates from different power plants as depicted in table 5, where a rate of 755 g/kWh is observed for oil-fired power plants [25]. Evidently, the average rate for Lebanese power plants is higher than that presented in the literature.

Table 4: Emission Factors of Powerplants in Lebanon in 2012 [26]

Plant	Fuel Used (Tonnes)	Production (GWh)	CO_2 (Gg)	Gg/GWh	g/kWh
Zouk	61,4242	2,398	1,896	0.79	790.65
Jiyeh	472,557	1,509	1,459	0.96	966.86
Hrayche	93,893	282	290	1.02	1028.36
Deir Aamar	535,918	2,895	1,708	0.58	589.98
Zahrani	576,009	3,130	1,836	0.58	586.58
Baalbeck	60,348	201	192	0.95	955.22
Tyre	106,258	336	338	1.005	1005.95

Table 5: Comparison of Emission Rates Based on Fuel Type [25]

Fuel Type	**CO_2 Emissions (g/kWh)**
Lignite	1140.1
Coal	915.8
Oil	755.6
Natural Gas	420.1

Based on what preceded, it is crucial to pinpoint the effect of emissions by comparing the emissions from the power sector per capita for a certain country. Table 6 shows this data for Jordan, Lebanon, Cyprus and Egypt. And because of the lack of recent data, this table is compiled for the base year of 2012.

Table 6: Per Capita Emission Rate from the Power Sector in Some Mediterranean Countries [27] [28] [29] [30]

Country	Emissions (Tons)	Population	Emission Rate (Tons/Capita)
Lebanon	13,980,000	4,916,000	2.84
Jordan	10,000,000	7,993,000	1.25
Cyprus	3,733,000	862,000	4.33
Egypt	90,000,000	87,810,000	1.02

CHAPTER II

LITERATURE REVIEW

Ever since global warming and climate change became a priority issue for all decision makers worldwide, a lot of research and work has been done to mitigate the situation and come out with scientific, economic and expert measures applicable to most countries. However, since Lebanon was a bit late to join the global effort, the country's main contributions can be seen in the three national communication reports submitted to the UNFCCC [15] [26] [27]. These reports aim at showing trends regarding the GHG inventory in Lebanon, as depicted in figure 4, and then suggesting mitigation strategies that align with the vision of the UNFCCC.

However, the issue is that these reports handle both the transport sector and power sector as a common sector, referred to as the energy sector, which does not highlight the high emission rate of the power sector. To be able to handle the issue, the Ministry of Environment (MoE) published 5 independent sectoral reports specific to the third communication report, where [28] was specific to the energy sector only and shed more light on the mitigation strategies regarding power generation, mainly through adopting the 2010 policy paper of the MoEW.

In Lebanon's Technology Needs Assessment (TNA) [29], Chaaban gives an overview on the current situation of the energy sector and describes existing policies and measures in regard to the power sector. The author then describes the multiple mitigation technology options to limit CO_2 emissions from the power sector. He mentions Combined Heat and Power (CHP), Combined Cycle Gas Turbines (CCGT), High Efficiency Generators, Wind Power, Photovoltaic Cells, Hydropower and Biomass.

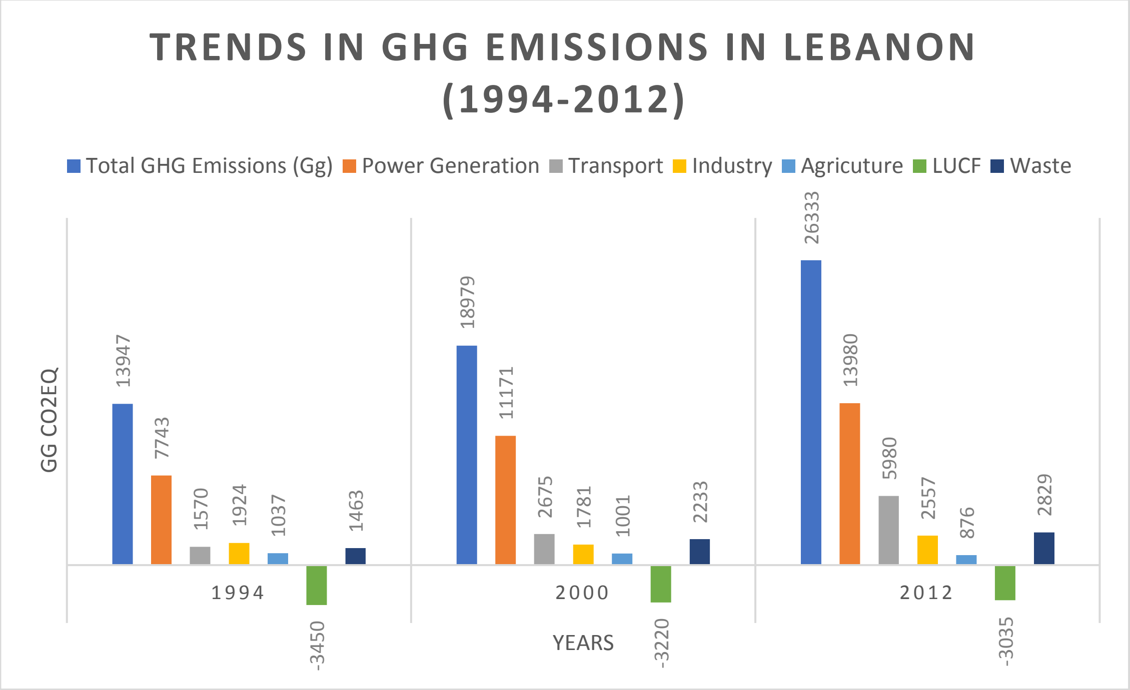

Figure 4: Trends in GHG Emissions in Lebanon **[27]**

In each category, Chaaban describes the technology, talks about the baseline scenario and then indulges into the specifics of the potential to reduce emissions with respect to the current situation, all while giving a score to each technology or strategy based on multiple criteria (reduction potential, fuel cost, etc.). To be able to do so, an expert consultation meeting was held with relevant stakeholders to present an overview of the proposed mitigation technologies for the energy sector, and to validate the proposed weights. The ranking was conducted individually, and all scoring sheets were collected, and an average scoring was calculated. For instance, the wind alternative scored 0.037, ranking as the second best option in terms of feasibility as a technology to be adopted to limit GHG emissions.

In another context to the issue of the power sector, the Lebanon Crisis Response Plan (LCRP) submitted by the UNDP and the Government of Lebanon (GoL) in 2017 and updated in 2019 [30], depicts a chapter on the energy sector in Lebanon. This chapter targets the issue of proper access to electricity as its main outcome, especially after the addition of the Syrian refugees to the Lebanese population, thus increasing demand for electricity by 447 MW. It states that “By the year 2020, all vulnerable populations in Lebanon will have improved, equitable and gender appropriate access to electricity in terms of quality, quantity and sustainability” [30]. Although this chapter does not target emissions from the power sector directly, it offers multiple solutions to the problem of power deficit in Lebanon and shows the effect of adopting such measures in terms of increasing access to proper electricity and at the same time reducing cost and emission rates.

Also targeting the Lebanese electricity sector and its problems, Fardoun et al. present a paper [17] on how to tackle the deficiency in supply from a pure technical viewpoint. The authors describe the problems at the stages of generation, transmission and distribution, and then offer recommendations on how to tackle the issue. Nevertheless, the paper does not specify nor quantify the impact of such recommendations, neither from a technical viewpoint nor from an economical and societal viewpoint.

Ibrahim et al. present a study where two generation plans are considered to be studied for the future of the Lebanese power sector. The authors carry out two optimizations; one pertaining to the environmental cost while the other tackles the tariff of the Lebanese electricity. The results show that adopting natural gas as fuel to all existing and new CCGT power plants is the most feasible approach [31]. The same authors present another journal article in which they study the five-year master plan for the electricity sector and model it. The authors present the results that highlight the possibility of the penetration of RE sources in Lebanon, allowing their share to exceed the 2020 target of 12% [32].

Moreover, Dagher and Ruble model the Lebanese electricity sector in LEAP in an attempt to assess the sector's future under several scenarios [33]. The authors suggest two alternative scenarios – one dominated by natural gas technologies while the other is dominated by renewable energy – and compare them to business as usual (BAU) affairs. They then assess the effects of these scenarios from both an economic and environmental perspective and conclude that both are a better alternative than proceeding with a BAU approach.

To encourage the usage of clean technologies, Lebanon's National renewable Energy Action Plan (NREAP) [34] was published in 2016 to pave the way into 2020; the year that Lebanon pledged to be the milestone when the country produces 12% of its energy needs from renewable energy sources. The NREAP sets targets and suggest methods and implementations to meet those targets. The action plan focuses on partnerships with the private sectors and several other incentives that will allow end users and larger institutions to adopt clean technologies in an easy and reliable manner.

From a policy-making perspective, two policy papers were developed by the Lebanese ministry of energy and water and were approved by the Lebanese government. The first policy paper [18] was published in 2010 and entails multiple reformations to the electricity sector in Lebanon. It focuses on rehabilitating the infrastructure by adding capacity to meet increasing demand, improve the transmission network to lower losses and improve the distribution network to have a more efficient process. The paper also mentions the importance of introducing renewable energy sources and developing demand-side management policies. The updated policy paper [19] was developed in 2019 to complement the first policy paper and to re-iterate the importance of adopting reformation to the electricity sector to meet national and international targets. The updated paper showcases a timeline that includes capacity additions, renewable energy penetration and repairs to the transmission and distribution networks.

The work done by Bouri and Assad [35] provides a mathematical model that calculates the annual losses incurred due to the electricity outages, but such approach only focuses on the dollar cost incurred. It does not discuss emissions and the reduction potential. That is why it is crucial to have an economic model for every suggested approach to be able to identify its dollar value with respect to the reduction in emissions.

In this aspect, Sathaye and Phadke investigate the cost of using CCGT instead of coal-fired power plants in India [36]. They estimated the cost of electricity generation from both sources through an economical model and then calculated the emission reduction based on multiple data sources. They noted that at a cost of $16 per oil barrel and $4.5 per million Btu of natural gas, every ton of carbon reduced would cost $81. However, this study was conducted in 2004 and it estimated that the advancement in CCGT technology would allow a decrease in cost to $7 per tC [36].

On another hand, a report by the European Wind Energy Association discusses in detail the economics of wind energy. This report gives insights on the capital, installation and other miscellaneous costs to install and use wind turbines, as depicted in table 9 [37]. Such data can be used to build an economic model for any country that intends to use wind farms, thus allowing to have an accurate estimate regarding the feasibility of implementing such initiative to help reduce CO_2 emissions.

At last but not least, Bustos et al. provided a full economic model with a sensitivity analysis for a PV farm in Chile [38]. This work analyzed multiple cities in

Chile where it was reported that that producing 92,523 MWh of electricity would have a net present value of 67 Million USD, without considering any incentives. The sensitivity analysis conducted varied over five main parameters: The initial cost, the operation and maintenance cost, the electricity price exported to the grid, the leverage and the interest rate of the leverage. Results showed that only 5% of the projects would have a positive NPV.

CHAPTER III

METHODOLOGY

The work presented in this thesis adopts the Low Emissions Analysis Platform (LEAP) software package, previously known as the Long-Range Energy Alternatives Planning System, as the tool to model the Lebanese power sector. LEAP has proven to be a powerful and reliable software capable of analyzing the economics and environmental impacts of any energy system, specifically power systems. What is advantageous about this tool is that it matches demand with several generation technologies while accounting for numerous variables that affect the process of generating, transmitting and distributing electric power.

The reliance on LEAP is showcased in a lot of literature. For instance, the medium and long-term forecast of the electricity demand and the several suggested scenarios that would allow a country to meet this demand adopt LEAP as their modelling tool in regions such as Pakistan, Ecuador, Greece, Panama, Thailand and Lebanon [39], [40], [41], [42], [43], [33]. Every author approaches the topic in a manner that suits policies and situation that currently govern the power sector in their respective area of interest. In all the cases, LEAP produces adequate and reliable results that prove beneficial in both an economical and environmental assessment.

The scope of this thesis covers four scenarios, in addition to a business as usual scenario. The natural gas (NG) scenario presented as CCGT technology deployment, renewable energy (RE) scenario, ministry of energy and water (MoEW) scenario and a combination scenario. The inputs and variables for every scenario are explained in a later section.

A. The Hierarchy in LEAP

1. Base Year

Lebanon’s “Intended Nationally Determined Contribution” (INDC) was developed after extensive consultations with stakeholders from relevant sectors such as energy, industry, agriculture, land-use and waste. The mitigation approaches were selected according to a bottom-up approach where existing sectoral plans are set as the basis of mitigation strategies. The INDC pledged a minimum reduction in GHG emissions by 15% in 2030 [16]. This pledge was made in 2015 in an attempt by the Lebanese government to contribute to the global effort in fighting climate change. Based on that, 2015 is chosen to be the base year in LEAP. The data entered for 2015 is retrieved from Lebanon’s first energy indicators report [22] and the 2015 solar PV status report in Lebanon [44]. This data was verified with EDL’s annual reports.

Before highlighting the data inputted to LEAP, it is essential to explain the hierarchy that LEAP follows. The software is comprised of 3 main modules. Demand, Transformations and Resources:

- **In the demand module**, the user can add multiple sub-modules to describe multiple entities that require electricity. For instance, one can divide demand between residential and industrial. In each sub-module, loads that consume electricity are added and their ratings are specified. Moreover, the number of appliances demanding electricity is also specified alongside the percentage of time a certain appliance is being used. This allows LEAP to convert the data into an energy value, using eq. (3).

$$Electricity\ Demand_X(kWh) = N_X \times \sum_{App(1)}^{App(n)} \frac{\%App \times I_{App}(kWh)}{100} \tag{3}$$

where the subscript “X” stands for the year being modeled, App(n) refers to the electric appliance used in a household, N_X stands for the number of households in a given year, %App is the percentage of households that use the electric appliance and I_{App} is the energy intensity level (amount of energy consumed) of a certain appliance over the course of a full year.

- **The transformation module** is responsible for the modelling of generation, transmission and distribution stages. At the top level, technical losses on the grid are specified. This way, LEAP is able to calculate total required energy that needs to be supplied, rather than only accounting for demand. To do so, LEAP uses eq. (4) and obtains the needed energy upon-which the needed generation dispatch rule is based.

$$Energy\ Required\ (kWh) = \frac{Electricity\ Demand\ (kWh)}{(100 - \%losses)} \times 100 \tag{4}$$

In addition to that, the load curve is entered allowing LEAP to account for peak power demand during a given year, and therefore LEAP dispatches the available units according to the specified load curve as in (1). Moreover, LEAP has the option of specifying a minimum reserve margin. This margin is used to plan for an unplanned surge in demand or in case any emergency occurred to the generating units. Lebanon does not have any reserve margin because Lebanon’s power utility is not able to supply the minimum electric energy requirements. At the bottom level, all existing generating units are specified, with all their characteristics (capacity, historical production, efficiency, maximum availability, dispatch rule, capital costs, O&M costs, etc.). LEAP uses this data to simulate energy generation to meet the requirements of the demand module. Energy produced is governed by eq. (5). If LEAP finds out that the energy produced is not sufficient, the software adds the remaining energy under a category called “imports”.

$$Energy\ Produced(MWh) \leq Capacity(MW) \times MaxAvailability(\%) \times 8760(h) \quad (5)$$

This inequality indicates that a generating unit need not always produce at its maximum availability. For instance, if a CCGT plant worked at full capacity 70% of the time in 2015, the same plant may need to be available 75% of the time in 2016, based on the energy required.

