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ASSESSMENT OF CO2 EMISSIONS FROM THE LEBANESE ENERGY SECTOR: A FIRST STEP TOWARDS CARBON CAPTURE AND STORAGE DEPLOYMENT IN LEBANON

by
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ABSTRACT

OF THE THESIS OF

Nour Fayez Mucharafieh for Master of Science
Major: Energy Studies

Title: Assessment of CO2 Emissions from the Lebanese Energy Sector: A First Step Towards Carbon Capture and Storage Deployment In Lebanon

Climate change is one of the major global challenges causing profound impacts on human and natural systems. The latest Intergovernmental Panel on Climate Change report stated that global Carbon Dioxide (CO_2) emissions must reach net zero levels in 2050 to be able to limit warming to 1.5°C. Carbon Capture and Storage (CCS) is one of the mitigation approaches needed to achieve the global climate targets. CCS involves capturing carbon dioxide (CO_2) from the stationary energy and industrial emission sources, compressing it for transportation and permanently storing it into a carefully selected geological formation. Although CCS is considered the only mitigation approach for deep emissions reductions from the energy and industrial sectors, its deployment in Lebanon is poorly understood.

In this context, this research aims to focus on the first component of the CCS value chain which is carbon source characterization. CO_2 emissions from the energy sector were assessed under the current baseline scenario. In addition, based on the future development trends of influencing factors, Low Emissions Analysis Platform (LEAP) was used to perform scenario analysis for the energy sector, assessing the 2020-2030 planning horizon. The scenario analysis includes modelling and evaluating CO2 emissions under the following potential future scenarios: **(i)** Business-as-usual, **(ii)** proposed energy structure adjustments by the MoEW's Updated Policy Paper for the Electricity Sector (2019), **(iii)** increased share of renewable energy in the Lebanese energy mix, **(iv)** proposed energy structure adjustments by the MoEW's Updated Policy Paper for the Electricity Sector (2019) and increased share of renewable energy, and **(v)** proposed energy structure adjustments by the MoEW's Updated Policy Paper for the Electricity Sector (2019) and different fuel type utilization.

Results showed that the forecasted CO_2 emissions are expected to be the highest, 16,905 thousand tonnes of CO_2 by 2030, under the implementation of proposed energy structure adjustments by the MoEW's Updated Policy Paper for the Electricity Sector (2019), with the use of Diesel Oil instead of Natural Gas in the energy industries (Scenario 4). The implementation of proposed energy structure adjustments, with the use of Natural Gas (Scenario 1), will generate the second highest CO_2 emissions,

around 13,162 thousand tonnes of CO_2 by 2030. Increasing the share of Renewable Energy, coupled with the implementation of the proposed energy structure adjustments, will reduce CO_2 emissions to 10,187 thousand tonnes of CO_2 by 2030. On the other hand, increasing the Renewable Energy share without implementing adjustments in the energy sector will not impact CO_2 generated by power plants, but will reduce the energy deficit and hence the reliance on private power generation.

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CHAPTER I

INTRODUCTION

Climate change is one of the major global challenges causing profound impacts on human and natural systems (Intergovernmental Panel on Climate Change, 2018). The rise in temperature is leading to direct and indirect impacts on natural ecosystems and ecological services, economy and society (Li, Cao, Wei, Wang, & Chen, 2019). According to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, since the mid-20th century, anthropogenic (human-made) impacts have been the major cause of the observed increase in temperature (Intergovernmental Panel on Climate Change, 2014). The sharp increase in global greenhouse gas (GHG) concentrations is accompanied with a rise in global mean temperatures (UNFCCC, 2019). GHG emissions resulting from human activities have reached record levels this century, around 50.8 billion tonnes in 2016, up to 48% increase since 1990. The two major sources of the global GHG emissions are the energy and industrial sectors (United Nations Development Programme & United Nations Framework Convention on Climate Change, 2019).

At the 21st Conference of the Parties (COP 21) in Paris, on 12 December 2015, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) have reached an agreement to limit climate change and to take the necessary measures and investments to control GHG emission and promote a sustainable future. The 197-member agreement aims to control the rise in the world's average surface temperatures to "well below" 2°C above pre-industrial times this century, while "pursuing efforts" for 1.5°C (United Nations Development Programme & United Nations Framework

Convention on Climate Change, 2019). Members of the agreement decided to specify actions, referred to as Intended Nationally Determined Contributions (INDCs), which will be taken to reduce emissions at national levels. However, according to the latest IPCC report, global warming is expected to surpass 1.5°C above pre-industrial levels with the current INDCs under the Paris Agreement. Limiting warming to 1.5°C implies increasing action to achieve carbon neutrality globally around 2050 (Rogelj, 2018). Lebanon has been a Party to the UNFCCC (Law 359/1994), and has ratified the Kyoto Protocol (Law 738/2006) and the Paris Agreement (Law 115/2019 and Decree 5599/2019). In 2020, Lebanon declared its Intended Nationally Determined Contributions where it pledged to reduce Greenhouse Gas (GHG) emissions by 20% by 2030 as an unconditional target (at the current national conditions) and by 31% as a conditional one (with additional international support). Reductions of emissions can be achieved after the successful implementation of mitigation strategies that target the main sources of GHG emissions. In Lebanon, the energy sector is the main contributor to GHG emissions with 63% of emissions, followed by transport (23%) and industry (8%) (MoE/UNDP/GEF, 2019).

Different mitigation strategies and approaches have been globally adopted to reduce emissions, including: (1) improving energy efficiency and promoting energy conservation, (2) promoting use of non-carbon energy sources (i.e. renewable energy), and (3) increasing carbon sequestration (i.e. afforestation, Carbon Capture, Utilization, and Storage)(Leung, Caramanna, Maroto-Valer, & Reviews, 2014). Along with energy conservation and increased use of non-carbon energy sources, carbon capture and storage (CCS) is expected to play a major role in controlling GHG emissions globally (Zaman & Lee, 2013). CCS involves a technology that captures carbon dioxide (CO_2)

from the stationary energy and industrial emission sources, compresses it for transportation and permanently stores it into a carefully selected geological formation (Global CCS Institute, 2019). CCS is viewed as the medium term "bridging technology" for controlling the concentration of CO_2 in the atmosphere (Horssen, 2011), where countries can still utilize fossil fuels while curbing climate change (Kern, Gaede, Meadowcroft, & Watson, 2016). It is considered the only mitigation option for deep emissions reductions from the industrial and power sectors (International Energy Agency, 2016) (Budinis, Krevor, Mac Dowell, Brandon, & Hawkes, 2018). According to the International Energy Agency's (IEA) Sustainable Development Scenario (SDS), CCS shall reduce 9% of the cumulative emissions between 2019 and 2050 (International Energy Agency, 2019). Without CCS the cost of mitigating climate change will increase by 138%, thus meeting the 2°C scenario may not be possible (Intergovernmental Panel on Climate Change, 2014).

The first component of CCS process value chain is carbon sources characterization where the major sources of CO_2 emissions are identified, and the profile of these sources, namely purity and available quantity, are then assessed. Understanding the characteristics of carbon sources is essential for all stages across the CCS process value chain (carbon capture/separation, transportation, and transformation/utilization), where it allows for the optimal selection of the carbon separation technologies and transportation infrastructure, and for the safe and efficient geological sequestration.

Considering the importance of CCS in meeting global climate targets and in light of the limited available research assessing the characteristics of major carbon sources in Lebanon (the first component of CCS value chain), this study assesses CO_2

emissions generated from the major stationary sources in Lebanon, namely the energy sector. Modelling of future CO_2 emission trends was conducted while considering the medium-term (2020-2030) planning horizon.

This study is part of the "CO_2 Capturing and Sequestration in Lebanon – A Full Cycle Assessment and Optimization towards Minimizing the Country Emissions Footprint" project being conducted at the American University of Beirut. The project is funded by King Abdullah University of Science and Technology (KAUST) and Munib and Angela Masri Institute of Energy and Natural Resources. It aims to map the current and expected future CO_2 emission sources in Lebanon, assess optimal capturing and gathering technologies with associated costs, assess and identify potential structures/sites for sequestration with the associated risks and cost, and assess potential use of CO_2 in future potential CO_2 based Enhanced Oil Recovery (EOR).

CHAPTER II

LITERATURE REVIEW

A. General Background

1. CCS Overview

Carbon Capture and Storage is a technology which aims at capturing and storing anthropogenic CO_2 emissions to prevent their release in the atmosphere. In the past decade, CCS has gained additional attention due to its ability to achieve climate targets while fossil fuel use continues to grow (Von Stechow, Watson, & Praetorius, 2011). According to the IPCC, CCS is crucial in the climate change mitigation strategies portfolio, as fossil fuel consumption is continuing to rise and carbon-intensive industries are expected to remain prominent (Intergovernmental Panel on Climate Change, 2014). After many years of technology and project experience, CCS is now a proven technology which is ready for deployment (International Energy Agency, 2016) (Global CCS Institute, 2019). Initially, carbon capture was commercially used in the 1930s to purify natural gas and other gas streams in the industrial sector. In 1972, CO_2 captured from natural gas processing facilities in Texas (United States of America) was piped and, for the first time, injected underground in commercial-scale Enhanced Oil Recovery (EOR) Operations, where CO_2 is injected to boost oil recovery from hydrocarbon reservoirs (Sweatman, Parker, & Crookshank, 2009). Since the early 1970s, more than 260 million tonnes (Mt) of anthropogenic CO_2 emissions has already been captured and stored. In 2019, 51 CCS facilities existed around the world, 19 of which are operational, four are under construction and the remaining are under development. The existing facilities have the current annual capture and storage capacity of around 40 Mt of CO_2 (Global CCS Institute, 2019).

2. CCS Value Chain

The CCS value chain comprises of the following four major stages:

a. Carbon Source Characterization

The first component of the CCS value chain is the carbon source characterization, which includes assessing the profile, namely purity and available quantity, of the major CO_2 sources (Pieri, 2018). The suitability of carbon sources for capture relies on several factors including: CO_2 volume, concentration, partial pressure, geographical location compared to the suitable reservoir and integrated system components (Intergovernmental Panel on Climate Change, 2005). Carbon source characterization is crucial for all the stages across the process value chain. The available quality and volume of CO_2 from the identified sources might impact the technical suitability of emissions for capture and storage, as well as the associated costs. Each carbon source has distinctive characteristics of how CO_2 is produced and it needs specific assessments to facilitate matching with carbon capture technologies (Pieri, 2018). For example, the analysis of flue gas from power plants is important in understanding the chemistry of separated CO_2 streams and the identification of the optimal combination of separation technologies for use (Lee, Keener, & Yang, 2009). Moreover, carbon source characterization is a key impediment for the design of the downstream components of the value chain. For instance, the captured gas stream may have impurities such as water vapor, H_2S, N_2, methane (CH_4), O_2, mercury, and hydrocarbons that may require specific handling or treatment (WRI, 2008). These impurities may impact transportation infrastructure conditions and design parameters mainly due to corrosion, altering of physical properties, density, viscosity and other factors (Pieri, 2018).

On the other hand, when implementing CCS, the upstream analysis of carbon sources is crucial for safe and efficient geological sequestration. According to Last and Schmick (2011), impurities present in CO_2 stream can have an impact on the chemical and physical properties (i.e. density, viscosity, interfacial tension) of the CO_2 and the process through which it interacts with aquifers water and the porous medium in the deep subsurface. Moreover, impurities can affect groundwater aquifers (Lee et al., 2009) and pore water chemistry (Last & Schmick, 2011).

Furthermore, in case the captured CO_2 is to be utilized, known as Carbon Capture Utilization and Storage (CCUS), the main characteristics of the carbon source should be identified for the receiver in order to assess the compatibility of the captured CO_2 with the each receiver's process and to consider any required modifications that might be essential to accept captured CO_2 (Pieri, 2018).

Limited literature is available on carbon source characterization in the context of CCS projects as well as in the general context. The IPCC was first to characterize the major global stationary carbon sources (quality and quantity) (Intergovernmental Panel on Climate Change, 2005). Patricio et al. (2017) identified CO_2 sources for the purpose of linking them to industrial processes where captured CO_2 can be used. They also developed a generic matrix which included the purity and the magnitude of flow of CO_2 gas streams (Patricio, Angelis-Dimakis, Castillo-Castillo, Kalmykova, & Rosado, 2017). Fennell, Florin, Napp, and Hills (2012) assessed the CO_2 characteristics in industrial and power generation sections. Moreover, a review of the CCS value chain, including carbon source characterization was done by (Pieri, 2018) (Karimi & Khalilpour, 2015).

In Lebanon, quantitative assessment of GHG emissions, including CO_2, is reported under the National Communications for the UNFCCC and computed according to the IPCC. Literature related to the characteristics (i.e. carbon content, impurities in the gas stream, flue gas characteristics…) of the stationary carbon sources (i.e. energy industries, industrial processes…) is limited. Moreover, no attempt has been made in the past to study the potential CCS value chain in the Lebanese context.

b. Carbon Capture

The main aim of CO_2 capture is to generate a concentrated stream that can be transported to a CO_2 storage site. CO_2 capture is mainly applied at large stationary sources (i.e. power plants, cement, iron and steel industries), as capturing from small sources (i.e. transportation vehicles, small industries…) is more technically and financially challenging (Intergovernmental Panel on Climate Change, 2005).
The selection of the carbon capture technology is strictly dependent on the carbon source and the type of fuel used. In general, carbon capture is the most studied component of the CCS value chain as it still contributes to 70-80 percent of the total cost of a CCS project.

Depending on where CO_2 is separated from the stream, carbon capture technologies are classified according to the following categories:

i. Pre-combustion capture

Pre-combustion capture involves capturing CO_2 prior the combustion of fuel. This is done through pretreating the fuel with oxygen or air to produce syngas composed of carbon monoxide and hydrogen. For coal, gasification process is undertaken to produce the syngas. The produced syngas then undergoes water gas shift reaction, where the carbon monoxide reacts in a catalytic convertor producing CO_2 and H_2. CO_2 is then separated following absorption processes (Intergovernmental Panel on Climate Change, 2005). Separation using physical sorbents is the most common technique (Leung et al., 2014; Pieri, Nikitas, Castillo-Castillo, & Angelis-Dimakis, 2018).

This capture technology has several advantages: (1) CO_2 is captured before it gets diluted with the combustion air, and (2) the CO_2 stream is at an elevated pressure making the separation process more efficient (Herzog & Golomb, 2004). Pre-combustion capture is commonly applied to Integrated Gasification Combined Cycle (IGCC) power plants running on coal. However, this technology is known to incur a production efficiency loss of 7–8% (Leung et al., 2014).

ii. Post-combustion capture

Post-combustion capture, also referred to as flue gas separation, is the most common capture technology (Leung et al., 2014). It involves capturing CO_2 from the flue gas produced by the combustion of fuel. The exhaust gas is directed into carbon capture equipment. The most common separation method is chemical absorption (Pieri, 2018).

Post-combustion CO_2 capture is challenged by the low levels of CO_2 in combustion flue gases (i.e. 7–14% for coal-fired and as low as 4% for gas-fired), thus increasing the energy requirements and related costs to separate the concentration of CO_2. It has been reported in literature that CO_2 post-combustion capture significantly increases the cost of electricity production (Leung et al., 2014).

iii. Oxy-fuel combustion capture

Oxy-fuel combustion uses pure oxygen instead of air for combustion, producing a flue gas which mainly consists of CO_2, H_2O, particulates and sulfur dioxide. The main advantage of using pure oxygen for combustion is the subsequent reduction in the amount nitrogen oxides in the flue gas, hence improving the separation process. After the removal of particulate matter and sulfur dioxide, significant amounts of CO_2 will remain (80–98% depending on the type of fuel). The relatively high costs of this technology, coupled with the corrosion problems due to the SO_2 concentration in the flue gas, has led to the slow deployment of oxy-fuel capturing technology (Leung et al., 2014; Pieri et al., 2018).

c. Carbon Transportation

Carbon transportation is the process of linking the captured CO_2 to the storage sites. Transportation can be done via pipelines, truck tankers, railroad tankers, or ships. Inland transportation is mostly favored due to its ability to handle large flowrates effectively. On the other hand, when flowrates are small, railroad tankers become the more economically attractive option (Pieri et al., 2018)(MoEW, 2019).

Transportation is lowest cost intensive component of CCS value chain. However, designing a safe, reliable and economically feasible transportation scheme requires careful planning and guidance. For example, when designing pipelines, attention should be given to pipeline integrity, flow assurance, operation requirements and health and safety issues (Peletiri, Rahmanian, & Mujtaba, 2018).

One major issue facing the transportation phase is the presence of impurities in the CO_2 stream, as they might change the pressure and temperature envelope causing instability in the flow (Leung et al., 2014).

d. Carbon Utilization and Storage

After capture and transportation, CO_2 can be utilized (process will be then referred to as Carbon Capture, Utilization and Storage) or stored in geological formations. Although meeting the climate goals relies on geological storage of CO_2, carbon utilization has also an important role to play. Mac Dowell et al. estimate that up to 700 Mt of CO_2 can be utilized by 2050 (Mac Dowell, Fennell, Shah, & Maitland, 2017). CO_2 can have several uses such as refrigerants, fire extinguishing gases, food and beverages…etc.

CO_2 storage involves injecting CO_2 in suitable geological formations. The storage of anthropogenic CO_2 emissions was first used as a GHG mitigation option in 1972. Currently, geological storage of anthropogenic CO_2 evolved from being a concept into an essential mitigation option to achieve global climate goals (Celia & Nordbotten, 2009; Leung et al., 2014; Van der Zwaan & Smekens, 2009). According to IPCC, in order to limit global warming to 1.5 degrees by 2050, around 5000-10000 Mt of CO_2 should be stored daily using CCS (Global CCS Institute, 2019).

CO_2 is compressed into a dense fluid state, referred to as supercritical, prior its injection into the carefully selected geological formation. Storage can be done in several sedimentary basins such as oil fields, depleted gas reservoirs, saline formations and others. In addition, the project must be economically feasible, and environmentally and socially suitable.

3. CCS in the Energy Sector

CO_2 emissions resulting from the energy sector are still rising despite the increasing share of renewable energy in the global energy mix, and the global climate actions. In 2018, energy-related CO_2 emissions increased by 1.7%, showing the sharpest increase in emissions since 2013. Around 80% of the primary energy supply relies on fossil fuels, resulting in 34% of the global GHG emissions (United Nations Development Programme & United Nations Framework Convention on Climate Change, 2019).

Governments are facing the dual challenge of achieving energy security while meeting their Intended Nationally Determined Contributions under the UNFCCC. The three pillars discussed in the literature for the mitigation of GHG emissions from the energy sector include: (1) improving energy efficiency, (2) switching to cleaner energy sources such as renewable energy, and (3) carbon sequestrations such as CCS (Damm & Fedorov, 2008; Huaman & Jun, 2014; Karimi & Khalilpour, 2015; Leung et al., 2014). The first pillar, energy efficiency, is an important action towards managing energy demand and reducing emissions. The second pillar, the use of non-carbon energy sources, is being widely implemented but it is facing techno-economic challenges. The first two pillars stresses on the important of reducing emissions. However, according to the latest IPCC report, reducing the emission levels is not enough to limit global warming. Limiting warming to 1.5°C implies increasing action to achieve carbon neutrality globally around 2050. The report emphasized on the role of the third pillar, namely CCS, to avoid the irreversible impacts of climate change (Rogelj et al., 2018). Researchers believe that the pathway to significantly reduce CO_2 emissions from the power sector is through the implementation of CCS (Deutch & Moniz, 2009; International Energy Agency, 2016; Karimi & Khalilpour, 2015).

CCS is viewed as the medium term "bridging technology" for controlling the concentration of CO_2 in the atmosphere (Horssen, 2011), where countries can still utilize fossil fuels while curbing climate change (Kern et al., 2016).

The global interest in capturing CO_2 from the power industries is gaining momentum. Currently, two facilities out of the 18 large-scale operating CCS facilities around the world capture CO_2 from power plants. Among the 16 planned CCS facilities globally, 10 projects will capture CO_2 from power plants.

B. Overview of the Energy Sector in Lebanon

The energy sector is vital for the development of the country. For years, the Lebanese energy sector has been struggling to ensure consistent electricity supply and quality of service while ensuring a balance in the sector's fiscal budget and the reduction of its deficit. The energy sector is facing several challenges, namely: (1) the tariff structure is fixed at a level less than the average production cost, (2) the power plants are relatively old, having high operational costs and low efficiencies (3) high technical losses on the distribution and transmission networks, (4) high non-technical losses caused by illegal connections on the distribution network, (5) increased demand due to the influx of Syrians displaced, and others. The mentioned challenged contributed to a cumulative debt of 30 billion USD caused by the energy sector (MoEW, 2019).

Under the Administrative Tutelage of the MoEW, the Lebanese energy sector is operated by the Electricité du Liban (EDL), an independent state-owned utility that generates, transmits, and distributes electricity to all Lebanese districts. The energy sector in Lebanon relies on fossil fuel combustion, where the majority of electricity is generated by power plants. Lebanon's primary energy requirements are mainly imported (except of hydropower), knowing that Lebanon does not yet have any energy sources. Despite the presence of several power plants in the country, a large energy deficit exits, which forces the Lebanese population to rely on private energy generation sources. Based on recent data from MoEW, in 2019, the total energy deficit was 10,735 GWh, accounting for 45% of the total demand. In other words, the Lebanese power plants satisfy only 47% of the energy demand in Lebanon.

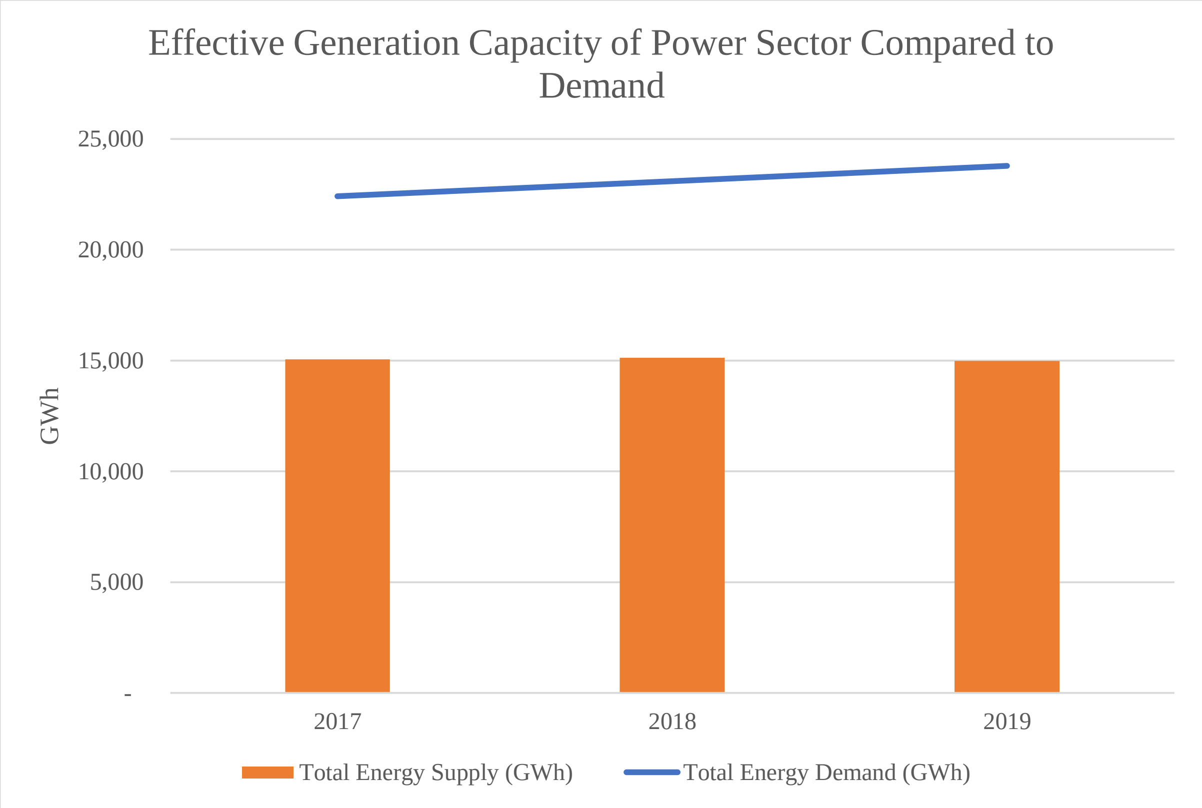

Figure 1: Effective generation capacity of power plants compared to demand

1. Energy Supply

The energy sector in Lebanon relies on fossil fuel combustion, where the majority of electricity is generated by seven power plants operated by EDL. In 2019, hydropower and solar energy contributed to around 3.77% of the total energy mix (including private generators), and 6% of the total energy produced by the public sector in Lebanon. To meet the energy demand, private energy generators are utilized. The MoEW is also relying on power barges in Zouk and Jiyeh, generated around 3018 GWh in 2019 (MoEW, 2020a).