- **The resources module** is automatically generated after adding data in the transformation module. It includes primary and secondary resources that are used to power the generating units (diesel oil, water, natural gas, etc.). The user can access the resources and specify their costs in order to perform an economic analysis in later stages. All costs pertaining to capital expenses, O&M expenses and fuel costs are discussed in a later section.

2. *Demand*

To model electricity demand in Lebanon for year 2015, the Lebanese power-consuming sector is divided into three sub-sectors: households (residential), industrial processes and other buildings (hotels, schools, offices, hospitals, commercial buildings and industrial buildings).

- In 2015, a household's electricity demand is estimated by breaking down the appliances that consume electricity. A typical household consumes electric energy for:
  a. Heating and cooling, including refrigeration, air-conditioning, water heating, space heating.
  b. Lighting.
  c. Other electric appliances.

Moreover, World Bank data [45] indicate a population of 6,533,000 in 2015, including domestic and foreign residents. At an average of 4 people per household, Lebanon would have had 1,600,000 households in 2015, all of which have access to electricity.

According to [22], Lebanon's households electricity consumption in 2014 amounted to 5,750 GWh, rising from 3,080 GWh in 2009. At an average increase of 534 GWh per year, the 2015 demand of households should amount to 6,280 GWh (this figure is used to verify if the data inputted to the model is precise).

- The indicators report submitted by the LCEC to the Lebanese government [22] estimates that around 4500 industrial factories consume electric energy at a yearly rate of 3,668 GWh, without including electricity consumption for lighting, ventilation and other domestic usages that occur in an industrial factory. These figures are applicable for the base year (2015). An industrial process consumes electricity according to the following breakdown [22]:
  a. Motors: 59%
  b. Process cooling: 22%
  c. Boilers: 4%

d. Air compressors: 1%

e. Lighting: 11%

f. Auxiliaries: 3%

It should be noted that the industrial building sector consumed 4,201 GWh of electricity in 2015 in total, however, 535 GWh are accounted for under the category “other buildings”, mainly because this category accounts for the industrial process itself and not building in which the process takes place. The other 535 GWh include office lighting, office heating and cooling, and water heating.

- The “other buildings” category includes data concerning schools, hospitals, offices, industrial buildings and touristic resorts. The annual electricity consumption is extracted from the data of the indicators report (LCEC). The total electricity consumption is estimated at 8,900 GWh per year.

3. *Transformations*

After setting up the demand in the base year, the transformations data is entered under current accounts (base year) in LEAP. The two sub-categories in the transformation module fall under electricity generation and transmission and distribution.

- Transmission and distribution: this sub-category is usually used to express the percentage losses incurred due to technical and non-technical problems. In 2018, the MoEW estimated total losses at 36% [19]. However, 21% of the losses are non-technical, meaning that even though EDL is not billing this non-technical loss, this energy is being delivered and consumed from a supply-demand standpoint, thus the 21% non-technical loss will not be accounted for as undelivered energy. This leaves 13% as technical losses on the distribution network. However, 2% of the losses take place on the transmission network and are added to the distribution network technical losses. In LEAP, 15% is entered as technical losses for 2015.

- Electricity Generation: the generation data is extracted from the MoEW reports and the LCEC reports from year 2015 till year 2018. The generating units in Lebanon are comprised of the following [19]:

i. Thermal power plants having an installed capacity of 1260 MW (heavy-fuel oil)
ii. Combined and Open -Cycle power plants with an installed capacity of 1069 MW (Diesel)
iii. Hydro-Power plants with an installed capacity of 282 MW.
iv. Power barges with a capacity of 375 MW (heavy-fuel oil)
v. PV capacity of 10 MW in 2015.
vi. Private generators covering the remaining energy deficit. (heavy-fuel oil)

The energy generated by EDL is summarized in Table 7. It should be noted that imports were not included as part of the generating units, mainly because imports should not be accounted for as emissions coming from Lebanese territory. This data is inserted as historical production in LEAP.

Table 7: Historical Production in Lebanon (2015-2018) **[44] [46] [20] [21]**

Year	**Thermal (TWh)**	**Combined Cycle (TWh)**	**Barges (TWh)**	**Hydro (TWh)**	**Solar (TWh)**	**Total (TWh)**
2015	2.57	6.41	2.69	0.48	0.014	12.164
2016	3.54	6.15	3.1	0.38	0.034	13.204
2017	5.18	5.83	3.07	0.43	0.053	14.563
2018	5.24	6.17	3.29	0.35	0.084	15.134

In addition to that, a 0% minimum planning reserve margin is used, and a system load curve is inserted into LEAP according to the energy consumption patterns of the Lebanese sectors as depicted in figure 5. Because of load shedding, obtaining an accurate yearly load curve for Lebanon is impossible because there is no instant when all feeders are connected to the grid, making the recording of the user's consumption patterns a mere impossibility. Nevertheless, using trends of load curves from Syria and Cyprus [47], [48], it was possible to obtain an approximation of what a Lebanese yearly load curve would look like.

The load curve allows LEAP to obtain a system load factor in order to account for peak power needs. This gives LEAP the ability to dispatch generation units to meet peak power demand whenever the need arises. Units are dispatched based on their merit order. The higher the order, the unit dispatches to cover base loads first, then intermediate loads and eventually peak loads.

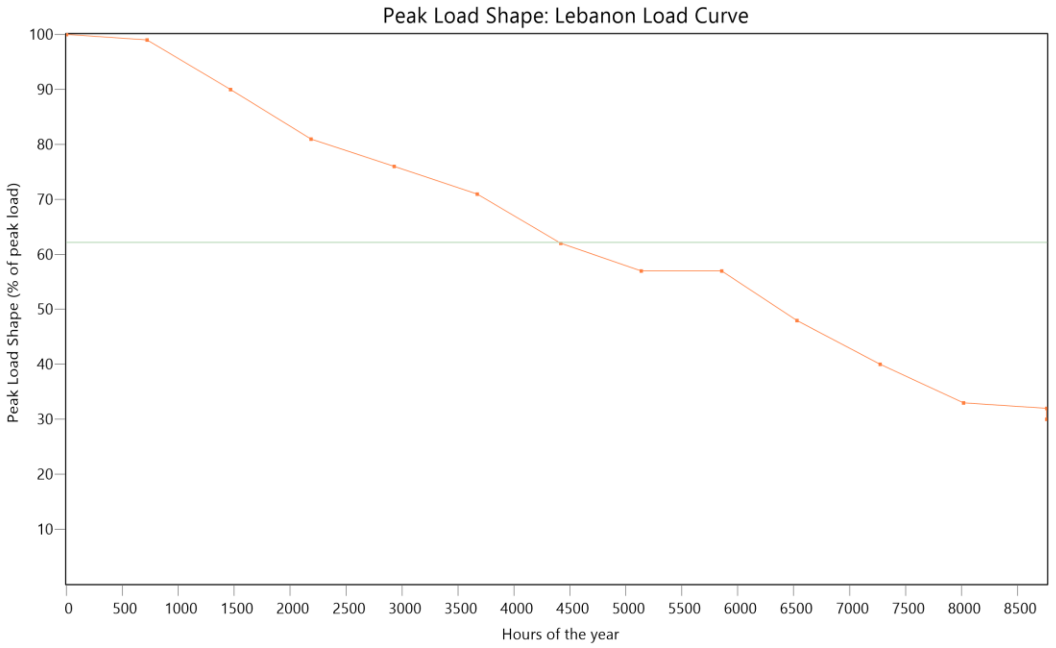

Figure 5: Peak Load Shape in Lebanon

Table 8 shows all the key variables that are entered in LEAP. This data is critical to achieve an accurate model. Salvage values are chosen to be zero because there is no historical record showing that old units were disposed or sold at a tangible price. The lifetime is chosen to be 30 years for all technologies including renewables, in order to easily annualize capital costs. Capacity credit is defined as “the ratio of the availability of the intermittent plant to the availability of a standard thermal plant” [39]. Available literature suggests capacity credits between 30% and 40%, thus this work adopted a 36% capacity credit according to [39]. The data pertaining to capital and running costs will be used in the economic feasibility section.

Table 8: LEAP Key Variables

Technology	Capex ($/MW)	Fixed Costs ($/MW/yr)	Variable Costs ($/MWh/yr)	Fuel Costs	Efficiency %	Max Availability %	Capacity Credit %	Lifetime (yrs)
Hydropower	4000000	29000	0	0	100	40	100	30
Thermal (HFO)	1800000	20000	3	300$/ton	30	50	100	30
Old CCGT (Diesel Oil)	1000000	11000	3	300$/ton	35	70	100	30
Barges (HFO)	0	15000	3	300$/ton	35	85	100	30
Private Generators (Diesel Oil)	100000	5000	1	300$/ton	35	100	100	30
Solar PV	1100000	20000	0	0	100	20	36	30
Upgraded CCGT (Natural Gas)	0	11000	3	0.05$/m^3	55	75	100	30
New CCGT (Natural Gas)	927000	11000	3	0.05$/m^3	60	80	100	30
Wind	1600000	44000	0	0	100	20	36	30
New Thermal (HFO)	1800000	20000	3	300$/ton	40	80	100	30

4. *Emissions*

After setting up all data in the base year, IPCC Tier 1 emissions are added to each technology that generates electricity. Tier 1 emissions are the default emission factors and parameters adopted exactly as suggested by the IPCC. The Tier 1 approach does not require country-specific data; available emission rates are applicable everywhere.

The emission rates could have been added manually, however, LEAP contains TED (technology database) that has all emission rates pertaining to different technologies and depends on which IPCC assessment is selected. The scope of this report adopts the latest IPCC assessment where the 100-year global warming potential values are expressed in terms of carbon dioxide equivalent (CO_2e) and are evaluated to be:

a. Carbon dioxide: 1 tCO_2e/ton of CO_2 emitted
b. Methane: 30 tCO_2e/ton of CH_4 emitted
c. Nitrous Oxide: 265 tCO_2e/ton of N_2O emitted

To be able to calculate the amount of GHGs emitted from each technology, LEAP uses eq. (6) and eq. (7) to obtain the energy inputted to each plant or process and then find out the mass of equivalent GHGs emitted from the oxidization of the fuel in every process.

$$E_{in}(TJ) = \frac{E_{out}(TJ)}{\mu} \qquad (6)$$

where E_{in} is the amount of energy inputted to the plant, E_{out} is the amount of energy outputted and μ is the plant's efficiency.

$$M_T = E_{in} \times \frac{[(\alpha_{CH4} \times GWP_{CH4}) + (\alpha_{N2O} \times GWP_{N2O}) + (\alpha_{CO2} \times GWP_{CO2})]}{1000} \qquad (7)$$

where

M_T is the mass of GHGs emitted in tCO_2e

α is the coefficient pertaining to every GHG and is expressed in kg/TJ

GWP is the global warming potential value for each greenhouse gas.

The coefficients for each GHG are expressed as follows:

- $\alpha_{CH4} = 3\ kg/TJ$
- $\alpha_{N2O} = 0.6\ kg/TJ$
- $\alpha_{CO2} = 20{,}000 \times F_{oxidized} \times \frac{M_{CO2}}{M_C}$, where $\frac{M_{CO2}}{M_C}$ is the ratio of molar masses, $F_{oxidized}$ is the percentage of carbon oxidized in the reaction and the factor of 20,000 is the mass of carbon required to produce 1TJ of heat value.

These coefficients pertain to HFO and were showcased as an example. Depending on the fuel type, LEAP uses different coefficients.

B. The Scenarios in LEAP

As stated before, the thesis incorporates a business as usual scenario, which is then compared against four alternatives described below.

1. Business as Usual (BAU) Scenario

The business as usual scenario predicts future trends in terms of demand and how supply would grow to meet the growing demand. Future projections are based on past trends, either in terms of electricity usage, or in terms of investment in the power sector.

a. Demand

The BAU scenario is based on the following assumptions:

- The number of households grows at a rate of 3% per year. This is because the average growth rate in population from 1960 till 2018 is roughly 2.4% [45]. The number has been adjusted to 3% to account for unexpected cases such as the case of the Syrian refugees in 2011. No change in appliance usage or appliance rating is assumed.
- Industrial growth is at 0.5% per year [22].
- Other buildings electricity consumption increases at a rate of 2% per year. This value has been adapted based on the assumption that total demand should increase at a rate between 2% and 5% [49]. This leads to an overall increase in demand of 2.1% per year.

b. Transformations

- The technical losses on the grid will gradually drop to reach 10% by 2030.
- The availability of existing thermal plants drops from 50% in 2019 to 30% in 2030 (depreciation).
- All capacities of EDL's generating units remain the same.
- CCGT plants operate at availabilities between 75% and 85% (2020-2030).
- CCGT will remain operational using diesel oil as fuel.
- PV capacity is expected to increase to 100 MW by 2020 and 300 MW by 2030.
- Hydro-power plants generate at a 30% availability and capacity remains unchanged.
- The needed increase in private generation capacity is automatically calculated by LEAP to meet the electricity demand and the peak power needs.

2. *Natural Gas (NG) Scenario*

The mitigation scenarios are inherited from the BAU scenario. The only changes are those made by the user to reflect the suggested alternative. For instance, since this scenario does not have to do with demand, the whole demand module remains unchanged. The following changes have been made to the electricity generation module:

i. Existing CCGT and OCGT plants have been upgraded to use natural gas as their feedstock fuel. Their respective capacities and availabilities remain unchanged. The efficiency of the process increases from 35% to 55%.
ii. Private generation capacity drops gradually starting in 2020 to reach 0 MW in 2025. This drop is substituted by new CCGT power plants.
iii. To substitute private generators, new CCGT power plants are built. Instead of strictly specifying the additions in capacity, LEAP is left to decide when to install capacity and by how many MW. LEAP will dispatch new CCGT to meet energy requirements.
iv. Since new generating units are being dispatched, the planning reserve margin is set to 10% starting 2021.

3. *Renewable Energy (RE) Scenario*

Though this alternative would not be directly saving on GHG emissions, especially if the existing fleet of traditional power plants remains unchanged, it is however limiting extra emissions by providing extra energy without outputting GHG gases into the atmosphere.

This scenario in LEAP assumes the following:

i. Hydropower plants remain unchanged in terms of capacity and availability.

ii. Private generation capacity increases up until 2020. It then remains unchanged.
iii. The capacity of PV and wind farms is automatically added by LEAP to maintain a 10% planning reserve margin starting 2021.
iv. Existing CCGT plants remain operational using diesel oil. No new CCGT units are added.

4. *Hybrid (COM) Scenario*

This scenario is a combination between the NG and RE scenarios. In a sense, it is considered as an optimization of the \$/tCO_2 removed. Not only does achieve an increased GHG reduction, but it also does it at a lower relative cost. The scenario assumes the following:

1. Existing CCGT and OCGT units are converted to natural gas starting 2020.
2. By 2022, the rented power barges are discontinued.
3. By 2025, private generation capacity drops to 0.
4. Existing thermal units remain operational.
5. The RE capacity reaches 1,000 MW by 2030.
6. The additional needed capacity is added via new CCGT units.
7. A reserve margin of 10% is adopted starting 2021.