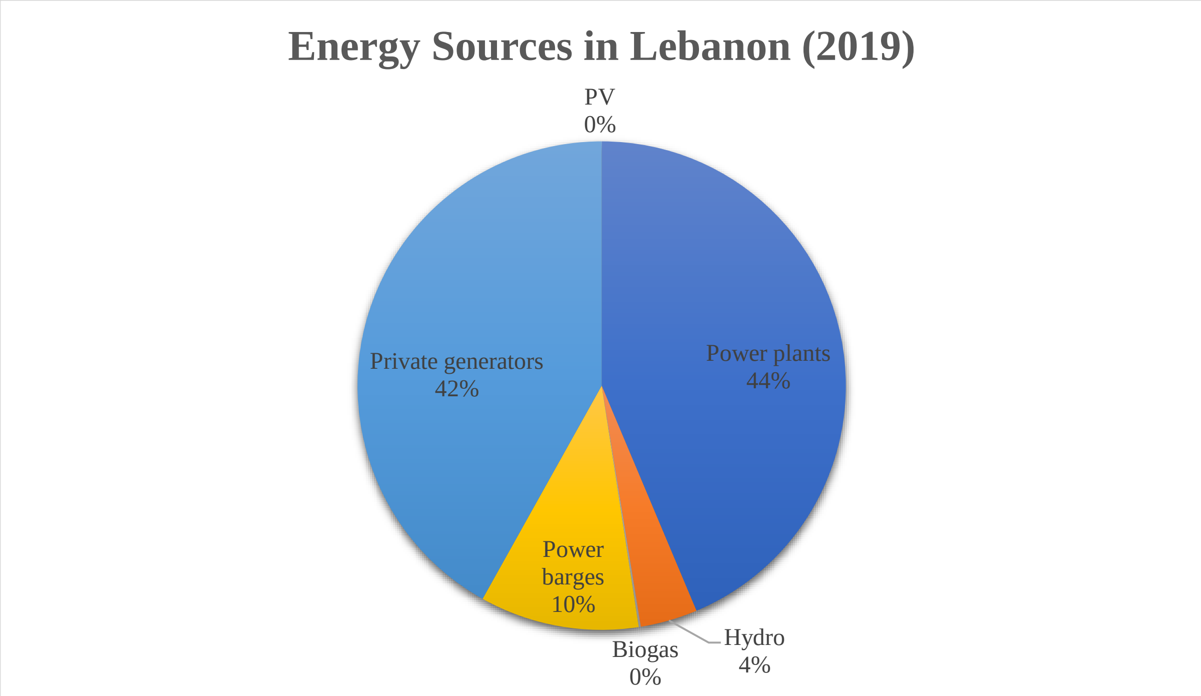

Figure 2: Percent contribution of different energy sources in Lebanon

The power plants in Lebanon run on fossil fuels where three plants operate on Heavy Fuel Oil (HFO), and the remaining four plants operate on diesel oil. Two of the power plants (Deir Aamar and Zahrani) use the Combined Cycle Gas Turbines (CCGT), however they still run on gas diesel oil since Natural Gas is not yet available in Lebanon. Zouk Thermal, Zahrani and Deir Ammar power plants have the highest production in 2019 considering that they have the highest installed capacity. Tyre, Baalbak and Hrayche have the lowest production capacity considering that they have the lowest installed capacity and efficiency, thus they are not operated regularly by EDL.

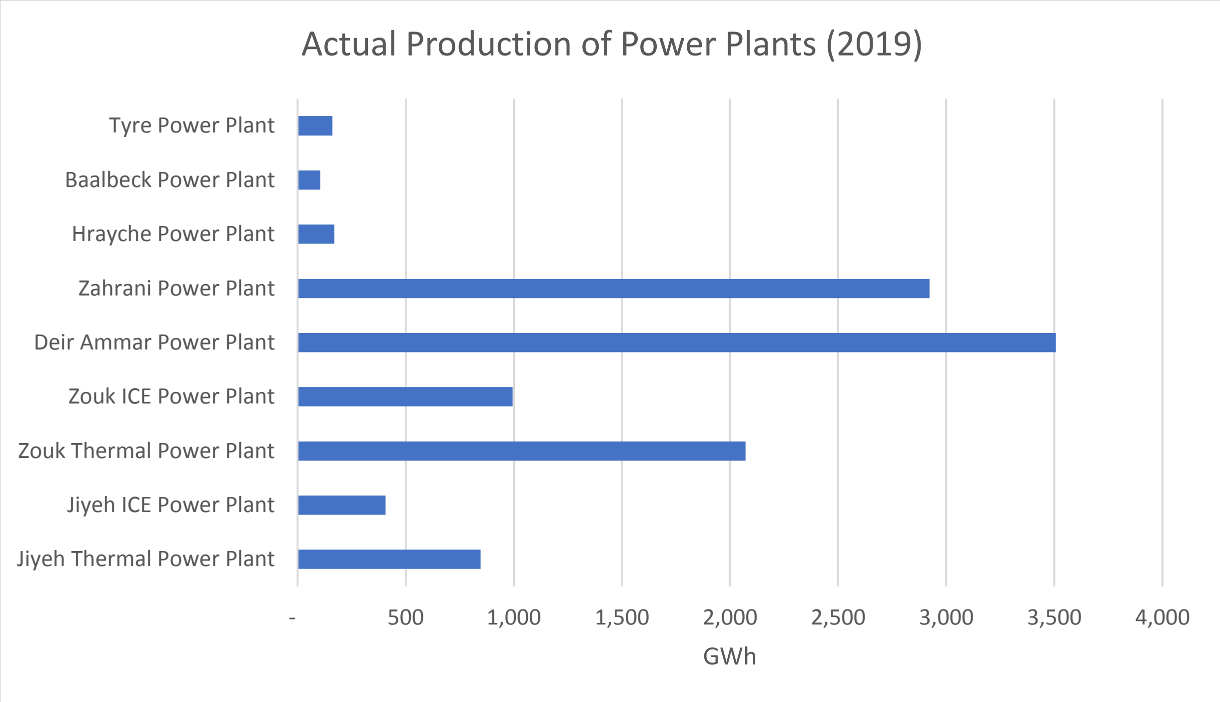

Figure 3: Actual production of power plants in 2019 (MoEW, 2020a)

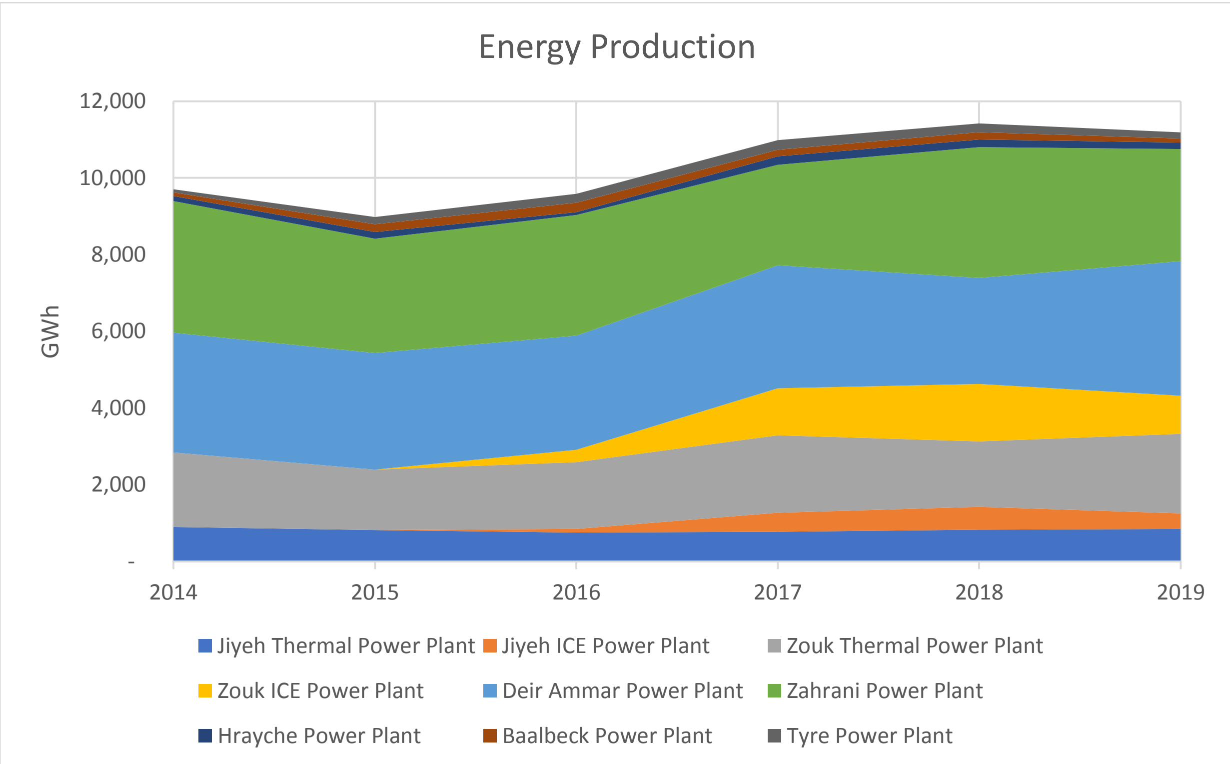

Figure 4: Actual production of power plants (2014-2019)

The table below represents the existing power plants in Lebanon, their installed and effective capacity in 2019 (MoEW, 2020a).

Table 1:Thermal power plants in Lebanon

Name of Facility	Year Established	Fuel Type	Installed Capacity (MW)	Effective Capacity 2019 (GWh)
Zouk Thermal Power Plant	1984-1987	HFO	607	2,072
Jiyeh Thermal Power Plant	1970-1981	HFO	343	847
Zouk ICE Power Plant	2017	HFO/NG	198	995
Jiyeh ICE Power Plant	2017	HFO/NG	78	407
Zahrani CCPP	1998-2001	DO/NG	469	2,924
Deir Ammar CCPP	1998-2002	DO/NG	464	3,508
Baalbeck OCGT	1996	DO	64	105
Tyr OCGT	1996	DO	72	161
Hrayche Power Plant	1983	HFO	35	170

2. Climate Change and the Energy Industry in Lebanon

The energy sector is the main contributor to GHG emissions with 63% of emissions, followed by transport (23%) and industry (8%) (MoE/UNDP/GEF, 2019). The energy sector is the main contributor to GHG emissions contributing to 63% of total GHG emissions. The total emissions from the energy sector were 22,803.26 Gg of CO2 emissions in 2015. Around 38% of the total emissions from the energy sector are emitted from the power plants. In 2020, Lebanon declared its Intended Nationally Determined Contributions where it aims to reduce GHG emissions by 20% by 2030 as an unconditional target (at the current national conditions) and by 31% as a conditional one (with additional international support) (MoE/UNDP/GEF, 2021). Reductions of emissions can be achieved after the successful implementation of mitigation strategies that target the main sources of GHG emissions.

Although around 38% of the emissions are associated with power plants' stationary emissions, the potential of CCS deployment is still not considered as a mitigation option in Lebanon. Relevant literature on CCS deployment in Lebanon is absent.

The management of the energy sector in Lebanon has been previously studied. Fardoun, Ibrahim, Younes, and Louahlia-Gualous (2012) assessed the challenges facing the electricity sector in Lebanon. Karaki, Chaaban, Al-Nakhl, and Tarhini (2002) studied the optimal investment plan of unit additions, without considering renewable energy. On the other hand, Chedid, Chaaban, and Salameh (2001) conducted policy analysis to investigate different capacity expansion scenarios and found out that mitigation measures are cheaper with natural gas rather than renewable energy.

Moreover, R. El-Fadel et al. (2010) studied the power sector through conducting a lifecycle analysis, while focusing on sustainability and considering environmental, economic and reliability dimensions. The study concluded that renewable energy sources are competitive when comparing the levelized cost of electricity. Dagher and Ruble (2011) used LEAP model to assess the alternative scenarios for the electricity sector and their general technical, economic, and environmental implications. The scenarios considered included the baseline scenario, renewable energy scenario and natural gas scenario. Wehbe (2020) also used the LEAP model to evaluate the environmental and economic perspective of increasing the generation capacity of the energy sector in Lebanon.

3. Policy Plan for the Electricity Sector

The MoEW released an updated policy paper for the electricity sector in March 2019 that was endorsed by the Council of Ministries in April 2019. The policy paper has two main general goals: (1) reduce Electricite du Liban's (EDL) financial deficit, and (2) improve electricity supply. The specific objectives of the plan include:

1. "Reduce technical and non-technical losses through the implementation of the transmission and distribution initiatives and the elimination of the non-technical losses.
2. Improve the electricity generation system in terms of efficiency and fuel type utilized, replacement of existing old plants by new ones and the conversion to Natural Gas.
3. Increase tariff rates to cover the electricity generation, transmission and distribution costs"

To meet the mentioned second objective, the plan aims to increase the capacity to meet total demand for electricity provided by EDL, therefore eliminating the need for private diesel generation by 2020. The electricity generation increase plan (2019-2030) is presented in the table below.

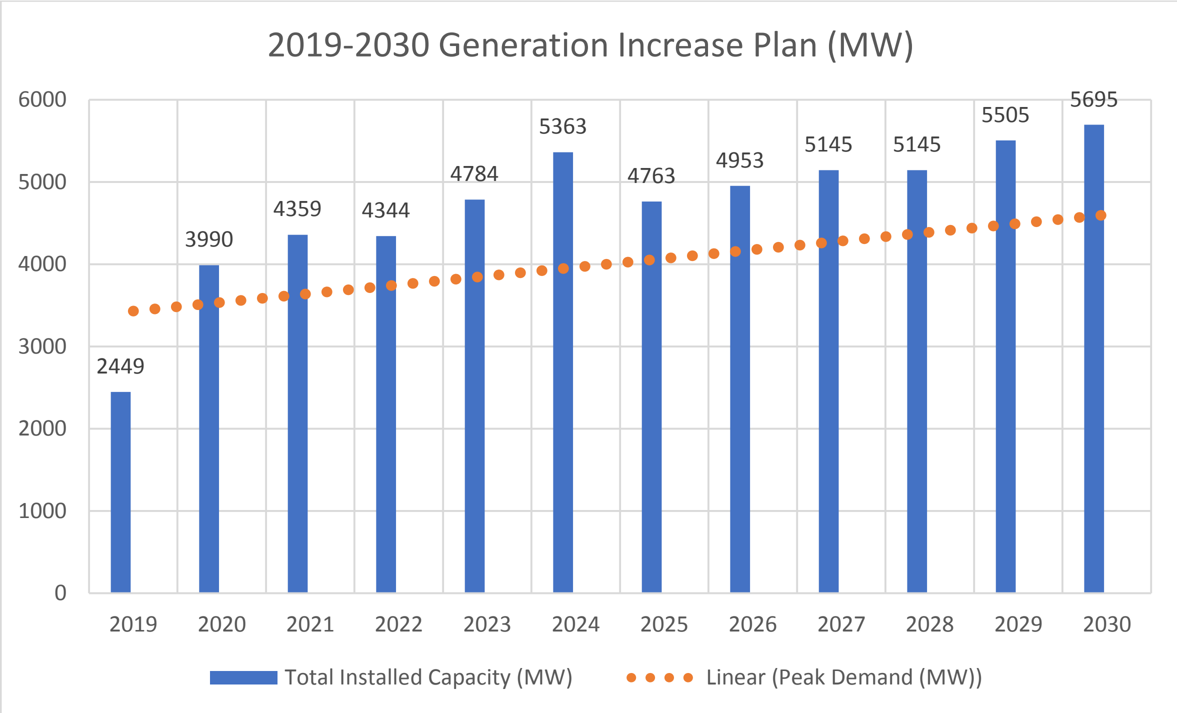

Figure 5: Electricity generation increase plan (MoEW, 2019)

In order to achieve this electricity generation increase target, short-term and a long-term plans were proposed by the Ministry of Energy and Water. For the short-term generation plan, temporary high voltage facilities (i.e. mobile substations) shall be implemented. Using 2019 available electricity capacity as a baseline, an addition 1450 MW capacity should be added in the short-term at specific sites as an initial stage to implementing the long term plan (MoEW, 2019).

On the longer term, 3100 MW of new permanent plants is required. Therefore, three permanent new power plants will be developed in Hrayche, Selaata and Zahrani. In addition, the existing plants of Zouk, Jiyeh and Hrayche will be replaced by new plants at the same locations (MoEW, 2019). The timeline for implementation in presented in Figure 6. Summary of the short and long-term electricity generation plan per industry is represented in Table 2.

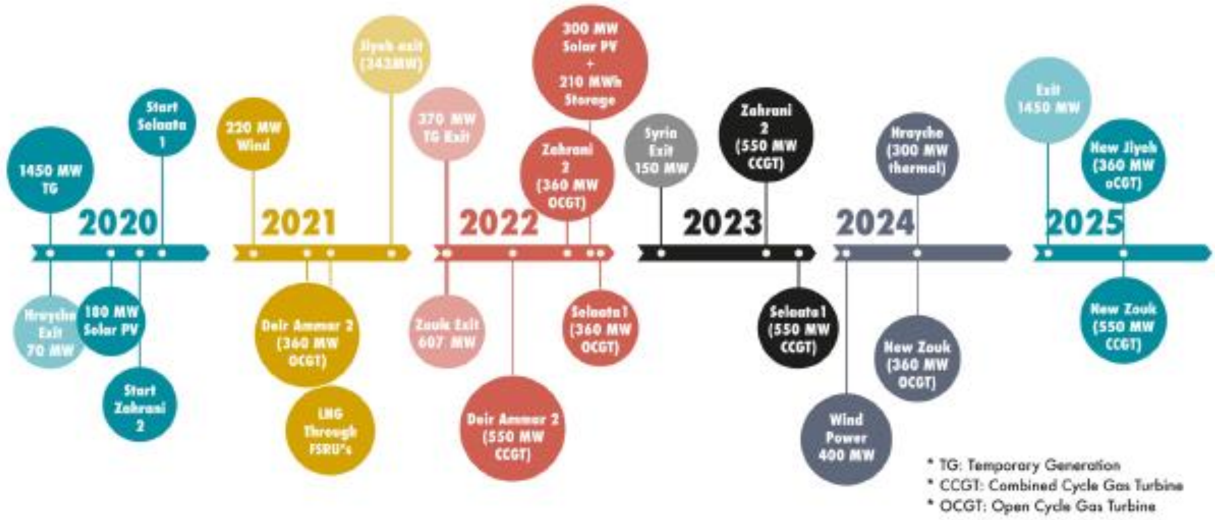

Figure 6: Timeline for Updated Policy Paper for the Electricity Sector implementation

Table 2: Proposed changes per energy industry (MoEW, 2019)

	Existing Capacity (MW)	Short Term (MW)	Long Term (MW)
Deir Ammar	455	450	550
Zahrani	455	700	550
Selaata	-	-	550
Hrayche	35	-	300
Zouk	250	100	550
Jiyeh	180	200	550
Tyre	70	-	70
Total	1445	1450	3120

CHAPTER III

OBJECTIVES

The study aims to focus on the first component of the carbon capture and storage value chain which is carbon source characterization. Considering the importance of characterization of carbon sources for the analysis of CCS technical and financial suitability, this study has the following primary aims:

- Calculate CO_2 emissions generated from each energy industry in Lebanon
- Perform scenario analysis for each energy industry, assessing the 2020-2030 planning horizons. The scenario analysis will include modelling and evaluating CO2 emissions under the following potential future scenarios: (1) Business-as-usual, (2) proposed energy structure adjustments by the MoEW's Updated Policy Paper for the Electricity Sector (2019), (3) increased share of renewable energy in the Lebanese energy mix, (4) proposed energy structure adjustments and increased share of renewable energy, and (5) proposed energy structure adjustments and different fuel type utilization.

CHAPTER IV

PROJECT SIGNIFICANCE AND OUTCOMES

This study will be the first research attempt done in Lebanon to assess any of CCS process value chain components. It will assess CO_2 emissions generated from the energy industries, contributing to at least 38% of total CO_2 emissions in Lebanon in 2015 (MoE/UNDP/GEF, 2019). The study will:

- Update the CO_2 inventory of the energy sector which was lastly updated in 2015.
- Model different scenarios and future trends of CO_2 emissions, thus informing policy making and allowing for the development of strategic environmental planning for Lebanon based on energy analysis and updated data.
- Assess the carbon content and Net Calorific Value of the fuel used in the power sector. Since 1994, Lebanon has been reporting to the UNFCCC using the least accurate IPCC emission calculation methodology (Tier 1). This study will enable Lebanon to improve its reporting mechanism to the UNFCCC where Tier 2 can be used instead on Tier 1.
- Serve as a solid reference for the assessment of other CCS value chain components, namely:
    - Allows for the selection of carbon capture and separation technologies.
    - Serves as basis for assessing the sustainability of potential CCS projects in Lebanon and for feasibility analyses studies.
    - Serves as a reference for assessing safe and efficient geological sequestration or potential utilizations of captured CO_2.

CHAPTER V

METHODOLOGY

The sections below describe the tasks followed to fulfill the objective of the study.

A. Assessment of Baseline Conditions

Assessing the baseline scenario of emissions comprised of three major stages: (1) collecting of activity data, (2) adopting the IPCC guideline and calculating emission factors, and (3) undertaking the CO2 emissions calculation process.

4. 1. Collecting Activity Data

Published data on the fuel consumed, power generated, and emissions from the power plants was gathered to develop an inventory database. The sources of data and the information available are listed in the table below.

Table 3: Sources of published data

Data Sources	Information Available
EDL	EDL Annual Report (2017): includes data on power production and fuel consumed.
Central Administration of Statistics (CAS)	Data on the amounts of fuel consumed and power generated in power plants for the period between 1995 and June 2019.
Ministry of Environment (MoE)	Lebanon's Third Biennial Report and Lebanon's Third National Communication to the UNFCCC reports which includes data on the emissions from the energy sector (1994-2015)

Data Sources	Information Available
Ministry of Energy and Water (MoEW)	Updated Electricity Policy Paper (2019) which forecast includes data on power plant capacities and existing energy demand, as well as forecasted energy demand.

After gathering all published data, meetings were held with several stakeholders, such as Ministry of Environment, Ministry of Energy and Water, EDL, Power Plants Production Managers, etc. to discuss the remaining data required and their relevant data sources.

Considering that all published data sets were from 2015 and before, data was collected again from the primary source of information – Ministry of Energy and Water. Recent data (2015-2019) on the energy demand, fuel consumption and energy generation at each power plant, and fuel quality testing were acquired and used.

5. 2. Adopting the IPCC Guidelines and Calculating Emission Factors

Emissions from stationary combustion are defined within the IPCC sector 1A, stationary combustion in energy industries (1.A.1). The category covered under 1.A.1 energy industries is 1.A.1.a.i electricity generation (1.A.1).

The 2006 IPCC Guidelines present three tiers for estimating emissions from fossil fuel combustion, represented in the table below.

Table 4: IPCC 2006 Guideline tiers for estimating emissions (Intergovernmental Panel on Climate Change, 2006)

	Description
Tier 1	Estimations are done based on the quantity of fuel combusted and average emission factors
Tier 2	Estimations are done based on quantity of fuel combusted and country-specific emission factors. Country-specific emission factors are calculated based on the data on carbon contents in the utilized fuels
Tier 3	Estimations are based on emission models or measurements conducted at individual plant levels

Since 1994, Lebanon has been reporting to the UNFCCC using the least accurate IPCC emission calculation methodology (Tier 1). This study calculated emissions using Tier 2 approach, which will enable Lebanon to improve its reporting mechanism to the UNFCCC. Based on data retrieved by the Ministry of Energy and Water on the quality of fuel used in power plants, country-specific emission factors were calculated following Tier 2 approach of the IPCC. This will enable Lebanon to improve its reporting mechanism to the UNFCCC, knowing that the uncertainty range associated with country-specific emission factors will be less than the uncertainty range of the default emission factors (Intergovernmental Panel on Climate Change, 2006).

To calculate Tier 2 emission factors, the following formula was used:

$$CO_2 \text{ Emissions} = \text{Fuel Consumption}_{\textit{(Metric Tonnes)}} \times \text{Carbon Content}_{\textit{(C \% by mass)}} \times \text{Oxidation Factor} \times (44/12)$$

Fuel consumption values in each power plant were multiplied by the carbon content of the fuel type used, oxidation factor (value of 1) and the ratio of the molecular weight of CO_2 to that of carbon which is 44/12.

The carbon content and NCV for Type A HFO used in Zouk and Jiyeh Thermal power plants were based on 6 fuel test results reported in an Environmental Assessment conducted by AF-Consult Switzerland Ltd, a third party consultancy firm, in 2018. For Type B HFO, 7 fuel test results, reported in the period between 2015 and 2020, were used for the calculation of emission factors. As for Diesel Oil, 15 fuel test results were collected from Deir Ammar Power Plant for the period 2012-2020.