5. *Ministry of Energy and Water (MoEW) Scenario*

This scenario adopts the generation expansion plan suggested by the Lebanese MoEW in 2019. It is modelled in order to identify its feasibility compared to the other scenarios. This plan can be summarized as follows:

1. By 2025, existing thermal plants are fully depreciated and new 300 MW are built.

2. By 2021, the rented power barges are removed from the grid.
3. By 2025, private generation capacity drops to 0.
4. By 2030, PV capacity reaches 480 MW.
5. By 2030, wind capacity reaches 660 MW.
6. Existing CCGT plants are converted to NG and 3,820 MW of new CCGT are built.

CHAPTER IV

RESULTS

This section presents the results of the simulation in LEAP.

A. Demand

Electricity demand changes in the same manner under all three scenarios. This change is subject to the expected increase in population and the approximated boost of the commercial sector. Demand values from 2015 till 2030 are showcased in Fig.6.

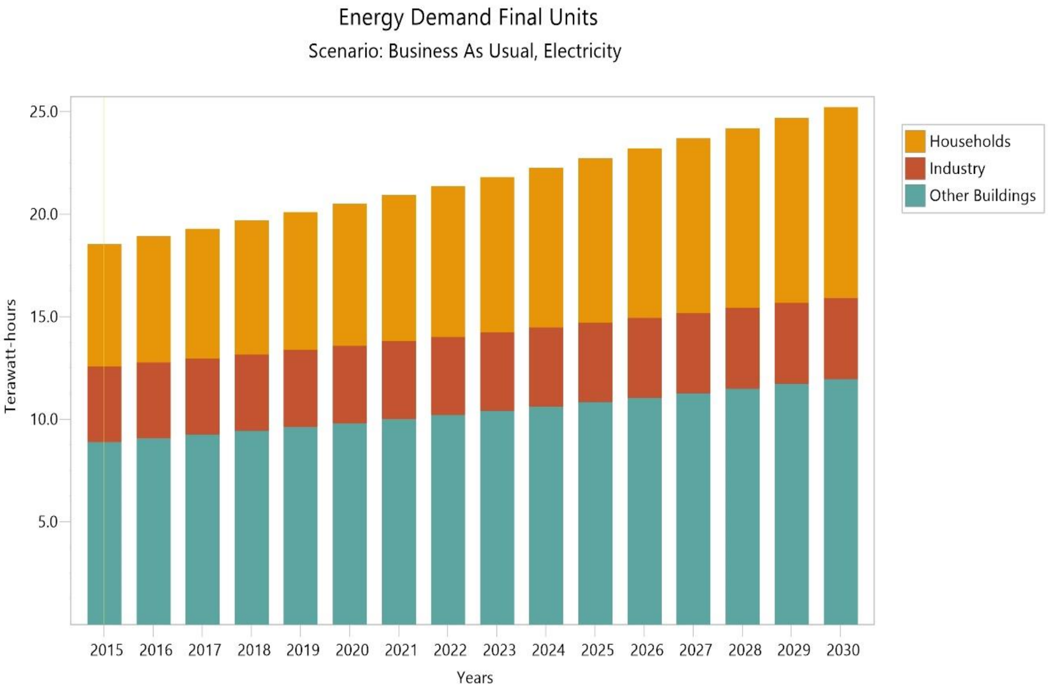

Figure 6: Electricity Demand

Demand increased from 18.54 TWh in 2015 to 25.23 TWh in 2030, an increase of 36% as seen in Table 9. The households constituted the biggest percentage increase of 77.3%, mainly because the population of Lebanon is rising at a rate of 3% per year [45].

Table 9: Electricity Demand in Lebanon (TWh)

Branches	2015	2020	2025	2030
Households	5.96	6.91	8.01	9.29
Industry	3.68	3.77	3.87	3.97
Other Buildings	8.90	9.83	10.85	11.98
Total	18.54	20.51	22.73	25.23

B. Electricity Generation

1. BAU

Figure 7 below shows the electricity output under current policies.

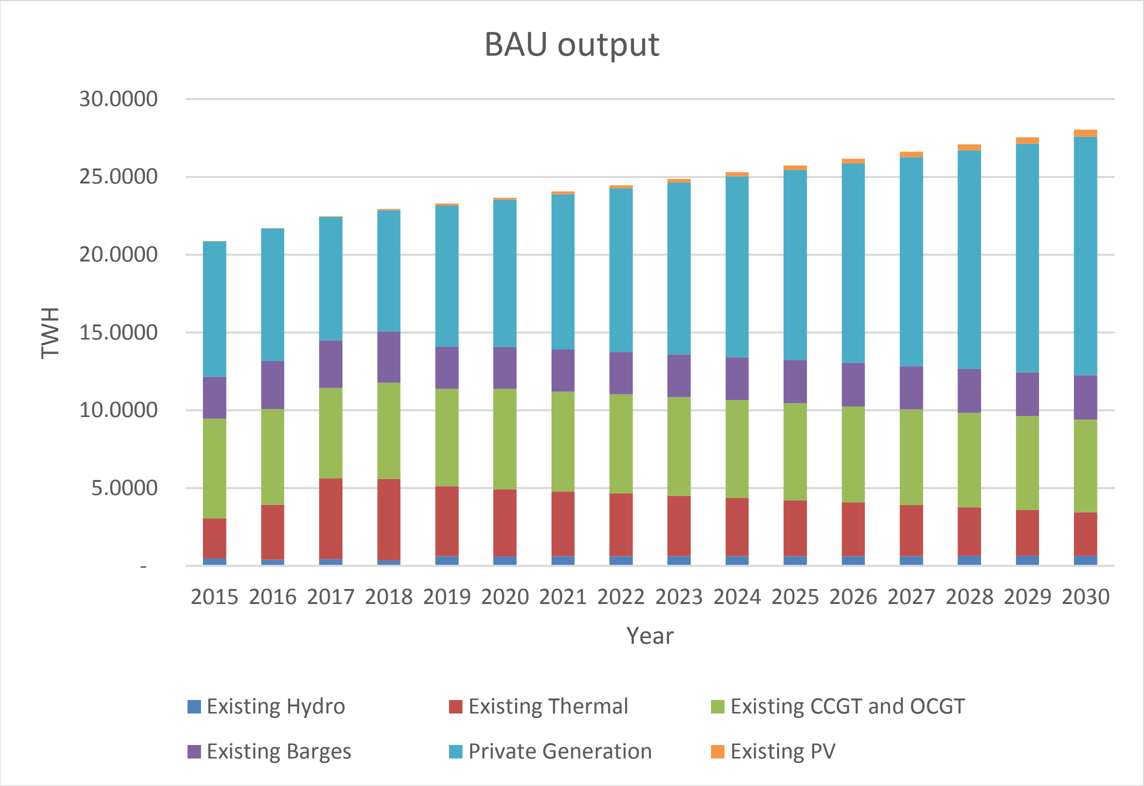

Figure 7: BAU Output

It is evident that under BAU conditions, no proper investment is made to the generating units, and as demand rises, the reliance is all on private generation. In 2020, the output of private generators is estimated at 9.45 TWh as depicted in Table 10. This value increases to reach 15.35 TWh in 2030, constituting 54.76% of the produced energy in that year. Moreover, the drop in output from thermal and CCGT units (due to depreciation) causes the electricity sector to rely more on private generation to provide the deficit between the growing demand and the declining supply. The increase in capacity of private generators is shown in Table 11.

At this stage, it is essential to identify the importance of meeting electricity requirements. In 2020, demand stood at 20.51 TWh. However, electricity supply is modelled at 23.6 TWh. This is because technical losses amount to 15%. Therefore, the electricity output accounts for losses on the grid and thus generates enough net energy to meet demand adequately.

Table 10: BAU Output (TWh)

Branch	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Existing Hydro	0.48	0.38	0.43	0.35	0.60	0.60	0.60	0.60	0.61	0.61	0.61	0.61	0.62	0.62	0.62	0.62
Existing Thermal	2.57	3.54	5.18	5.24	4.50	4.31	4.17	4.03	3.88	3.74	3.59	3.44	3.28	3.13	2.97	2.81
Existing CCGT and OCGT	6.41	6.15	5.83	6.17	6.26	6.45	6.41	6.37	6.33	6.28	6.23	6.18	6.13	6.08	6.02	5.96
Existing Barges	2.69	3.10	3.07	3.29	2.71	2.70	2.71	2.73	2.74	2.75	2.77	2.78	2.79	2.80	2.81	2.82
Private Generation	8.70	8.50	7.90	7.80	9.06	9.45	9.97	10.51	11.06	11.63	12.21	12.81	13.42	14.05	14.69	15.35
Existing PV	0.01	0.03	0.05	0.08	0.11	0.14	0.17	0.20	0.23	0.26	0.29	0.32	0.35	0.38	0.41	0.44
Upgraded CCGT and OCGT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
New CCGT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
New Wind	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
New Thermal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	20.8	21.7	22.4	22.93	23.27	23.66	24.05	24.46	24.87	25.29	25.72	26.16	26.62	27.08	27.55	28.03

Table 11: Capacity Change Under BAU (MW)

Units	2016	2018	2020	2022	2024	2026	2028	2030
Existing Hydro	282.00	282.00	282.00	282.00	282.00	282.00	282.00	282.00
Existing Thermal	1,260.00	1,260.00	1,260.00	1,260.00	1,260.00	1,260.00	1,260.00	1,260.00
Existing CCGT and OCGT	1,069.00	1,069.00	1,069.00	1,069.00	1,069.00	1,069.00	1,069.00	1,069.00
Existing Barges	380.00	380.00	380.00	380.00	380.00	380.00	380.00	380.00
Private Generation	1,082.00	1,206.00	1,330.00	1,463.00	1,602.00	1,749.00	1,902.00	2,063.00
Existing PV	23.07	54.00	100.00	140.00	180.00	220.00	260.00	300.00
Total	4,096.07	4,251.00	4,421.00	4,594.00	4,773.00	4,960.00	5,153.00	5,354.00

It is essential to indicate that all the data from 2015 till 2018 are historical data. From 2019 onward, the results are based on LEAP’s simulations.

2. *NG Scenario*

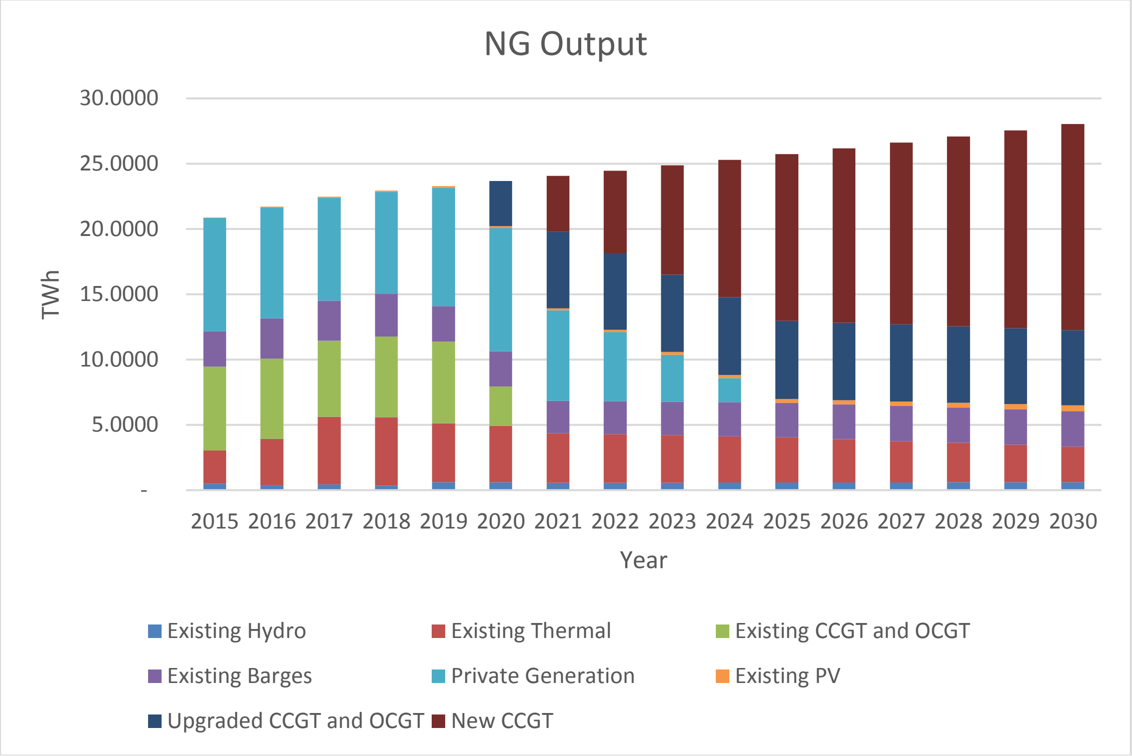

Figure 8: NG Scenario Output

Similar to the BAU, this scenario achieves the needed electric energy requirements. However, instead of relying on private generators, it is evident – see figure 8 – that new CCGT power plants produce the required energy. The upgraded CCGT and OCGT stands for the switch of the existing CCGT and OCGT plants from using Diesel oil to natural gas.

By 2030, 56% of the produced electric energy comes from the newly built CCGT power plants, as depicted in Table 12, while more than 76% of total electric energy comes from gas-fired power plants. Moreover, a significant drop in the output of existing thermal units, in addition to the complete halt of private generation, is observed. This is a good sign in terms of GHG emissions, as natural gas outputs less CO_2 emissions than Diesel oil or HFO.

At this stage, it may be argued that the added capacity depicted in table 13 does not represent a new powerplant. This is true, as LEAP simulates the addition of capacity endogenously, in steps specified by the user. And since Lebanon has existing powerplants that have the ability to incorporate additional units without the need to build new powerplants, LEAP is left to decide the exact amount of addition needed.

Before moving further, it is important to note that the total capacity in the NG scenario is greater than that of the BAU scenario. This discrepancy can be noted after the year 2020. This is because of the planning reserve margin that has been set to 10% in all scenarios except the BAU. Under BAU conditions, only required capacity is added to meet needed demand (achieve a 0% reserve margin). In the other scenarios, additional capacity is added to account for unexpected surge in demand or any other emergency. And because the capacity credit of RE sources is not 100%, every MW of PV or wind is not as reliable as a MW of another conventional generating technology.

Table 12: NG Scenario Output (TWh

Branch	2016	2018	2020	2022	2024	2026	2028	2030
Existing Hydro	0.38	0.35	0.60	0.56	0.58	0.59	0.60	0.60
Existing Thermal	3.54	5.24	4.31	3.72	3.54	3.30	3.01	2.71
Existing CCGT and OCGT	6.15	6.17	3.01	-	-	-	-	-
Existing Barges	3.10	3.29	2.70	2.52	2.61	2.67	2.70	2.73
Private Generation	8.50	7.80	9.45	5.29	1.82	-	-	-
Existing PV	0.03	0.08	0.14	0.18	0.24	0.30	0.37	0.43
Upgraded CCGT and OCGT	-	-	3.43	5.88	5.95	5.94	5.85	5.76
New CCGT	-	-	-	6.29	10.53	13.34	14.52	15.77
New Wind	-	-	-	-	-	-	-	-
New Thermal	-	-	-	-	-	-	-	-
Total	21.70	22.93	23.66	24.46	25.29	26.16	27.08	28.03

Table 13: Capacity Added Under NG Scenario (MW)

Branch	2016	2018	2020	2022	2024	2026	2028	2030
Existing Hydro	282.0	282.0	282.0	282.0	282.0	282.0	282.0	282.0
Existing Thermal	1,260.0	1,260.0	1,260.0	1,260.0	1,260.0	1,260.0	1,260.0	1,260.0
Existing CCGT and OCGT	1,069.0	1,069.0	500.0	-	-	-	-	-
Existing Barges	380.0	380.0	380.0	380.0	380.0	380.0	380.0	380.0
Private Generation	1,082.0	1,206.0	1,330.0	798.0	266.0	-	-	-
Existing PV	23.1	54.0	100.0	140.0	180.0	220.0	260.0	300.0
Upgraded CCGT and OCGT	-	-	569.0	1,069.0	1,069.0	1,069.0	1,069.0	1,069.0
New CCGT	-	-	-	1,116.0	1,802.0	2,230.0	2,401.0	2,579.0
New Wind	-	-	-	-	-	-	-	-
New Thermal	-	-	-	-	-	-	-	-
Total	4,096.1	4,251.0	4,421.0	5,045.0	5,239.0	5,441.0	5,652.0	5,870.0

3. *RE Scenario*

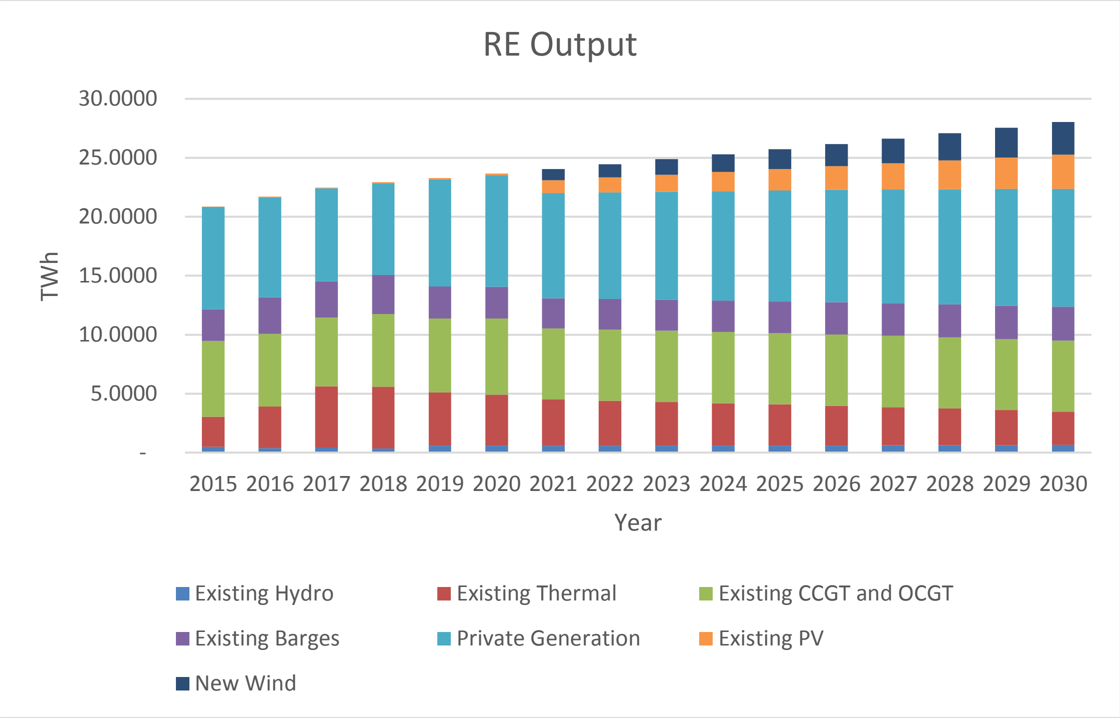

Figure 9: RE Scenario Output

As seen in Table 14 and figure 9, adopting RE technologies would allow for less reliance on private generators to meet the growing demand. Although it is impossible to completely stop the usage of private generators, using RE as a source of electricity would compensate by a certain amount. For instance, under BAU in 2030, private generators contributed 15.35 TWh of electricity. In this scenario however, their contribution amounted to 10 TWh, where the 5.35 TWh difference was covered by both solar PV and wind farms. The only issue with RE technologies is their capacity factor (availability). For instance, 3,769 MW of wind and solar technologies produced 5.7 TWh of electricity in 2030, while 2,709 MW of thermal, CCGT, and barges outputted 11.7 TWh.

Nevertheless, the total electric energy produced by RE sources in 2030 is 6.3 TWh. This value constitutes 22.5% of the total energy production, which means that under such conditions, Lebanon would be able to fulfill its unconditional pledge to supply 15% of its electricity from RE sources [16].

Table 14: RE Scenario Output (TWh)

Branch	2016	2018	2020	2022	2024	2026	2028	2030
Existing Hydro	0.4	0.4	0.6	0.6	0.6	0.6	0.6	0.6
Existing Thermal	3.5	5.2	4.3	3.8	3.6	3.4	3.1	2.8
Existing CCGT and OCGT	6.2	6.2	6.5	6.0	6.0	6.1	6.0	6.0
Existing Barges	3.1	3.3	2.7	2.6	2.7	2.7	2.8	2.9
Private Generation	8.5	7.8	9.5	9.0	9.3	9.5	9.8	10.0
Existing PV	0.0	0.1	0.1	1.3	1.6	2.0	2.4	2.9
Upgraded CCGT and OCGT	-	-	-	-	-	-	-	-
New CCGT	-	-	-	-	-	-	-	-
New Wind	-	-	-	1.1	1.5	1.9	2.3	2.8
New Thermal	-	-	-	-	-	-	-	-
Total	21.7	22.9	23.7	24.5	25.3	26.2	27.1	28.0

Table 15: Capacity Addition Under RE Scenario (MW)

Branch	2016	2018	2020	2022	2024	2026	2028	2030
Existing Hydro	282.0	282.0	282.0	282.0	282.0	282.0	282.0	282.0
Existing Thermal	1,260.0	1,260.0	1,260.0	1,260.0	1,260.0	1,260.0	1,260.0	1,260.0
Existing CCGT and OCGT	1,069.0	1,069.0	1,069.0	1,069.0	1,069.0	1,069.0	1,069.0	1,069.0
Existing Barges	380.0	380.0	380.0	380.0	380.0	380.0	380.0	380.0
Private Generation	1,082.0	1,206.0	1,330.0	1,330.0	1,330.0	1,330.0	1,330.0	1,330.0
Existing PV	23.1	54.0	100.0	930.0	1,165.0	1,410.0	1,667.0	1,935.0
Upgraded CCGT and OCGT	-	-	-	-	-	-	-	-
New CCGT	-	-	-	-	-	-	-	-
New Wind	-	-	-	830.0	1,065.0	1,310.0	1,566.0	1,834.0
New Thermal	-	-	-	-	-	-	-	-
Total	4,096.1	4,251.0	4,421.0	6,081.0	6,551.0	7,041.0	7,554.0	8,090.0

The effect of the capacity credit is clearly seen in this scenario. Under BAU, 5,354 MW are needed to meet the needed power demand. Under Re, 8,090 MW are present by 2030. This is because a planning reserve margin of 10% is required, but more importantly, a capacity credit of 36% is used, which means that new RE capacity is triple the amount of the added capacity of a conventional generating unit.

4. Hybrid Scenario

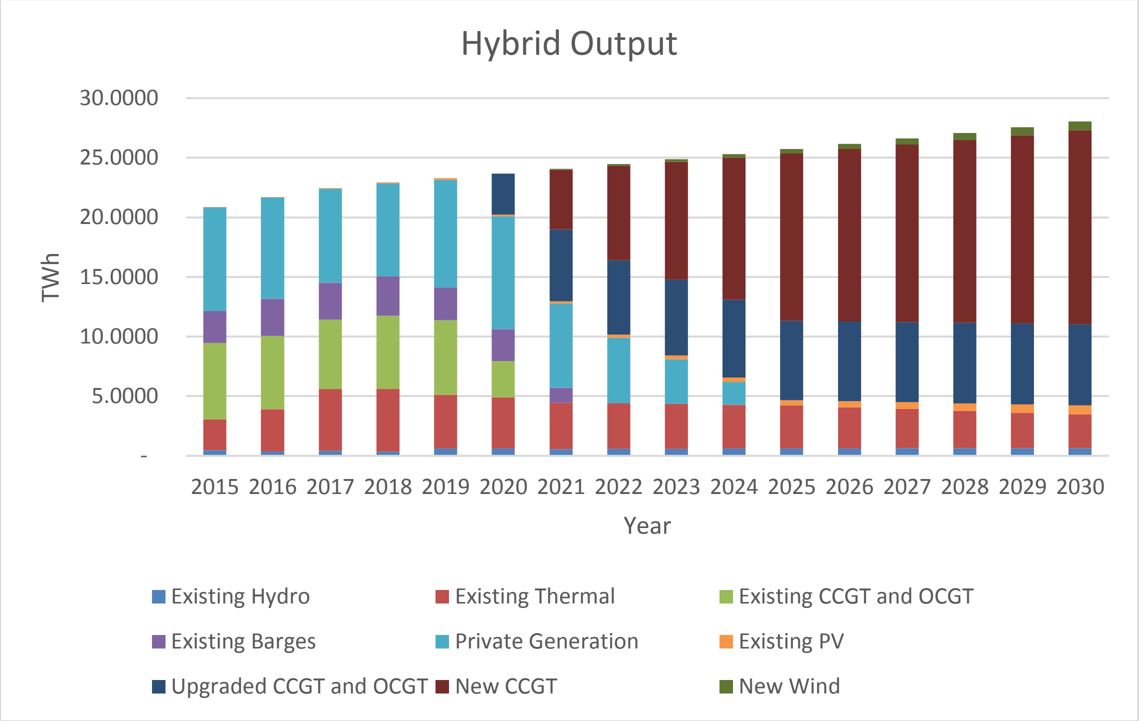

Figure 10: Hybrid Scenario Output (TWh)

It is evident that in this scenario, the results look similar to those of the NG scenario. But, if one takes a closer look at table 16, one notices that there is an additional contribution for the wind and solar energy sources. Overall, RE sources under this scenario contributed to 7.8% of the total energy produced. By 2030, 1,000 MW of PV and wind are present, and the added CCGT units amount to 2,707 MW.

Table 16: COM Scenario Output (TWh)

Branch	2016	2018	2020	2022	2024	2026	2028	2030
Existing Hydro	0.4	0.4	0.6	0.6	0.6	0.6	0.6	0.6
Existing Thermal	3.5	5.2	4.3	3.9	3.7	3.5	3.1	2.8
Existing CCGT and OCGT	6.2	6.2	3.0	-	-	-	-	-
Existing Barges	3.1	3.3	2.7	-	-	-	-	-
Private Generation	8.5	7.8	9.5	5.5	1.9	-	-	-
Existing PV	0.0	0.1	0.1	0.2	0.4	0.5	0.6	0.8
Upgraded CCGT and OCGT	-	-	3.4	6.2	6.5	6.7	6.8	6.8
New CCGT	-	-	-	7.9	11.9	14.5	15.3	16.2
New Wind	-	-	-	0.1	0.3	0.4	0.6	0.8
New Thermal	-	-	-	-	-	-	-	-
Total	21.7	22.9	23.7	24.5	25.3	26.2	27.1	28.0

5. MoEW Scenario

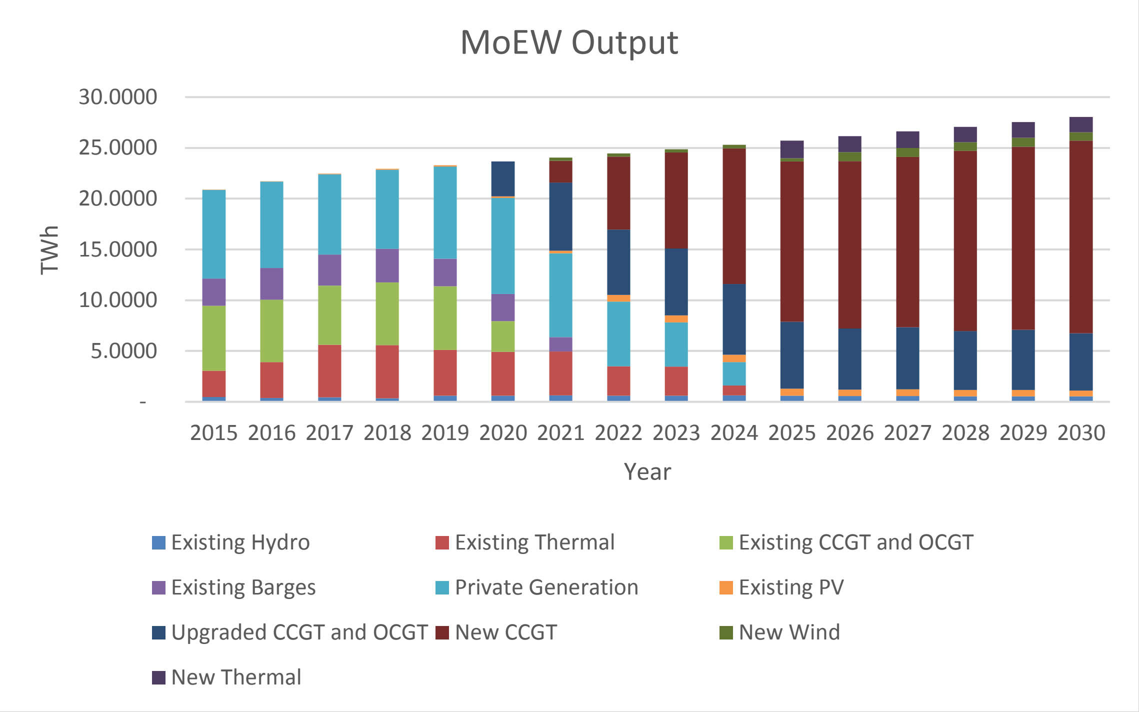

Figure 11: MoEW Scenario Output

This scenario is similar to the combination scenario depicted in the previous section, but with more emphasis gas-fired generating units, where their share comprises more than 85% of generated energy in 2030. In addition to that, almost all of the existing fleet is replaced starting 2025. This is highlighted in table 18, where the removed capacity is replaced by new CCGT plants and renewable energy sources.