Table 5: Emission factors per power plant

	Fuel Type	**Average fuel consumption (2019)**	**Net calorific value**	**Total energy**	**% Carbon content**	**Carbon content**	**Oxidation factor**	**Molecular weight**	**CO2 Emission Factor**	
Unit		*kg*	*MJ/kg*	*TJ*	*%weight*	*kg/TJ*			*kg CO2/Kwh*	*ton CO2/TJ*
Jiyeh Thermal Power Plant	HFO- Type A	302,783,000	38.80	11,747.98	84.70	21,830	1	3.667	1.11	80.04
Jiyeh ICE Power Plant	HFO- Type B	79,775,000	40.96	3,267.58	82.00	20,020	1	3.667	0.59	73.40
Zouk Thermal Power Plant	HFO- Type A	578,131,000	39.36	22,755.24	85.80	21,799	1	3.667	0.88	79.93
Zouk ICE Power Plant	HFO- Type B	198,003,000	40.96	8,110.20	82.00	20,020	1	3.667	0.60	73.40
Deir Ammar Power Plant	DO	595,883,000	42.81	25,511.61	86.36	20,171	1	3.667	0.54	73.96
Zahrani Power Plant	DO	579,468,000	42.81	24,807.03	86.36	20,173	1	3.667	0.63	73.97
Hrayche Power Plant	HFO	54,683,650	38.80	2,121.73	84.70	21,830	1	3.667	1.00	80.04
Baalbeck Power Plant	DO	28,368,000	42.81	1,214.43	86.36	20,173	1	3.667	0.86	73.97
Tyre Power Plant	DO	48,022,000	42.81	2,055.82	86.36	20,173	1	3.667	0.94	73.97

The table below shows the comparison between the default and country-specific emission factors:

Table 6: Comparison between default and country-specific emission factors

	Default Emission Factor (tonnes/TJ)	Calculated Country – Specific Emission Factors (tonnes/TJ)
Gas Diesel Oil	74.1	73.96
Heavy Fuel Oil	77.4	73.40 - 80.04

6. 3. Calculating CO_2 Emissions

After calculating the emission factors, CO2 emissions will be calculated using the following formula:

$$\text{Emissions}_{GHG,\,fuel} = \text{Fuel Consumption}_{fuel} \times \text{Emission Factor}_{GHG,\,fuel}$$

Where:

- Emissions $_{GHG,\,fuel}$ = emissions of a given GHG by type of fuel (kg GHG)
- Fuel Consumption $_{fuel}$ = amount of fuel combusted (TJ)
- Emission Factor $_{GHG,fuel}$ = default emission factor of a given GHG by type of fuel (kg gas/TJ).
-

B. Assessment of Potential Scenarios

To perform the required scenario analysis, the Low Emissions Analysis Platform (LEAP), which is an accounting and scenario-based modeling platform developed by the Stockholm Environment Institute, will be used. The model is user friendly and has been widely used for energy policy and analysis. According to Stockholm Environment Institute, at least 37 countries have used LEAP to help develop their INDC submitted to the UNFCCC's Paris climate conference in 2015 (Stockholm Environment Institute, 2019). Many researchers have been using this model. In Lebanon, the researchers who used it include M. El-Fadel, Chedid, Zeinati, and Hmaidan (2003), (Ghaddar & Mezher, 1999), Chedid et al. (2001), Dagher and Ruble (2011), and others. The model has been also used in other countries such as Malaysia (Safaai, Noor, Hashim, Ujang, & Talib, 2011), Thailand (Mulugetta, Mantajit, & Jackson, 2007), Vietnam (Kumar, Bhattacharya, & Pham, 2003), China (Cai, Wang, Wang, Zhang, & Chen, 2007) and other countries.

In general, projecting GHG emissions can follow bottom-up or top-down approaches. The top-down approach follows economic interlinkages while the bottom-up involves a detailed assessment per specific technology. This study will use the LEAP model which follows bottom-up approach. The scenario analysis/projections will be based on 2019 data and will consider 2020-2030 planning horizons. The conducted scenario analysis is subject to uncertainty due to the unstable social, economic and political situation in Lebanon, which was not accounted for in this research.

This study modelled and evaluated five potential future scenarios for Lebanon's energy sector. The scenarios studied include:

1. Business-as-Usual (BAU) Scenario

The BAU scenario assumed that the energy demand will continue to increase, with the absence of additional investments in the national energy generation capacity and climate mitigation options. The BAU scenario was based on the following assumptions:

- Investments in the generation capacity of power plants will stay the same.
- Technical losses in the public distribution grid will be 12.93%, based on MoEW forecasts.
- Technical losses in the distribution grid of power generators is the same as the public one, which is estimated to be equal 12.93%.
- Demand growth of 3% per year and an exceptional 5.24% decrease in 2022, based on MoEW forecasts.
- Based on a feasibility study conducted by the MoEW, decrease in power output per year: 0.13% for Zouk and Jiyeh Thermal power plants; 0.01-0.13% for Deirm Ammar and Zahrani; 0.0006% for Zouk and Jiyeh ICE power plants; and 0.13% for Tyre, Baalbak, and Hrayche power plants.
- Based on a feasibility study conducted by the MoEW, decrease in efficiency per year: 0.06% for Zouk and Jiyeh Thermal power plants; 0.02% for Deir Ammar and Zahrani; 0.001% for Zouk and Jiyeh ICE power plants; and 0.06% for Tyre, Baalbak, and Hrayche power plants.
- Zouk, Jiyeh and Hrayche power plants will continue to rely on Heavy Fuel Oil; and Deir Ammar, Zahrani, Baalbak and Tyre power plants will continue to rely on Diesel oil.
- Private power generators will continue to satisfy the Lebanese population unmet energy demand.

- The availability of each power plant is the ratio of energy produced by the actual capacity and energy that the reference unit power could have produced during the same period. The table below presents the percent availabilities of power plants.

Table 7: Percent availabilities of power plants

Availability (%) of Power Plants												
	2019	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Jiyeh Thermal Power Plant	28.19	28.15	28.12	28.08	28.04	28.01	27.97	27.93	27.90	27.86	27.82	27.79
Jiyeh ICE Power Plant	59.61	59.61	59.61	59.61	59.61	59.61	59.61	59.61	59.61	59.60	59.60	59.60
Zouk Thermal Power Plant	38.97	38.92	38.87	38.82	38.77	38.72	38.67	38.62	38.57	38.52	38.47	38.42
Zouk ICE Power Plant	57.34	57.34	57.34	57.34	57.34	57.34	57.34	57.34	57.34	57.34	57.33	57.33
Deir Ammar Power Plant	86.30	86.18	86.11	86.05	86.00	85.97	85.96	85.90	85.86	85.81	85.77	85.73
Zahrani Power Plant	71.16	71.07	71.01	70.97	70.92	70.89	70.89	70.84	70.80	70.77	70.73	70.70
Hrayche Power Plant	55.39	55.32	55.25	55.17	55.10	55.03	54.96	54.89	54.82	54.75	54.67	54.60
Baalbeck Power Plant	18.65	18.63	18.60	18.58	18.56	18.53	18.51	18.48	18.46	18.43	18.41	18.39
Tyre Power Plant	25.52	25.49	25.46	25.42	25.39	25.36	25.32	25.29	25.26	25.22	25.19	25.16

2. *Scenario 1: Proposed Energy Structure Adjustments by the MoEW's Updated Policy Paper for the Electricity Sector – 2019*

This scenario was based on the proposed energy structure adjustments by the MoEW's Updated Policy Paper for the Electricity Sector – 2019, where emissions according to the new plan of increasing the electricity generation capacity were modelled. Scenario 1 was based on the following assumptions:

- Demand growth of 3% per year and an exceptional 5.24% decrease in 2022, based on MoEW forecasts.
- Energy structure adjustments will start in Year 2021 and will include:
  - Decommissioning of existing Hrayche, Jiyeh Thermal (343 MW), and Zouk Thermal (607MW)
  - Addition of 1450 MW Temporary Generation (Power Barges), and then decommissioning starting 2023 till 2027
  - Addition of Deir Ammar 2 OCGT (360 MW), and Deir Ammar 2 CCGT (550 MW CCGT) power plants
  - Addition of Zahrani 2 CCGT (550 MW CCGT) and Zahrani 2 OCGT (360MW) power plants
  - Addition of Selaata 1 OCGT (360MW) and Selaata 1 CCGT (550 MW) power plants
  - Addition of New Zouk OCGT (360MW) and New Zouk CCGT (550MW)power plants
  - Addition of new Hrayche thermal power plant (300 MW)
  - Addition of Jiyeh OCGT Power Plant (360MW OCGT), and Jiyeh CCGT (550MW CCGT) power plants
  - Addition of: 480 MW solar and 620 MW wind
- In 2022, the technical losses are expected to be reduced to 7.83% of the total generation capacity and will remain constant till 2030, based on MoEW forecasts.
- All power plants will be operated using Natural Gas

- Emission factors will be based on Tier 1 approach by the IPCC, where default emission factors were used.
- Efficiency of new CCGT power plants is assumed to be equal to 52.5%, while the availability is 92%.
- Efficiency of new OCGT power plants is assumed to be equal to 42%, while the availability is 90%.
-

3. *Scenario 2: Increased Share of Renewable Energy in the Lebanese Energy Mix*

This scenario considers the increase in the share of renewable energy in the Lebanese energy mix, namely the provisions in the National Renewable Energy Action Plan (NREAP), which is expected to be released by MoEW's Lebanese Center for Energy Conservation (LCEC) later in 2021. Considering that the NREAP is still not released, this study used the International Renewable Energy Agency (IRENA) report which, according to the LCEC, the NREAP will be based on. The IRENA report specified the expected increase in the capacity of each renewable energy source, however didn't specify how the percent share will increase per year. In the scenario, the following was assumed:

- Demand growth of 3% per year and an exceptional 5.24% decrease in 2022, based on MoEW forecasts.
- Installed capacities of RE by 2030 are: 2000 MW wind, 601 MW hydropower, 3000MW PV and 13 MW biogas.
-

4. *Scenario 3: Proposed Energy Structure Adjustments and Increased Share of Renewable Energy*

In Scenario 3, CO_2 emissions are modelled while combining Scenario 1 - the energy structure adjustments proposed by the MoEW Policy Paper for the Electricity Sector 2019 and Scenario 2 - the increased share of RE proposed by the IRENA report (2020). In the scenario, the following was assumed:

- Demand growth of 3% per year and an exceptional 5.24% decrease in 2022, based on MoEW forecasts.
- Energy structure adjustments will start in Year 2021 and will include:
    - Decommissioning of existing Hrayche, Jiyeh Thermal (343 MW), and Zouk Thermal (607MW)
    - Addition of 1450 MW Temporary Generation (Power Barges), and then decommissioning starting 2023 till 2027
    - Addition of Deir Ammar 2 OCGT (360 MW), and Deir Ammar 2 CCGT (550 MW CCGT) power plants
    - Addition of Zahrani 2 CCGT (550 MW CCGT) and Zahrani 2 OCGT (360MW) power plants
    - Addition of Selaata 1 OCGT (360MW) and Selaata 1 CCGT (550 MW) power plants
    - Addition of New Zouk OCGT (360MW) and New Zouk CCGT (550MW)power plants
    - Addition of new Hrayche thermal power plant (300 MW)
    - Addition of Jiyeh OCGT Power Plant (360MW OCGT), and Jiyeh CCGT (550MW CCGT) power plants

    - Addition of: 480 MW solar and 620 MW wind

- In 2022, the technical losses are expected to be reduced to 7.83% of the total generation capacity and will remain constant till 2030, based on MoEW forecasts.
- Installed capacities of RE by 2030 are: 2000 MW wind, 601 MW hydropower, 3000 MW PV and 13 MW biogas.
- All power plants will be operated using Natural Gas
- Emission factors will be based on Tier 1 approach by the IPCC, where default emission factors were used.
-

5. *Scenario 4: Proposed Energy Structure Adjustments and Different Fuel Type Utilization*

Due to the remaining uncertainty related to the supply of natural gas in Lebanon, this scenario assumes the use of diesel oil in the power plants in Lebanon, taking into account the proposed energy structure adjustments proposed by the MoEW's Updated Policy Paper for the Electricity Sector - 2019.

Scenario 4 was based on the following assumptions:

- Demand growth of 3% per year and an exceptional 5.24% decrease in 2022, based on MoEW forecasts.
- Energy structure adjustments will start in Year 2021 and will include:
    - Decommissioning of existing Hrayche, Jiyeh Thermal (343 MW), and Zouk Thermal (607MW)
    - Addition of 1450 MW Temporary Generation (Power Barges), and then decommissioning starting 2023 till 2027

- Addition of Deir Ammar 2 OCGT (360 MW), and Deir Ammar 2 CCGT (550 MW CCGT) power plants
- Addition of Zahrani 2 CCGT (550 MW CCGT) and Zahrani 2 OCGT (360MW) power plants
- Addition of Selaata 1 OCGT (360MW) and Selaata 1 CCGT (550 MW) power plants
- Addition of New Zouk OCGT (360MW) and New Zouk CCGT (550MW)power plants
- Addition of new Hrayche thermal power plant (300 MW)
- Addition of Jiyeh OCGT Power Plant (360MW OCGT), and Jiyeh CCGT (550MW CCGT) power plants
- Addition of: 480 MW solar and 620 MW wind

- In 2022, the technical losses are expected to be reduced to 7.83% of the total generation capacity and will remain constant till 2030, based on MoEW forecasts.
- All power plants will be operated using Diesel Oil
- Emission factors will be based on Tier 1 approach by the IPCC, where default emission factors were used.

C. Assessment of Shadow Price of Carbon

In Lebanon, Carbon Tax or Shadow Price of Carbon (SPC) are absent. SPC are adopted in numerous countries to incentivize the use of renewable energy and energy efficiency. In this study, the SRC was assumed to be in the range of US$40-80 per ton of CO2 in 2020, rising to US$50-100 per ton of CO2 by 2030, consistent with the High-

Level Commission on Carbon Prices (World Bank, 2017). The High-Level Commission on Carbon Prices concluded that the mentioned ranges will allow for the achievements of the Paris Agreement, given that a supportive policy environment is present.

CHAPTER VI

RESULTS AND DISCUSSION

A. Baseline Assessment

After the collection of activity data, Tier 2 approach of the IPCC Guidelines was used to calculate country-specific emission factors for each power plant in Lebanon. In Lebanon, regular testing of carbon content and net calorific value of the fuel received are absent. Only few fuel sampling test results are available with values related to the percent by mass of carbon and net calorific value. After calculating country-specific emission factors, results showed that the difference between Tier 2 country specific emission factors and Tier 1 default emission factors is less than 1%.