Table 17: MoEW Scenario Output (TWh)

Branch	2016	2018	2020	2022	2024	2026	2028	2030
Existing Hydro	0.4	0.4	0.6	0.6	0.6	0.6	0.5	0.5
Existing Thermal	3.5	5.2	4.3	2.9	1.0	-	-	-
Existing CCGT and OCGT	6.2	6.2	3.0	-	-	-	-	-
Existing Barges	3.1	3.3	2.7	-	-	-	-	-
Private Generation	8.5	7.8	9.5	6.4	2.3	-	-	-
Existing PV	0.0	0.1	0.1	0.7	0.7	0.6	0.6	0.6
Upgraded CCGT and OCGT	-	-	3.4	6.4	7.0	6.0	5.8	5.6
New CCGT	-	-	-	7.2	13.4	16.5	17.7	19.0
New Wind	-	-	-	0.3	0.3	0.9	0.8	0.8
New Thermal	-	-	-	-	-	1.6	1.5	1.5
Total	21.7	22.9	23.7	24.5	25.3	26.2	27.1	28.0

Table 18: Capacity Addition Under MoEW Scenario

Branch	2016	2018	2020	2022	2024	2026	2028	2030
Existing Hydro	282.0	282.0	282.0	282.0	282.0	282.0	282.0	282.0
Existing Thermal	1,260.0	1,260.0	1,260.0	917.0	310.0	-	-	-
Existing CCGT and OCGT	1,069.0	1,069.0	500.0	-	-	-	-	-
Existing Barges	380.0	380.0	380.0	-	-	-	-	-
Private Generation	1,082.0	1,206.0	1,330.0	900.0	300.0	-	-	-
Existing PV	23.1	54.0	100.0	480.0	480.0	480.0	480.0	480.0
Upgraded CCGT and OCGT	-	-	569.0	1,069.0	1,069.0	1,069.0	1,069.0	1,069.0
New CCGT	-	-	-	1,270.0	2,180.0	3,100.0	3,460.0	3,820.0
New Wind	-	-	-	220.0	220.0	660.0	660.0	660.0
New Thermal	-	-	-	-	-	300.0	300.0	300.0
Total	4,096.1	4,251.0	4,421.0	5,138.0	4,841.0	5,891.0	6,251.0	6,611.0

C. Emissions

1. BAU

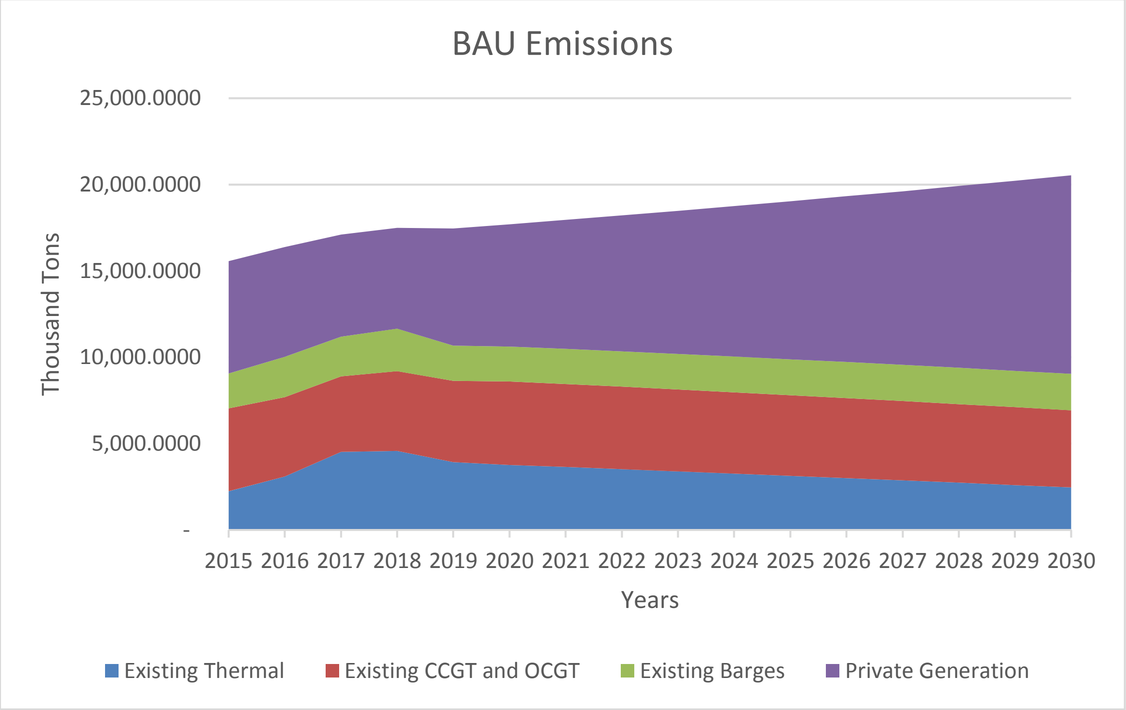

Figure 12: BAU Emissions

The BAU is considered to be the reference scenario in terms of emissions. The other four scenarios will be compared to it and their analysis will be based upon whether they have a significant reduction potential with respect to the BAU scenario or not. The emissions under BAU conditions are depicted in figure 12.

It is evident that the fleet of private generators is the main contributor in terms of GHG emissions. For instance, in 2030, private generators alone emitted 11.5 million metric tons of CO_2eq. This comprises 56% of the overall emissions during that year. In addition to that, private generators use Diesel Oil as their input fuel, which yields a much higher emission rate than natural gas.

2. *NG Scenario*

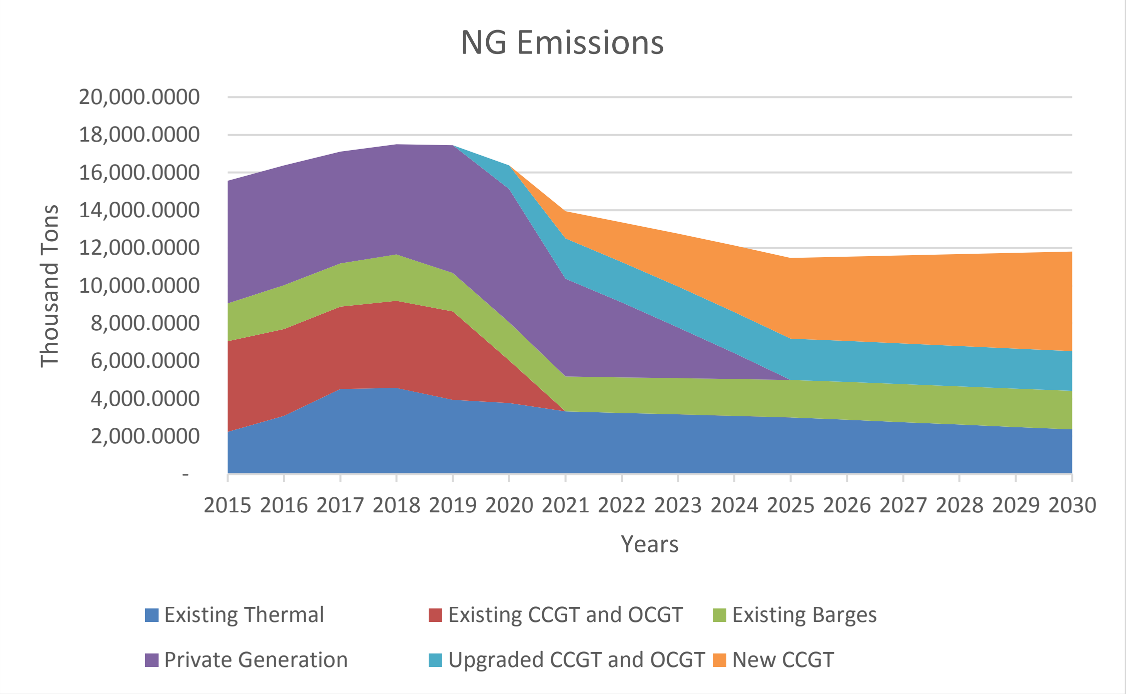

Figure 13: NG Scenario Emissions

In 2020, a significant drop is expected in terms of GHG emissions. This drop can be related to the adoption of natural gas as a fuel to the existing CCGT and OCGT fleet. The effect of introducing new CCGT plants is seen starting in 2021. Looking at table 19, it is evident that using NG on the existing CCGT units would lead to substantial reductions. For instance, existing CCGT emitted 4,605 Gg in 2016. The same unit would emit 2,047 Gg in 2030 after using NG as fuel.

Table 19: NG Scenario Emissions (Million Tons CO_2eq)

Branch	2016	2018	2020	2022	2024	2026	2028	2030
Existing Thermal	3.1	4.6	3.8	3.3	3.1	2.9	2.6	2.4
Existing CCGT and OCGT	4.6	4.6	2.3	-	-	-	-	-
Existing Barges	2.3	2.5	2.0	1.9	2.0	2.0	2.0	2.0
Private Generation	6.4	5.8	7.1	4.0	1.4	-	-	-
Upgraded CCGT and OCGT	-	-	1.3	2.2	2.2	2.2	2.1	2.1
New CCGT	-	-	-	2.1	3.5	4.5	4.9	5.3
Total	16.4	17.5	16.4	13.4	12.1	11.5	11.7	11.8

Figure 14 provides a comparative analysis regarding emissions between the BAU scenario and the Natural Gas alternative. Overall, in the time span between 2020 and 2030 71,346 Gg would be avoided by adopting this alternative. Under BAU conditions, Lebanon would emit 293,760 Gg from 2015 till 2030. Therefore, this scenario is reducing 24.28% in terms of GHG emissions.

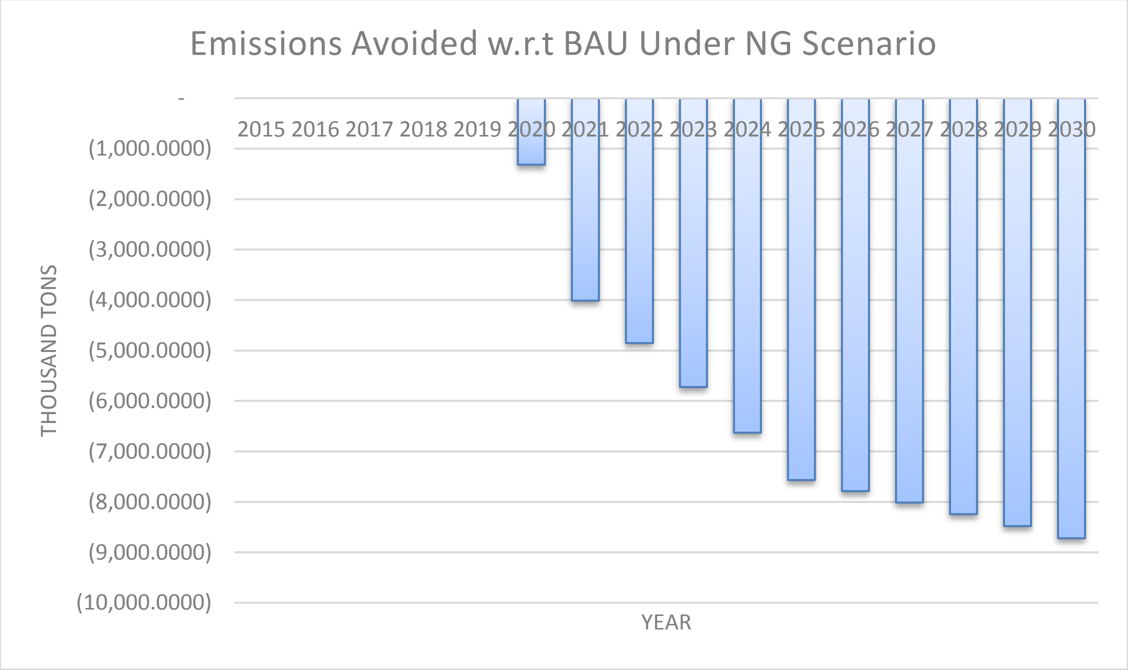

Figure 14: Avoided Emissions (NG)

3. *RE Scenario*

Under this scenario, 25,887 Gg are avoided with respect to the BAU scenario overall (15-year span) as depicted in figure 15. This decrease in emissions is not as significant as the natural gas scenario, mainly because when adopting RE technologies, it is not possible to completely stop the usage of private generators. Figure 16 highlights the emissions from this scenario.

From analyzing both the natural gas alternative and the RE alternative, it is clear that both scenarios do indeed have a reduction potential in terms of GHG emissions.

However, it is also evident that a combination of both alternatives into a new scenario would yield more CO_2 reduction at an even lower cost. The results of this option will be showcased in the coming section.

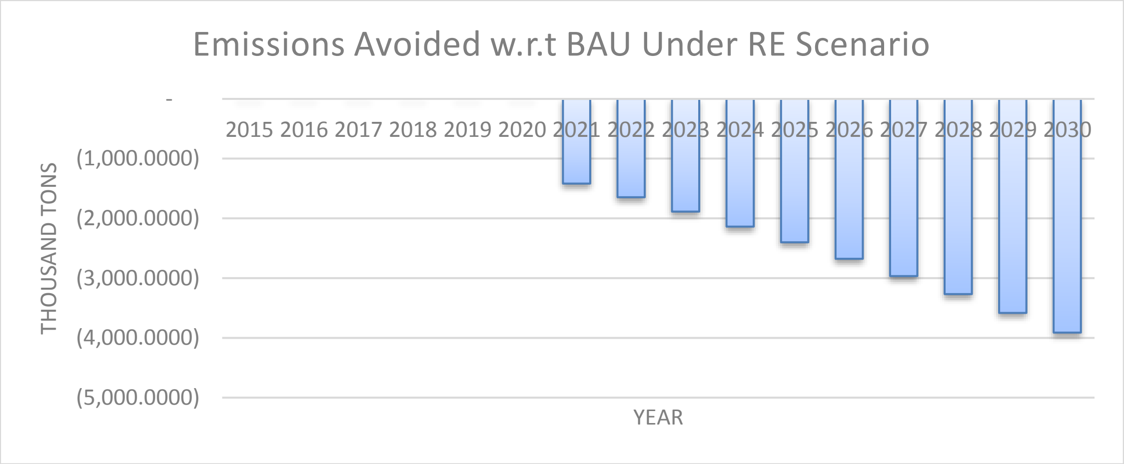

Figure 15: RE Senario Emissions Avoided

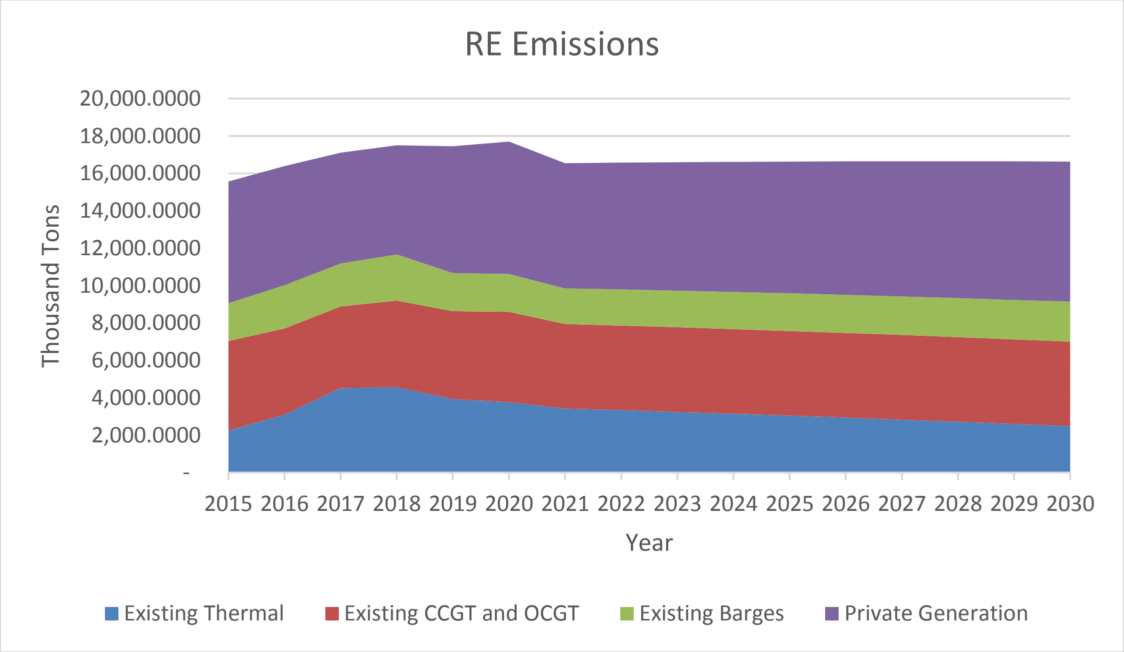

Figure 16: RE Scenario Emissions

4. *Hybrid Scenario*

Figure 17 showcases the emissions resulting from the combined scenario of NG and RE. As expected, this scenario achieves an increase in reduction in terms of GHG emissions. Overall, 82,613 Gg of CO_2eq are avoided. Figure 18 highlights this increase in avoided emissions.

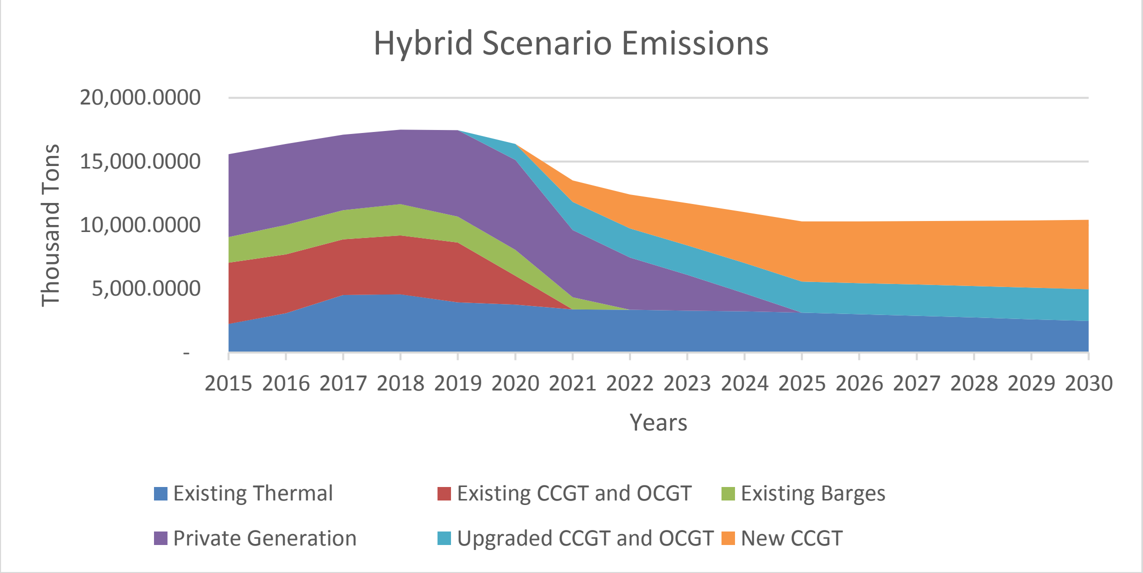

Figure 17: Hybrid Scenario Emissions

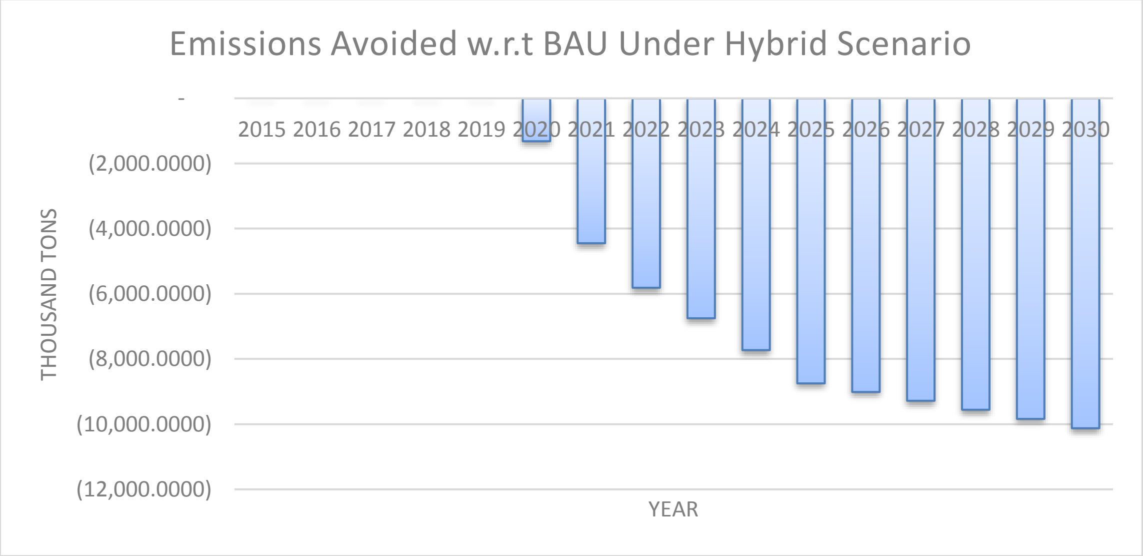

Figure 18: Hybrid Scenario Emissions Avoided

5. MoEW Scenario

Similar to the previous scenario, the MoEW plan achieves even greater reduction in emissions, because it adds to the COM scenario by removing existing thermal powerplants and adding additional CCGT units. Figure 19 showcases the overall emissions under this alternative. In total, 98,264 Gg CO_2eq are avoided as depicted in figure 20. Table 20 serves as a comparison of all four scenarios with respect to the BAU approach. However, this comparison is not conclusive as it is necessary to perform an economic feasibility of all scenarios to be able to decide which approach is optimal.

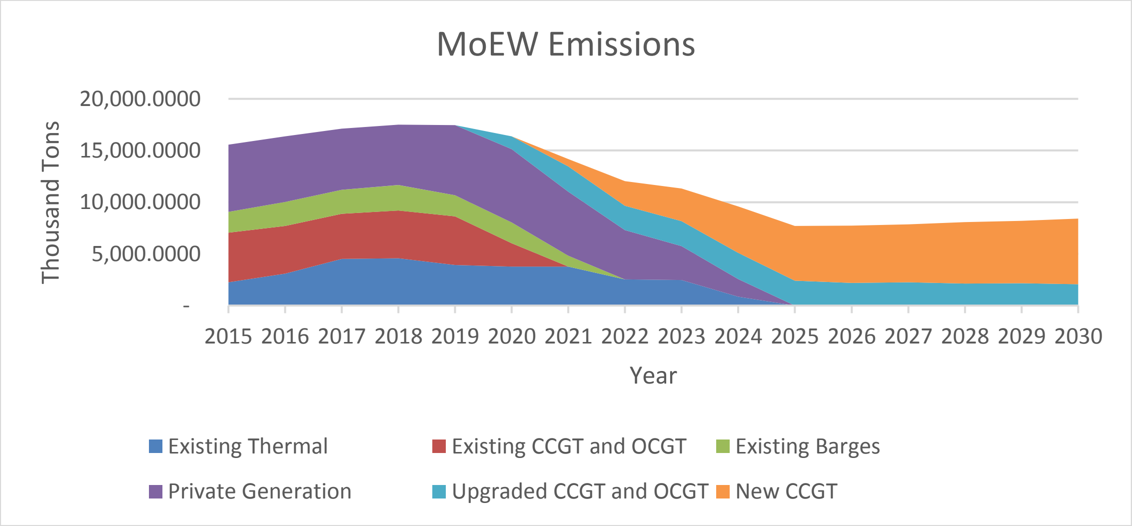

Figure 19: MoEW Scenario Emissions

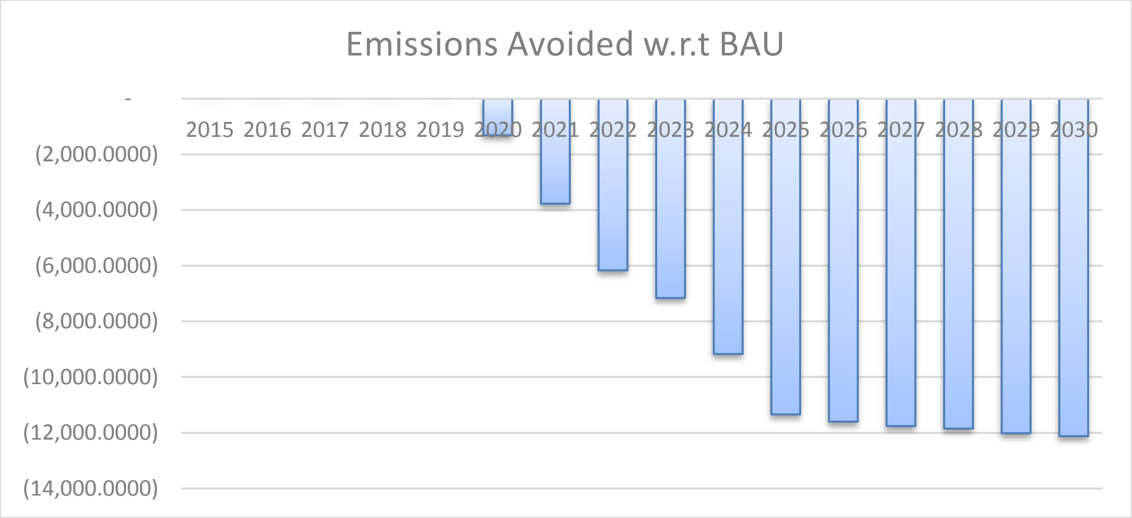

Figure 20: Emissions Avoided Under MoEW Scenario

Table 20: Emission Reduction Potential W.R.T BAU Scenario

Scenario	Total Overall Emissions (Gg CO_2eq)	Emission Reduction w.r.t BAU (Gg CO_2eq)	% Emission Reduction
BAU	293,760	/	
NG	222,413	(71,346)	24.3
RE	267,872	(25,887)	8.8
Hybrid	211,146	(82,613)	28.1
MoEW	195,495	(98,264)	33.4

CHAPTER V

ECONOMIC FEASIBILITY

In this section, an economic evaluation of the suggested alternatives will be evaluated. LEAP allows the user to specify capital costs, fixed costs, variable costs, fuel costs, lifetime and interest rates for every technology in every scenario. LEAP then outputs costs in terms of investment costs (pertaining to capital costs) and costs of production (pertaining to O&M and fuel costs) using eq. (8) and eq. (9). Afterwards, the yearly costs are discounted according to the discount rate specified and then summed up to obtain a net present value (NPV) relative to a certain year of choice, as indicated in eq. (10). In table 8, all cost variables are listed. These data are retrieved from the updated Annual Technology Baseline (ATB) report published by the National Renewable Energy Lab (NREL) [50] and are verified by the data published by the U.S. Energy Information Administration [51].

$$CapCost\ (\$) = CAPEX(\$/MW) \times Capacity(MW) \quad (8)$$

where CapCost is the total investment (capital) cost made and CAPEX is the capital expenditure value representing the dollar cost of every MW installed while also accounting for project finances (interest accrued throughout the time of the project).

$$\begin{gathered} ProdCost\ (\$/year) = [FixedCost((\$/MW)/year) \times Capacity(MW)] \\ +[VarCost((\$/MWh)/year) \times E(MWh)] + [FuelCost(\$/kg) \times FM(kg/year)] \quad (9) \end{gathered}$$

where ProdCost is the cost of producing electricity every year, E is the energy output of the process and FM is the mass of the fuel used in every plant in every year.

$$NPV(\$) = \sum_{0}^{n} \frac{CapCost(\$) + ProdCost(\$)}{(1+r)^{n}} \quad (10)$$

where n is the index year and r in the rate of return (discount rate).

At this stage, it is of utmost importance to explain the assumptions that LEAP makes when performing an economic feasibility:

1. Capital Costs are incurred at the end of the year.
2. Operating costs are incurred at the middle of the year.

According to what preceded, eq. (10) can be expressed as

$$NPV(\$) = \sum_{1}^{n} \frac{CapCost(\$)}{(1+r)^{n}} + \sum_{0}^{n} \frac{ProdCost(\$)}{(1+r)^{n+0.5}} \quad (11)$$

This modification assumes that capital costs are incurred in the form of a lump sum, which is never the case. It is critical to annualize capital costs. The software allows for multiple annualization methods; however, the author adopts the default method used by LEAP, that is the capital recovery factor (CRF) approach. The CRF is defined as

$$A = P \times \frac{r \times (1+r)^{n}}{(1+r)^{n} - 1} \qquad (12)$$

where A is the annual payment, P is the present capital cost, r is the interest rate and n is the annualization period. LEAP assumes that n is equal to the lifetime of the technology.

LEAP then discounts the annualized costs according to (11).

Table 21 and 22 showcase the cashflows extracted directly from LEAP. These cashflows were then validated manually via Excel by applying the necessary equations to obtain capital and running costs. The numbers below are unaltered, meaning that they are neither annualized, nor discounted. They simply reflect the true cost of every scenario, divided between capital costs and running costs.

Table 21: Cashflow for First Five Years

	Years	2015	2016	2017	2018	2019
BAU	Total	$1,612,523,379	$1,725,155,547	$1,804,301,889	$1,853,680,980	$1,844,337,434
	Capital	$0.00	$23,182,000	$19,423,000	$27,000,000	$31,500,000
	Running	$1,612,523,379	$1,701,973,547	$1,784,878,889	$1,826,680,980	$1,812,837,434
NG	Total	$1,612,523,379	$1,725,155,547	$1,804,301,889	$1,853,680,980	$1,844,337,434
	Capital	$0.00	$23,182,000	$19,423,000	$27,000,000	$31,500,000
	Running	$1,612,523,379	$1,701,973,547	$1,784,878,889	$1,826,680,980	$1,812,837,434
RE	Total	$1,612,523,379	$1,725,155,547	$1,804,301,889	$1,853,680,980	$1,844,337,434
	Capital	$0.00	$23,182,000	$19,423,000	$27,000,000	$31,500,000
	Running	$1,612,523,379	$1,701,973,547	$1,784,878,889	$1,826,680,980	$1,812,837,434
MoEW	Total	$1,612,523,379	$1,725,155,547	$1,804,301,889	$1,853,680,980	$1,844,337,434
	Capital	$0.00	$23,182,000	$19,423,000	$27,000,000	$31,500,000
	Running	$1,612,523,379	$1,701,973,547	$1,784,878,889	$1,826,680,980	$1,812,837,434
Combination	Total	$1,612,523,379	$1,725,155,547	$1,804,301,889	$1,853,680,980	$1,844,337,434
	Capital	$0.00	$23,182,000	$19,423,000	$27,000,000	$31,500,000
	Running	$1,612,523,379	$1,701,973,547	$1,784,878,889	$1,826,680,980	$1,812,837,434

The aim behind displaying the first 5 years is to highlight their irrelevance for the feasibility study. As expected, they all have the same costs, mainly because they already happened, and any suggested scenario starts taking effect in 2020 and onward. The reason behind having these five years is to showcase historical trends and how these trends compare to future changes.

In the continuation of table 21 below, it can be seen how the capital costs of the four scenarios are much greater than those of the BAU scenario. This is expected, especially that all four scenarios introduce new added capacities. On the other hand, running costs in the four scenarios (except the RE) are lower than that in the BAU. This is because of the decreased reliance on diesel oil, and the increase in the efficiency of the new processes, allowing the fuel consumption to decrease.