The results of the baseline assessment showed that in 2019, the total CO_2 generated by the Power Plants is estimated to be 7,727,838 tonnes of CO_2. Zouk Thermal, Zahrani and Deir Ammar Power Plants generate around 72% of the total CO_2 emissions from the energy industries in Lebanon.

Table 8: Total CO_2 emissions per power plant in Lebanon (2019)

Power Plant	Fuel Type	Installed Capacity (MW)	Actual Production (GWh)	Fuel Consumption (tonnes)	Emission Factor (kg CO_2/kWh)	Total CO_2 Emissions (tonnes CO2/year)
Jiyeh Thermal Power Plant	HFO-Type A	343	846.99	302783	1.11	940,343
Jiyeh ICE Power Plant	HFO-Type B	78	407.29	79775	0.59	239,857
Zouk Thermal Power Plant	HFO-Type A	607	2072.37	578131	0.88	1,818,800
Zouk ICE Power Plant	HFO-Type B	198	994.52	198003	0.60	595,329
Deir Ammar Power Plant	DO	464	3507.59	595883	0.54	1,886,883

Zahrani Power Plant	DO	469	2923.74	579468	0.63	1,834,905
Hrayche Power Plant	HFO	35	169.82	29469	1.00	169,829
Baalbeck Power Plant	DO	64	104.57	28368	0.86	89,828
Tyre Power Plant	DO	72	160.96	48022	0.94	152,063

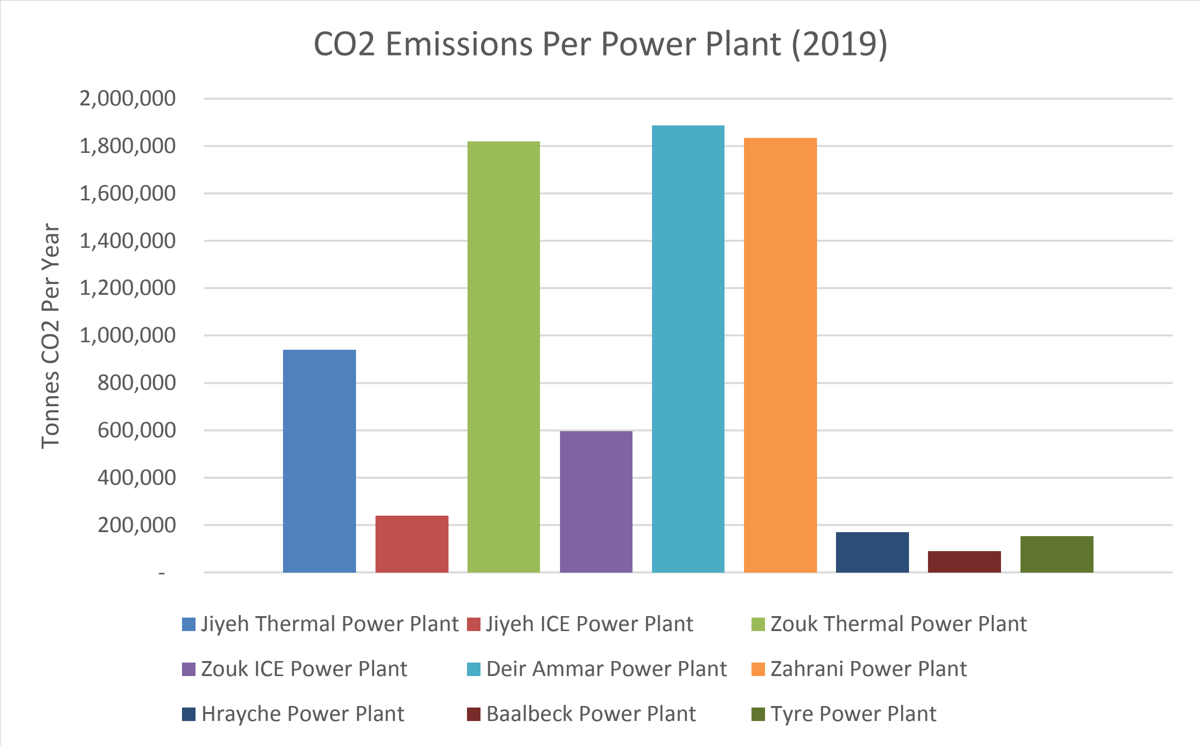

Figure 7: CO_2 emissions per power plant

Aligned with the 2015 results of the National Greenhouse Gas Inventory Report and Mitigation Analysis for the Energy Sector in Lebanon (MoE/UNDP/GEF, 2015), Zouk Thermal, Zahrani, and Deir Aamar power plants were the highest emitters of CO2 emissions in 2019, considering that they have the largest installed capacity, electricity generation and fuel consumption. However, the three least efficient power plants with the highest CO_2 emissions intensity were: Hrayche, Tyre and Jiyeh Thermal power plants (Figure 9 and Figure 10).

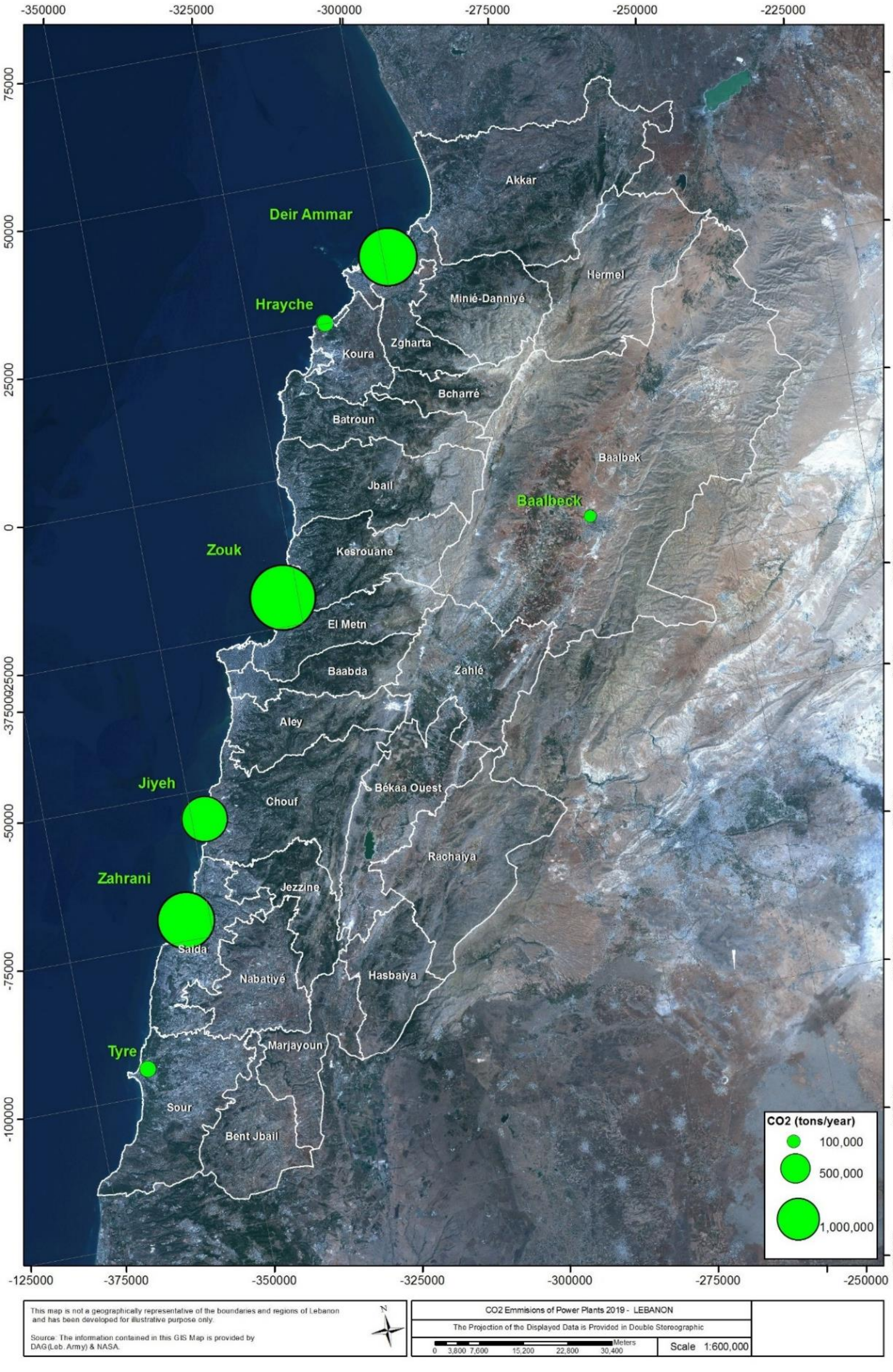

Figure 8: Map of CO2 emissions from the power sector in 2019

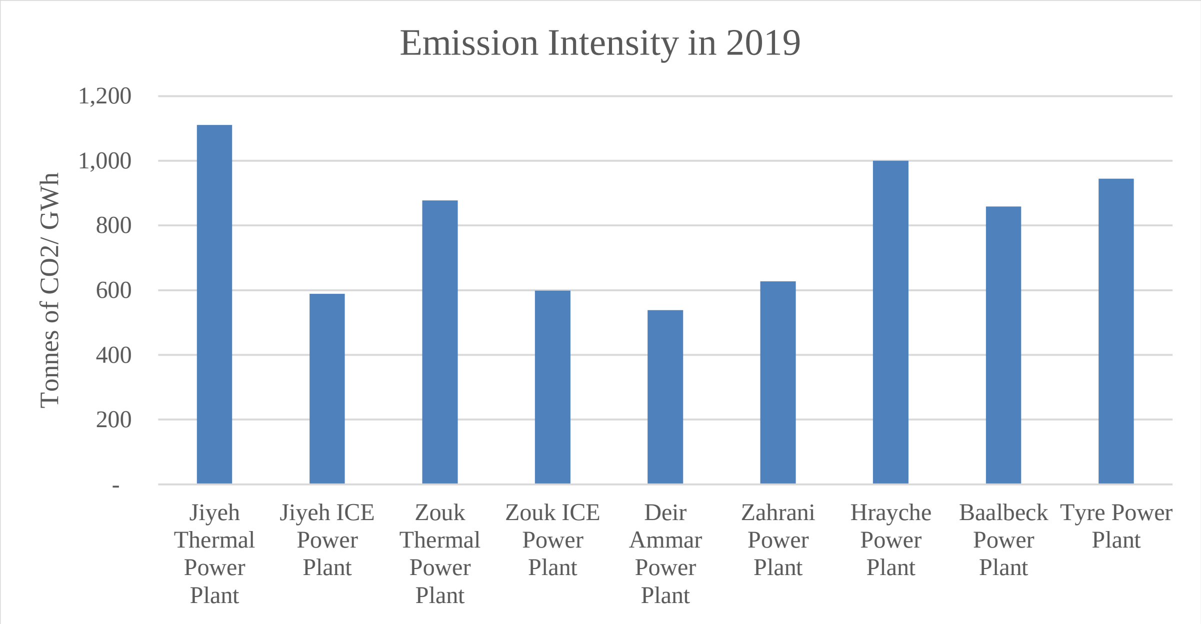

Figure 9: Emissions intensity of power plants in Lebanon

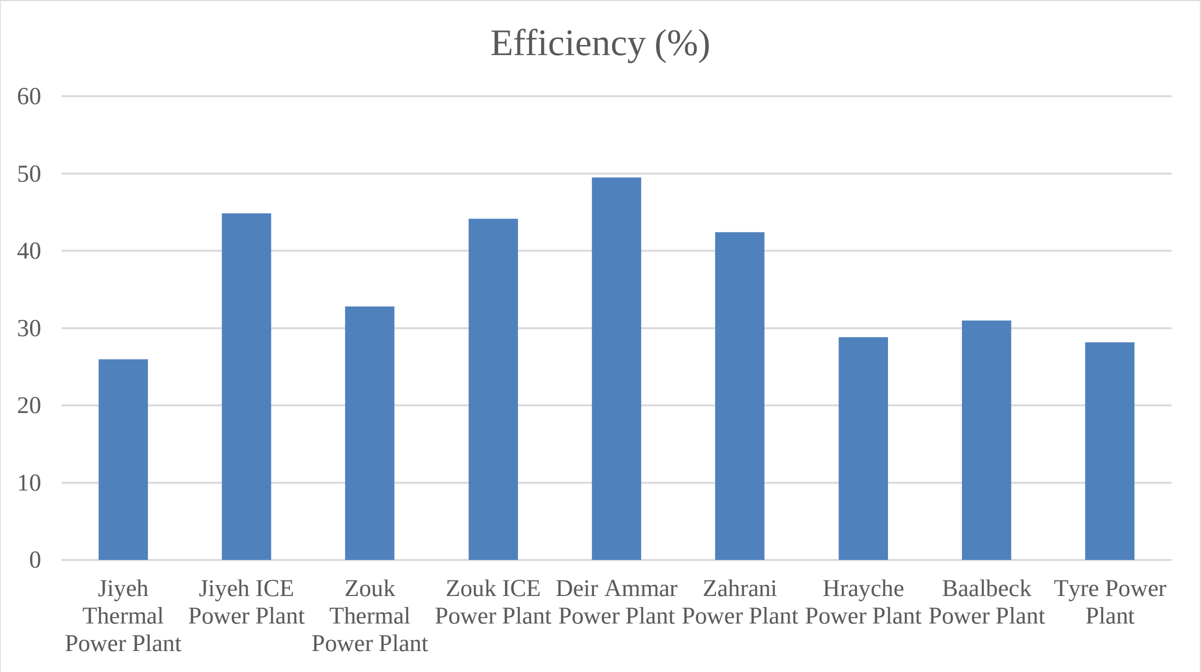

Figure 10: Percent efficiency of power plants in Lebanon

B. Scenario Analysis

1. Business-As-Usual Scenario

A Business-as-Usual (BAU) scenario aims to support the decisions of policy makers by informing them about how emissions will likely change temporally under certain given conditions. BAU scenarios aim to provide policy makers with the necessary support to design or amend energy and climate change policy and investment decisions.