Table 22: Cashflow for years 2020-2030

	Years	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
BAU	Total	$1,867,333,193	$1,888,534,500	$1,913,303,649	$1,938,746,551	$1,964,692,875	$1,991,445,793	$2,018,641,936	$2,046,498,104	$2,075,228,126	$2,104,559,053	$2,134,511,555
	Capital	$31,500,000	$28,600,000	$28,700,000	$28,900,000	$29,000,000	$29,300,000	$29,400,000	$29,500,000	$29,800,000	$30,000,000	$30,100,000
	Running	$1,835,833,193	$1,859,934,500	$1,884,603,649	$1,909,846,551	$1,935,692,875	$1,962,145,793	$1,989,241,936	$2,016,998,104	$2,045,428,126	$2,074,559,053	$2,104,411,555
NG	Total	$1,655,486,471	$1,981,781,294	$1,484,109,421	$1,385,618,638	$1,283,804,293	$1,177,754,987	$928,894,553	$927,336,439	$923,909,244	$921,318,165	$918,650,430
	Capital	$31,500,000	$740,425,000	$338,107,000	$339,034,000	$340,888,000	$342,742,000	$98,014,000	$100,795,000	$101,722,000	$103,576,000	$105,430,000
	Running	$1,623,986,471	$1,241,356,294	$1,146,002,421	$1,046,584,638	$942,916,293	$835,012,987	$830,880,553	$826,541,439	$822,187,244	$817,742,165	$813,220,430
RE	Total	$1,867,333,193	$3,698,561,868	$2,080,720,448	$2,097,621,181	$2,112,528,995	$2,127,644,335	$2,143,917,444	$2,159,747,674	$2,173,581,514	$2,189,096,674	$2,203,146,882
	Capital	$31,500,000	$1,934,300,000	$306,700,000	$314,300,000	$320,200,000	$326,700,000	$334,800,000	$342,900,000	$349,400,000	$358,000,000	$365,600,000
	Running	$1,835,833,193	$1,764,261,868	$1,774,020,448	$1,783,321,181	$1,792,328,995	$1,800,944,335	$1,809,117,444	$1,816,847,674	$1,824,181,514	$1,831,096,674	$1,837,546,882
MoEW	Total	$1,655,486,471	$2,062,615,087	$2,142,359,097	$1,183,862,699	$1,081,140,181	$1,515,480,337	$1,527,188,332	$486,767,467	$825,986,252	$499,040,774	$838,971,149
	Capital	$31,500,000	$773,720,000	$1,173,570,000	$333,720,000	$509,850,000	$1,049,850,000	$1,046,990,000	$0.00	$333,720,000	$0.00	$333,720,000
	Running	$1,623,986,471	$1,288,895,087	$968,789,097	$850,142,699	$571,290,181	$465,630,337	$480,198,332	$486,767,467	$492,266,252	$499,040,774	$505,251,149
Combination	Total	$1,655,486,471	$2,169,152,087	$1,589,003,901	$1,311,414,461	$1,204,692,913	$1,092,662,698	$843,116,000	$840,072,001	$836,962,601	$833,801,314	$830,601,231
	Capital	$31,500,000	$995,380,000	$592,135,000	$417,859,000	$419,713,000	$421,567,000	$176,839,000	$178,693,000	$180,547,000	$182,401,000	$184,255,000
	Running	$1,623,986,471	$1,173,772,087	$996,868,901	$893,555,461	$784,979,913	$671,095,698	$666,277,000	$661,379,001	$656,415,601	$651,400,314	$646,346,231

A preliminary NPV calculation was undertaken to obtain primary results for the comparative analysis. The cashflows remain non-annualized and start from the year 2020. A 5% interest rate is adopted. It is of utmost importance to state that a 5% interest rate is used for comparative purposes; it does not reflect current Lebanese market rates. Table 23 below shows the obtained results.

Table 23: Preliminary NPV

Scenario	NPV ($)	Difference w.r.t BAU ($)	$/tCO$_2$
BAU	$16,862,571,461	/	/
NG	$10,877,981,231	($5,984,590,230)	($83)
RE	$19,287,834,643	$2,425,263,181	$93
Combined	$10,643,632,291	($6,218,939,170)	($58)
MoEW	$11,158,141,734	($5,704,429,726)	($75)

From a primary perspective, the NG, MoEW and combined scenarios are a win-win approach w.r.t the BAU scenario. They all have achieved reductions in terms of GHG emissions and are less costly than proceeding with current policies. Only the RE scenario has a positive cost relative to the BAU. This is also expected, as the RE scenario is not a feasible one. Not only does it keep relying on the existing fleet, the capacity factor and capacity credit of RE sources cause a spike in terms of investment costs, without showing a significant decrease in running costs.

Before proceeding, it is critical to show that the cost calculation methodology adopted in this work is the same as that in LEAP. LEAP does not account for inflation directly, as this feature was removed according to the senior developer of the software [52]. Moreover, the model in LEAP starts off at year 2015, so all years from 2015 up until 2030 should be included in the validation of the cost model. All capital costs are annualized according to the CRF. Table 24 highlights the results obtained through Excel. Table 25 shows the results presented in LEAP). Evidently, the numbers are exactly matching, which indicates that the cost methodology adopted in this work is reliable.

Table 24: Validation NPV

Scenario	NPV ($)	Difference w.r.t BAU ($)
BAU	$20,875,307,661	/
NG	$15,343,937,313	($5,531,370,347)
RE	$21,055,710,923	$180,403,262
Combined	$14,736,987,843	($6,138,319,818)
MoEW	$14,449,094,673	($6,426,212,988)

Table 25: LEAP Cost Summary

Cumulative Costs & Benefits: 2015-2030.					
Discounted at 5.0% to year 2015. Units: Million 2015 U.S. Dollar					
Sector	Business As Usual	Combination	Natural Gas	Renewable Energy	MoEW
Demand	-	-	-	-	-
Households	-	-	-	-	-
Industry	-	-	-	-	-
Other Buildings	-	-	-	-	-
Transformation	1,345.3502	2,501.9043	2,176.8870	2,924.2594	2,847.4106
Transmission and Distribution	-	-	-	-	-
Electricity Generation	1,345.3502	2,501.9043	2,176.8870	2,924.2594	2,847.4106
Resources	-	-	-	-	-
Production	-	-	-	-	-
Imports	19,529.9575	12,235.0836	13,167.0503	18,131.4515	11,601.6840
Exports	-	-	-	-	-
Other Costs					
Unmet Requirements	-	-	-	-	-
Environmental Externalities	-	-	-	-	-
Non Energy Sector Costs	-	-	-	-	-
Total Net Present Value	20,875.3077	14,736.9878	15,343.9373	21,055.7109	14,449.0947
GHG Emissions (Mill Tonnes CO2e)	293.7602	211.1469	222.4139	267.8730	195.4956

As stated before, a 5% interest rate is used in the case to verify that LEAP's NPV and the calculated NPV do indeed match. Later sections cover a wide range of interest rates, allowing the economic feasibility to target multiple scenarios.

To proceed, it is necessary to account for inflation. After the previous validation step, the first five years are disregarded. Cashflows start at year 2020 from now on hereafter. For the scope of this thesis, a 3% inflation rate is applied to the cashflows through (13)

$$C' = C \times (1 + i)^n \quad (13)$$

where C' is the inflated cashflow, C is the initial cashflow, i is the inflation rate and n is the year of occurrence of the cashflow.

Table 26 below shows the updated cashflows after accounting for inflation and annualizing the capital costs. For descriptive purposes, only the BAU scenario is showcased to highlight how inflation and annualization impact cashflows from 2020 until 2025. The new cashflows are adopted hereon after.

Table 26: Updated Inflated Cashflows for Years 2020-2025

Years	2020	2021	2022	2023	2024	2025
Total	$1,867,333,193	$1,888,534,500	$1,913,303,649	$1,938,746,551	$1,964,692,875	$1,991,445,793
Capital	$31,500,000	$28,600,000	$28,700,000	$28,900,000	$29,000,000	$29,300,000
Inflated Capital	$32,445,000	$30,341,740	$31,361,264	$32,527,204	$33,618,948	$34,985,732
Inflated+Annul	$2,110,593	$4,084,367	$6,124,462	$8,240,404	$10,427,364	$12,703,237
Running	$1,835,833,193	$1,859,934,500	$1,884,603,649	$1,909,846,551	$1,935,692,875	$1,962,145,793
Inflated Running	$1,863,167,200	$1,944,256,176	$2,029,145,034	$2,118,013,681	$2,211,077,487	$2,308,532,587

It is seen how inflation increases both capital and running costs. Moreover, it is evident that annualizing capital costs distributes the investment over the lifetime, which is much more realistic.

At this stage, a very important question arises. What are the main drivers behind the cost of every scenario? What if one key cost variable changes, will that impact the overall feasibility of a scenario? Based on the preceding questions, the thesis work will incorporate a sensitivity analysis in which interest rates and fuel prices are varied. This allows the results to become more comprehensive, in the sense that they will encompass a wide range of key variables, thus making sure that the correct scenario is chosen to be the most feasible.

First of all, the NPV for the five scenarios is computed for every interest rate in the range of 0.25% to 20%, in increments of 0.25. MATLAB was used to extract cashflows from the Excel file and then perform the necessary computations. The results are showcased in figure 21. It is clear that the NG, MoEW and COM scenarios are always a feasible option, no matter what the interest rate is. However, regarding the RE scenario, it can be noted that when the interest rate is below 4.5%, the RE scenario tends to be an acceptable alternative. Beyond the 4.5 rate, the NPV of the RE exceeds that of the BAU. In general, all NPV curves have a negative slope, because the higher the interest rate, the more discounting occurs, making the NPV of the cost drop down. This can be proven by looking at eq. (10) and (11) where the interest rate variable is located in the denominator, making it inversely proportional to the NPV, thus allowing for negative-sloped curves.

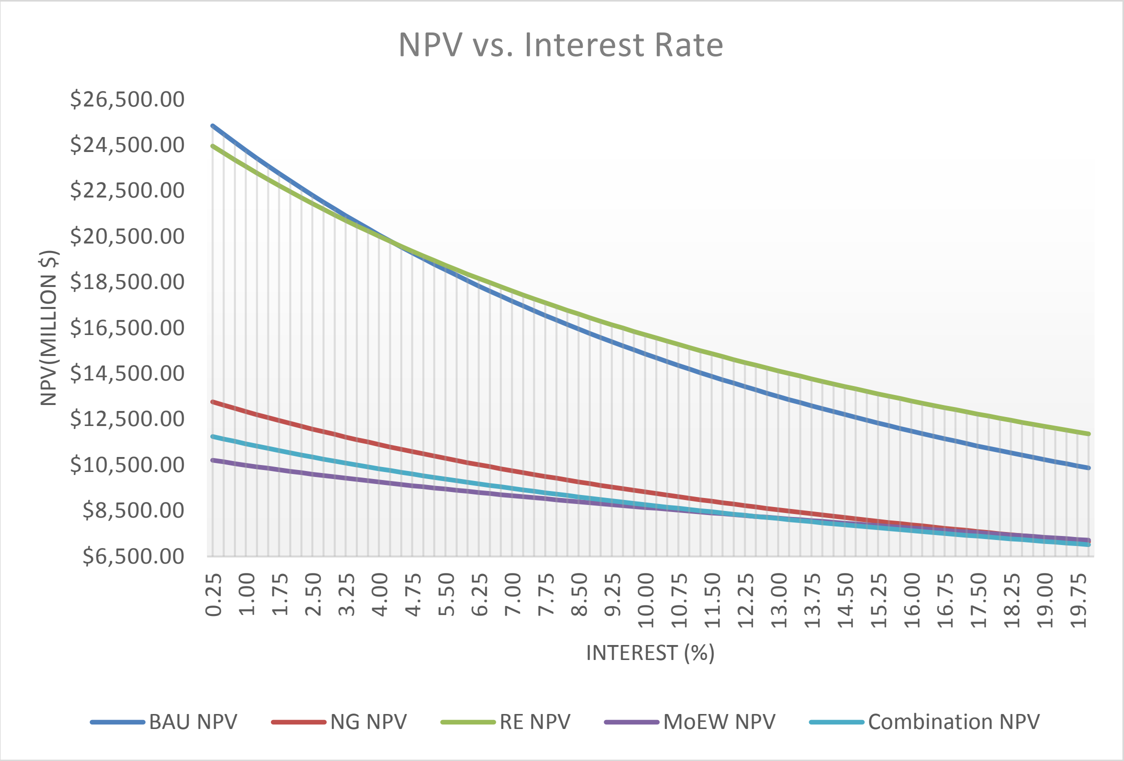

Figure 21: Interest Rate Sensitivity Analysis

What has been mentioned above is reflected specifically in figure 22, where the cost of avoiding CO_2 emissions is displayed as a function of the varying interest rate. It is evident that the MoEW, NG and COM scenarios have a negative $/tCO$_2$ value. This negative value indicates that these approaches allow for reductions in emissions while saving on the overall cost. The RE scenario on the other hand has a negative emission removal cost while the interest rate is below 4.5%. Beyond that, the cost incurred is positive. Compared to the other scenarios, the RE approach is deemed to be not feasible. However, the cost does not exceed 30$/tCO$_2$ removed; a value that can be considered acceptable compared to other methods such as carbon capture and storage. At this stage, it is crucial to highlight some of the emissions avoidance costs. In [53], Gillingham provides a marginal abatement cost curve, where GHG reduction costs range from -100$/tCO$_2$ to 40$/ tCO$_2$. For instance, using solar PV yields a cost of 30$/tCO$_2$, a figure very similar to the results obtained in this work. On the contrary, using carbon capture technologies on existing powerplants would have a higher cost, approximately 40$/tCO$_2$ removed.

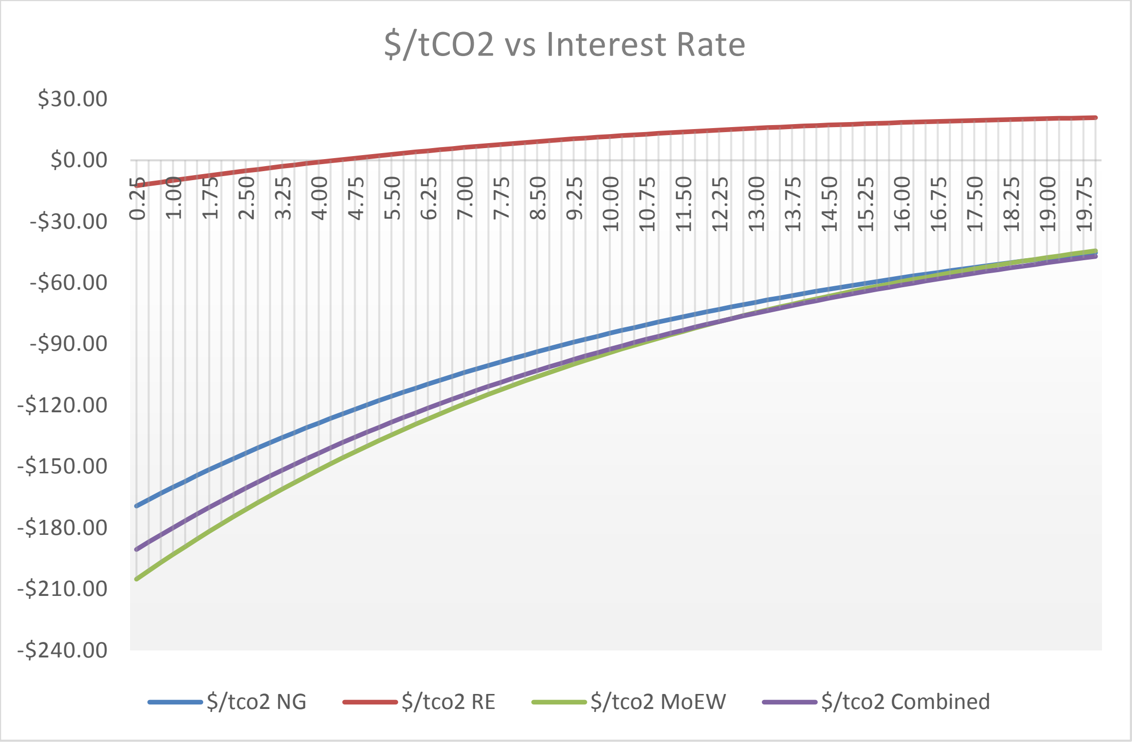

Figure 22: $/tCO2 vs Interest Rate

In addition to that, fuel prices are also varied. A sensitivity analysis is carried out while varying natural gas prices from 0.03$/cubic meter to 0.52$/cubic meter in increments of 0.1. This range is chosen based on the trends of natural gas prices. A database of prices is extracted starting from January of 1997 up until March of 2020. The prices spiked in 2005 to reach values greater than 50 cents/cubic meter of natural gas.