In this study, the BAU scenario assumed that the energy demand will continue to increase, with the absence of additional investments in the national energy generation capacity and climate mitigation options. The baseline information collected previously was used to develop the BAU scenario which projects the emissions using the data of Year 2019.

The BAU scenario was developed under the assumption of a demand growth of 3% per year and an exceptional 5.24% decrease in 2022 (Figure 11). According to MoEW Electricity Policy Paper (2019), the demand in 2022 was expected to decrease by 8%, due to a projected increase in electricity supply and tariff rates. However, due to the uncertainty related to the increase of energy supply, the decrease in demand in 2022 was revised by the MoEW to be 5.24% instead of 8%.

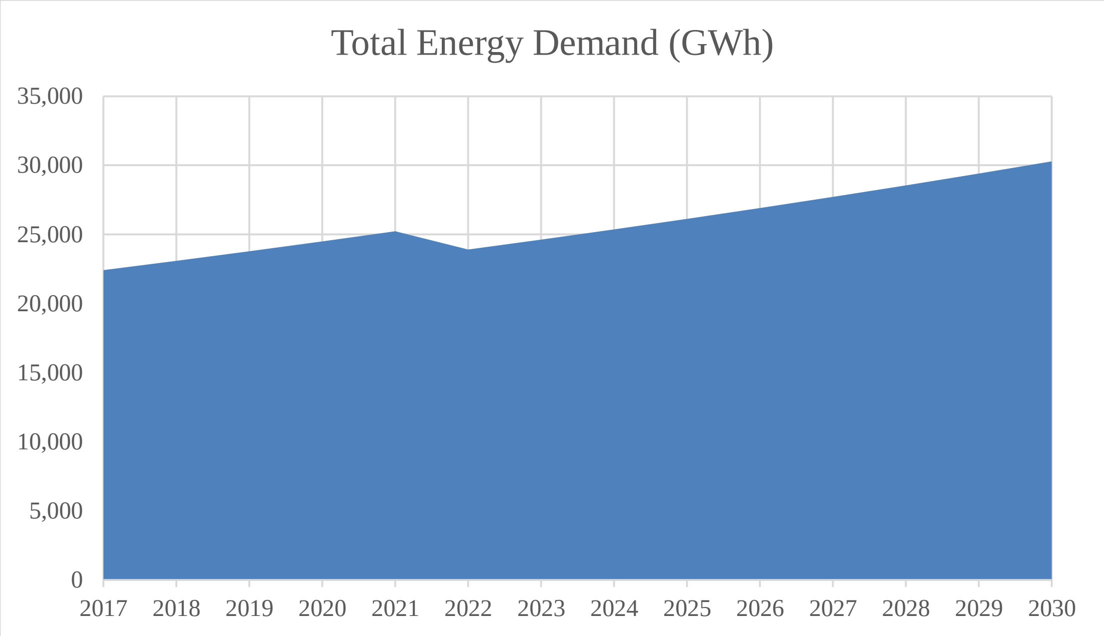

Figure 11: Forecasted growth in energy demand

In the BAU scenario, it was estimated that the efficiency and power output for each power plant will be reduced due to the Wear and Tear (W&T) of equipment. Based on a feasibility study conducted by the MoEW, W&T was estimated for each power plant, depending on the technology adopted. The percent decrease in power output and efficiency of OCGT power plants were assumed to be the same as thermal power plants.

Table 9: Expected decrease in power output and efficiency of power plants per year

Technology	**Decrease in Power Output per year**	**Decrease in Efficiency per year**
Thermal Power Plants	0.13%	0.06%
CCGT	0.01-0.13%	0.02%
Reciprocating Engines	0.0006%	0.001%

The technical losses on the transmission and distribution grids were also included in the BAU scenario. According to the Electricity Policy paper (2019)

(MoEW, 2019), the technical losses on the grid are estimated to be 12.93%. The BAU was developed under the assumption that the technical losses will remain the same in studied period. Under the above assumptions, the energy generation capacity of the power plants will increase by around 1% in 10 years.

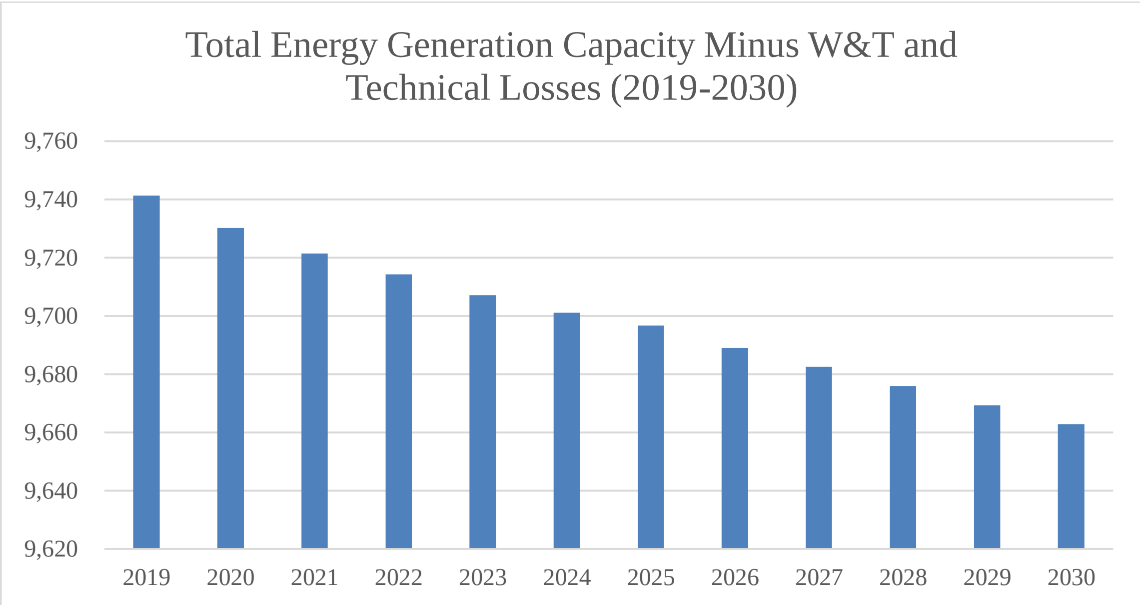

Figure 12: Projected energy generation capacity (2019-2030)

After applying the specific emission factors, CO_2 emissions under the BAU were forecasted. Results show that despite the decrease in the energy output of the power plants, the total CO_2 emissions were increasing due to the increase in the use of private generators and temporary energy sources. CO2 emissions from power plants will not significantly change.

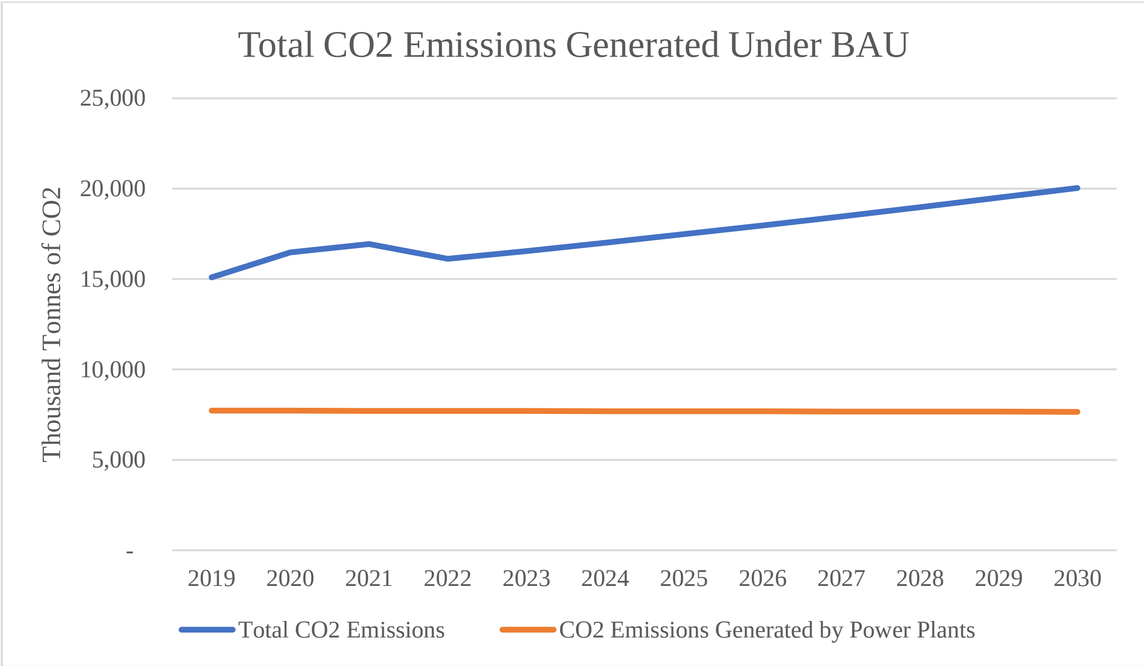

Figure 13: CO_2 emissions under BAU scenario

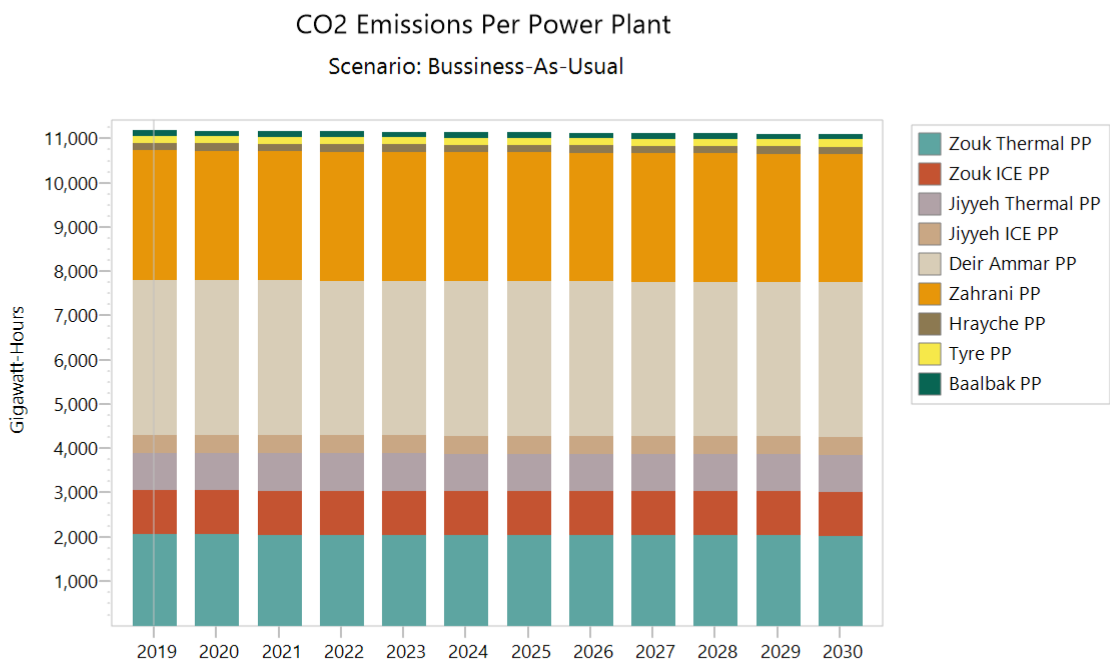

Figure 14: CO2 emissions per power plant under BAU

2. *Scenario 1: Proposed Energy Structure Adjustments by the MoEW's Updated Policy Paper for the Electricity Sector – 2019*

As mentioned previously, the MoEW released an updated policy paper for the electricity sector in March 2019 that was endorsed by the Council of Ministries in April 2019. Two of the specific objectives of the policy paper include:

a. Reducing the technical losses through the implementation of the transmission and distribution initiatives.

According to data from the MoEW, the technical losses are expected to decrease following the trend below. In 2022, the technical losses are expected to be reduced to 7.83% of the total generation capacity and will remain constant till 2030.