What is clear, as depicted in figure 23 is that NG prices have no effect whatsoever on the BAU and RE scenarios, mainly because both scenarios have no unit that adopts NG as its fuel. Nevertheless, the three other scenarios may have looked pretty much feasible at all times, but the results show that when natural gas prices increase beyond 0.35$/cubic meter, the RE and BAU scenarios start becoming the better alternative. To probe further, the curves suggest a high correlation between the NG, MoEW and COM scenarios in terms of their reliance on NG. They all increase at almost the same rate, indicating that the effect NG holds on the three scenarios is pretty much similar.

Figure 24 reiterates the fact that beyond the NG price of 35 cents/cubic meter, the MoEW, NG and COM scenarios will have a positive cost of emission removal. Compared to the RE scenario, closer investigation suggests that adopting the RE approach becomes the most feasible beyond prices of 0.37$/cubic meter of natural gas. In this 2-cent margin (0.35-0.37), the three other scenarios maintain their advantage over the RE scenario, even though their $/tCO$_2$ value is positive. This is an indicator that positive carbon removal costs are acceptable, as long as they remain feasible as compared to the business as usual approach.

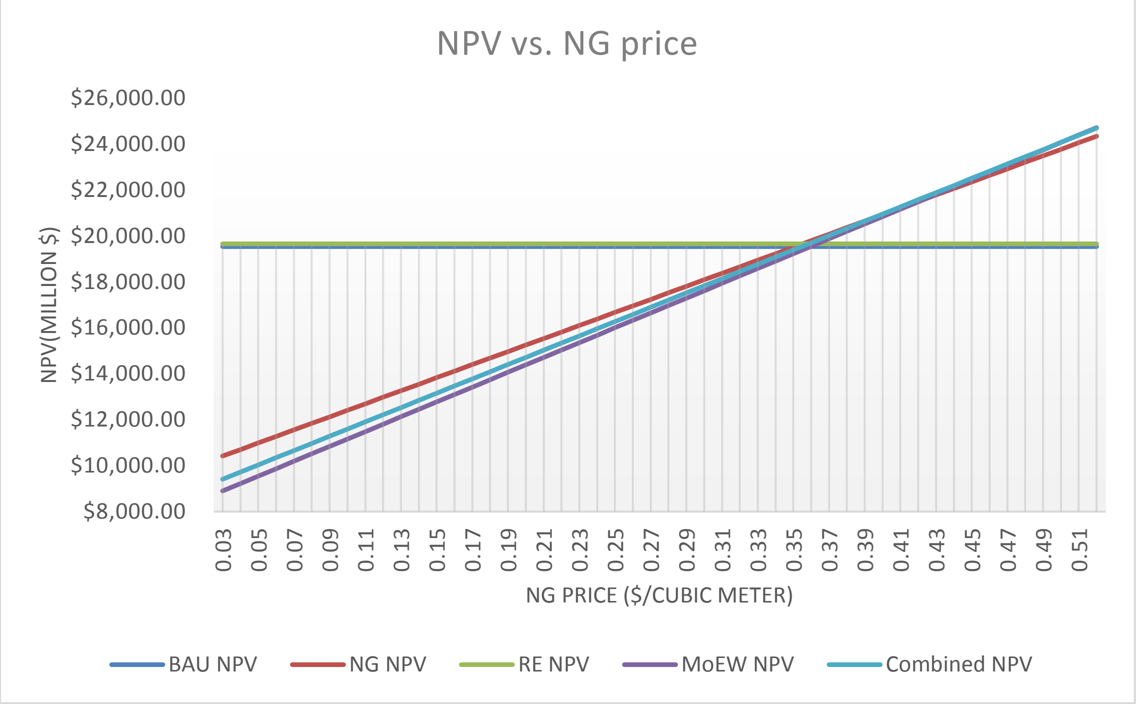

Figure 23: NG Sensitivity Analysis

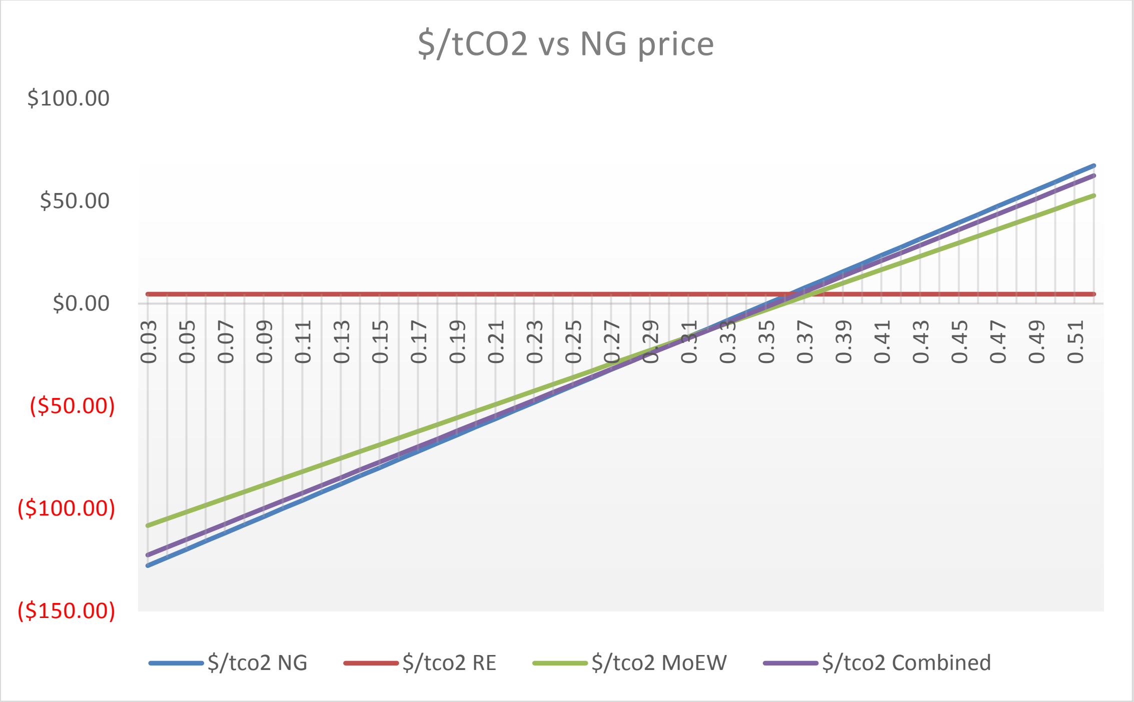

Figure 24: $/tCO2 vs. NG Prices

At last but not least, HFO and Diesel prices are varied according to trends from 1990 up until 2019. The work assumes that both fuels have almost equal prices as both are residuals of the refining process of crude oil. To further indulge on the matter, a ton of heavy fuel oil in January of 2016 had a cost of 290$. During that same date, the ton of crude oil was priced at 285.2$.

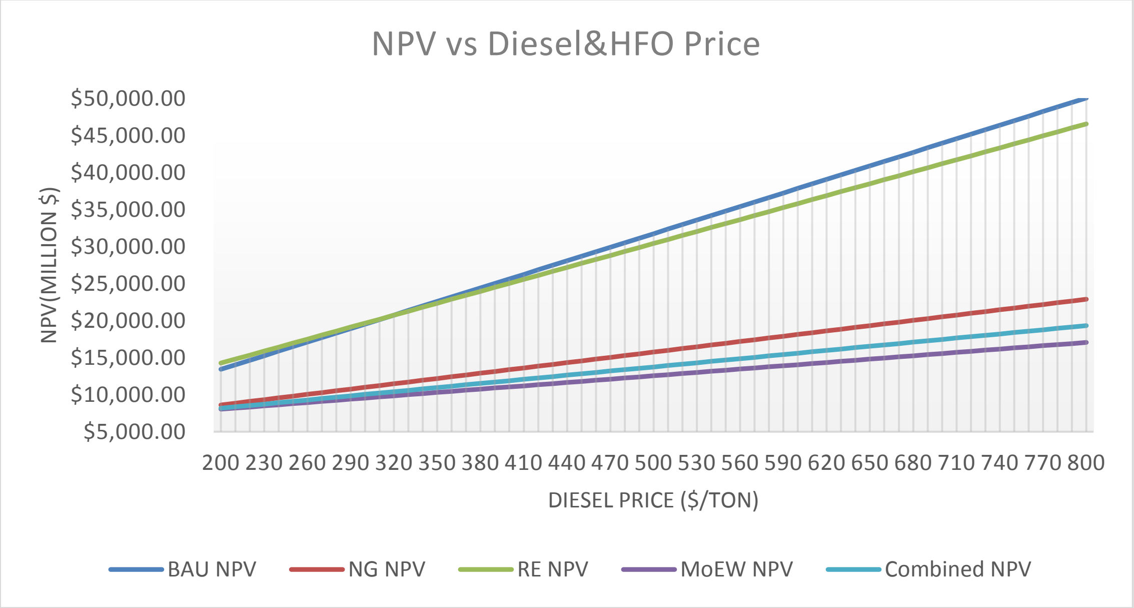

Figure 25: HFO and Diesel Sensitivity Analysis

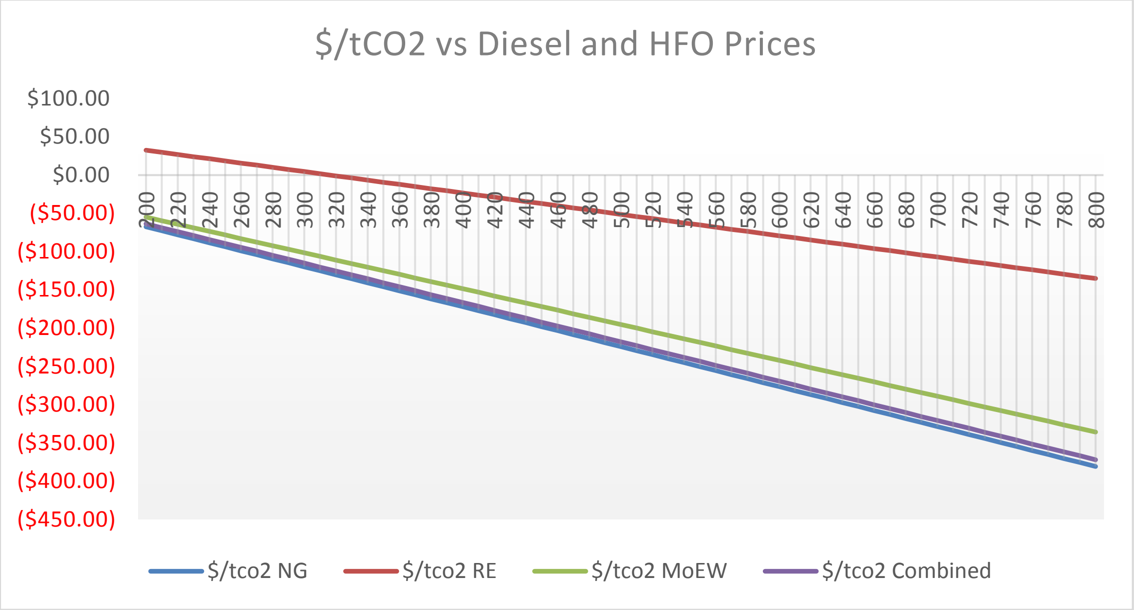

Figure 26: $/tCO2 vs HFO and Diesel Prices

The results show that beyond the price of 325$/ton, all four scenarios become economically feasible, as the BAU scenario, with its heavy reliance on HFO and Diesel, becomes very costly. It is true that all scenarios show an increase in cost with the increase in price, however, some scenarios are affected more by this increase. For instance, the BAU scenario costs increases by 600 million USD whenever the prices of HFO and Diesel rises by 10$/ton. On the other hand, the cost of the NG scenario goes up by 200 million USD for every 10$ increase in fuel price. This is a clear indicator that the BAU scenario heavily relies on HFO and Diesel, which makes it an economically catastrophic approach on all aspects, especially when prices increase beyond 300 USD/ton of fuel. The table below serves as a brief comparison regarding the sensitivity analysis and economic feasibility results.

Table 27: Summary of Feasibility Results

Approach	Observation	Recommendation
Vary Interest Rate	Beyond 4.5% interest, all scenarios are feasible. Only the RE scenario is not feasible below 4.5%	Apply the MoEW scenario as it has the lowest cost throughout all interest rates.
Vary NG Price	Beyond a NG price of 0.35\$/m^3, the RE scenario becomes the feasible option. Below that, the other three approaches are way better.	Apply a combination approach so that spikes in NG price will not drastically affect the cost
Vary HFO and Diesel Prices	Almost all the time, all scenarios are a go-to approach, except for when the price is below325$/ton, then the RE scenario tends to be more costly.	Immediately cease current trends in electricity production and shift to a scenario where reliance is not only on HFO and Diesel.

CHAPTER VI

CONCLUSION

The work presented in this thesis incorporated the economic feasibility of four scenarios that are adopted to reduce GHG emissions in Lebanon and to have a proper generation expansion plan to meet the growing electricity demand. The scenarios are evaluated from a technical and economical perspective.

LEAP software is used to model the Lebanese power sector and build a business as usual scenario up to year 2030. This BAU scenario will be the comparable reference for the four scenarios in this study. All suggested scenarios were modelled, and the corresponding results proved that in terms of GHG reduction, all scenarios are technically and economically feasible, though with different levels. The financial data were extracted from LEAP and then were mathematically manipulated via Excel, to obtain preliminary NPVs. These NPVs were validated with the financial summary in LEAP, where it was highlighted that the cost model adopted in this work matches the one adopted in LEAP. Three out the four scenarios proved to be less costly than the BAU approach under current market conditions.

To inspect further, a sensitivity analysis was carried out in MATLAB, where it was shown that the variation in the interest rates and fuel costs does indeed have an effect on the feasibility of a scenario. The cost of natural gas directly affected the feasibility of the NG, MoEW and COM scenarios, especially at prices greater than 35 cents/cubic meter. On the other hand, diesel and HFO prices influenced the feasibility of the BAU and RE scenario to a greater extent than they did to the three other scenarios. The sensitivity analysis pertaining to the interest rate affected the costs of all scenarios without changing the outcome of whether a scenario is economically viable or not, except for the case of the RE scenario, where low interest rates favor the latter of the BAU approach.

In short, the work gives an extensive overview on how to proceed in the medium term, in order to be able to provide adequate power supply, while maintaining international pledges to reduce GHG emissions by 15%. CO_2 emissions were studied under four scenarios compared to a business as usual approach for the Lebanese power sector, supplemented by an economic feasibility and sensitivity analysis.

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