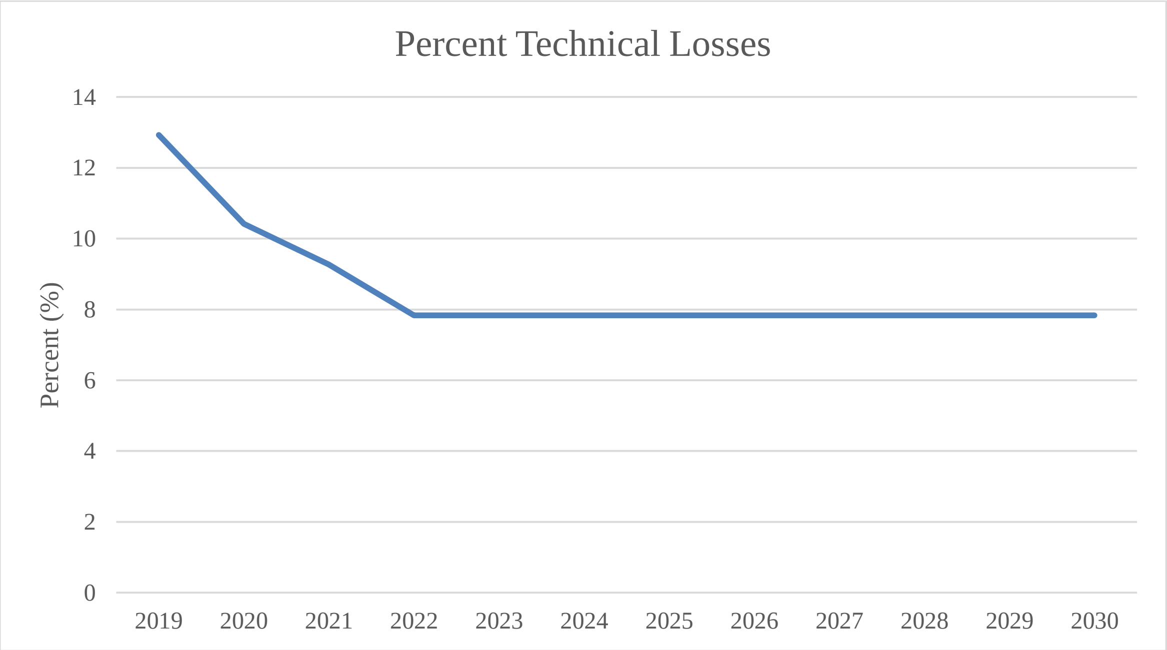

Figure 15: Projected decrease in technical losses in the transmission and distribution grid (2019-2030) (MOEW, 2020b)

b. Improving the electricity generation system in terms of efficiency and fuel type utilized, replacement of existing old plants by new ones and the conversion to Natural Gas.

In order to achieve this electricity generation increase target, short-term and a long-term plans were proposed by the MoEW. For the short-term generation plan, temporary high voltage facilities (i.e. mobile substations) shall be implemented. Using 2019 available electricity capacity as a baseline, an addition 1450 MW capacity should be added in the short-term at specific sites as an initial stage to implementing the long term plan (MoEW, 2019).

On the longer term, 3100 MW of new permanent plants is required. Therefore, three permanent new power plants will be developed in Hrayche, Selaata and Zahrani. In addition, the existing plants of Zouk, Jiyeh and Hrayche will be replaced by new plants at the same locations (MoEW, 2019). All new power plants will be operated using Natural Gas.

Considering that Lebanon faced unusual circumstance in 2020, which indeed affected the efficacy of the execution of the Policy Paper, an assumption was made that the implementation of interventions will start in 2021 instead of 2020.

Table 10: Potential interventions in the energy sector proposed by the Updated Policy Paper for the Electricity Sector – 2019

Year	Proposed Interventions in the Energy Sector
2021	• Addition of 1450 MW Temporary Generation (Power Barges) • Initiation of construction works in Selaata 1 and Zahrani 2 • Addition of 180 MW Solar PV • Decommissioning of existing Hrayche Power Plant
2022	• Decommissioning of existing Jiyeh Thermal Power Plant (343 MW) • Addition of 220 MW of Wind

	• Addition of Deir Ammar 2 OCGT Power Plant (360 MW OCGT)
2023	• Removal of 370 MW of Temporary Generation (Power Barges) • Decommissioning of Zouk Thermal Power Plant (607 MW) • Addition of Deir Ammar 2 CCGT Power Plant (550 MW CCGT) • Addition of Zahrani 2 OCGT Power Plant (360 MW OCGT) • Addition of 300 MW Solar PV • Addition of Selaata 1 OCGT Power Plant (360 MW OCGT)
2024	• Addition of Zahrani 2 CCGT Power Plant (550 MW CCGT) • Addition of Selaata 1 CCGT Power Plant (550 MW CCGT)
2025	• 400 MW Wind • Addition of New Zouk OCGT Power Plant (360 MW OCGT) • Addition of new Hrayche Thermal power Plant (300 MW thermal)
2026	• Addition of Jiyeh OCGT Power Plant (360MW OCGT) • Addition of New Zouk CCGT Power Plant (550 MW CCGT) • Decommissioning of 1450 MW of Temporary Generation (Power Barges)
2027	• Addition of Jiyeh CCGT Power Plant (550MW CCGT)

Table 11: Proposed changes in generation capacity (Terawatt-Hours)

Branch	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Jiyyeh Thermal PP	0.85	0.85	0.84	-	-	-	-	-	-	-	-	-
Jiyyeh ICE PP	0.41	0.41	0.41	0.35	0.30	0.25	0.24	0.27	0.25	0.26	0.26	0.27
Jiyeh OCGT PP	-	-	-	-	-	-	-	1.85	1.74	1.79	1.84	1.90
Jiyeh CCGT PP	-	-	-	-	-	-	-	2.90	2.71	2.79	2.88	2.97
Zouk Thermal PP	2.07	2.07	2.07	1.79	-	-	-	-	-	-	-	-
Zouk ICE PP	1.00	0.99	0.99	0.86	0.74	0.61	0.58	0.65	0.61	0.63	0.65	0.67
Zouk CCGT PP	-	-	-	-	-	-	-	-	2.71	2.79	2.88	2.97
Zouk OCGT PP	-	-	-	-	-	-	1.65	1.85	1.74	1.79	1.84	1.90
Deir Ammar PP	3.51	3.50	3.50	-	-	-	-	-	-	-	-	-

Deir Ammar 1 Upgraded PP NG	-	-	-	3.16	2.74	2.26	2.12	2.39	2.24	2.31	2.38	2.45
Deir Ammar 2 OCGT PP	-	-	-	2.45	2.12	1.75	1.65	1.85	1.74	1.79	1.84	1.90
Deir Ammar 2 CCGT PP	-	-	-	-	3.32	2.74	2.57	2.90	2.71	2.79	2.88	2.97
Zahrani PP	2.92	2.92	2.92	-	-	-	-	-	-	-	-	-
Zahrani 1 Upgraded PP NG	-	-	-	3.20	2.77	2.28	2.14	2.42	2.26	2.33	2.40	2.47
Zahrani 2 OCGT PP	-	-	-	-	2.12	1.75	1.65	1.85	1.74	1.79	1.84	1.90
Zahrani 2 CCGT PP	-	-	-	-	-	2.74	2.57	2.90	2.71	2.79	2.88	2.97
Hrayche PP	0.17	0.17	-	-	-	-	-	-	-	-	-	-
Hrayche Thermal PP Upgraded NG	-	-	-	-	-	-	0.46	0.52	0.48	0.50	0.51	0.53
Baalbak PP	0.11	0.10	0.10	0.09	0.08	0.06	0.06	0.07	0.06	0.07	0.07	0.07
Tyre PP	0.16	0.16	0.16	0.14	0.12	0.10	0.09	0.10	0.10	0.10	0.10	0.11
Selaata 1 OCGT PP	-	-	-	-	2.12	1.75	1.65	1.85	1.74	1.79	1.84	1.90
Selaata 1 CCGT PP	-	-	-	-	-	2.74	2.57	2.90	2.71	2.79	2.88	2.97
Barges	2.70	2.95	14.38	12.44	8.58	7.08	6.65	-	-	-	-	-
Private Generators	10.73	11.88	0.75	-	-	-	-	-	-	-	-	-
Hydro	0.97	0.74	0.74	0.64	0.55	0.46	0.43	0.48	0.45	0.47	0.48	0.50
PV	0.00	0.15	0.49	0.43	0.80	0.66	0.62	0.70	0.65	0.67	0.69	0.71
Biogas	0.03	0.06	0.06	0.06	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Wind	-	0.39	0.39	0.33	0.29	0.24	0.63	0.71	0.66	0.68	0.71	0.73
Total	26	27	28	26	27	28	28	29	30	31	32	33

Based on MoEW's plans to reduce technical losses, increase generation capacity and shift to Natural Gas as a source of fuel, CO_2 emissions were modelled. As shown in Figure 16 and Figure 17, total CO_2 emissions in 2022 dropped due to the halt in the operations of Jiyeh Thermal, Zouk Thermal and Zahrani power plants and a decrease in energy demand. Total CO_2 emissions remain to decrease with the years due to increase in the generation capacity and a decrease in the use of private diesel generators. On the other hand, emissions from power plants started to increase again due to the addition of new thermal power plants. However, the emission intensity (tonnes of CO_2/GWh) was decreasing due to the improvement in the efficiency of the power plants and the use of Natural Gas instead of HFO and DO (Figure 18). Emission intensity of Baalbak and Tyre didn't improve as no adjustments were suggested to be implemented in these two industries by the MoEW Updated Policy Paper for the Electricity Sector.

By the Year 2025, the potential CO2 emissions generated by the power plants in Lebanon are expected to account for 8,658 thousand tonnes, with the majority being emitted by Deir Ammar, Zahrani and Selaata Power Plants. However in Year 2030, with all the MoEW's proposed energy structure adjustments being implemented, the total CO_2 emissions generated by power plants are expected to be around 13,164 thousand tonnes of CO_2 with the majority being emitted from Zouk, Deir Ammar and Zahrani power plants.

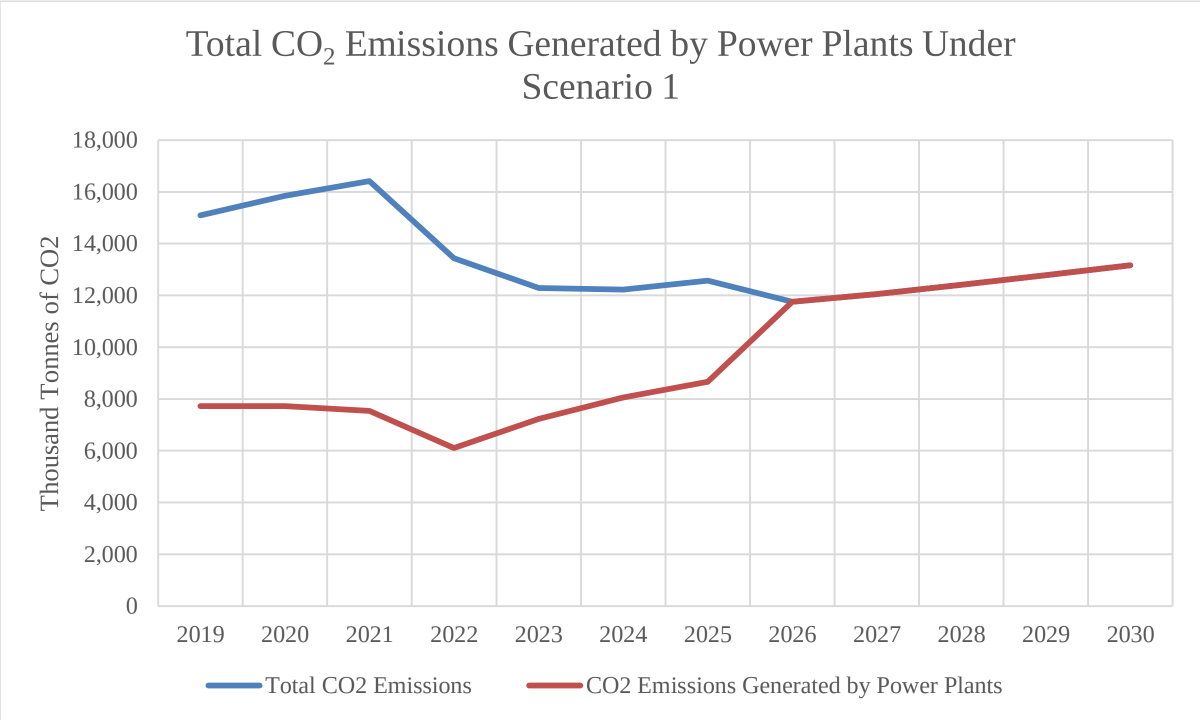

Figure 16: Total CO_2 emissions under the MoEW Updated Policy Paper for the Electricity Sector – 2019 Scenario

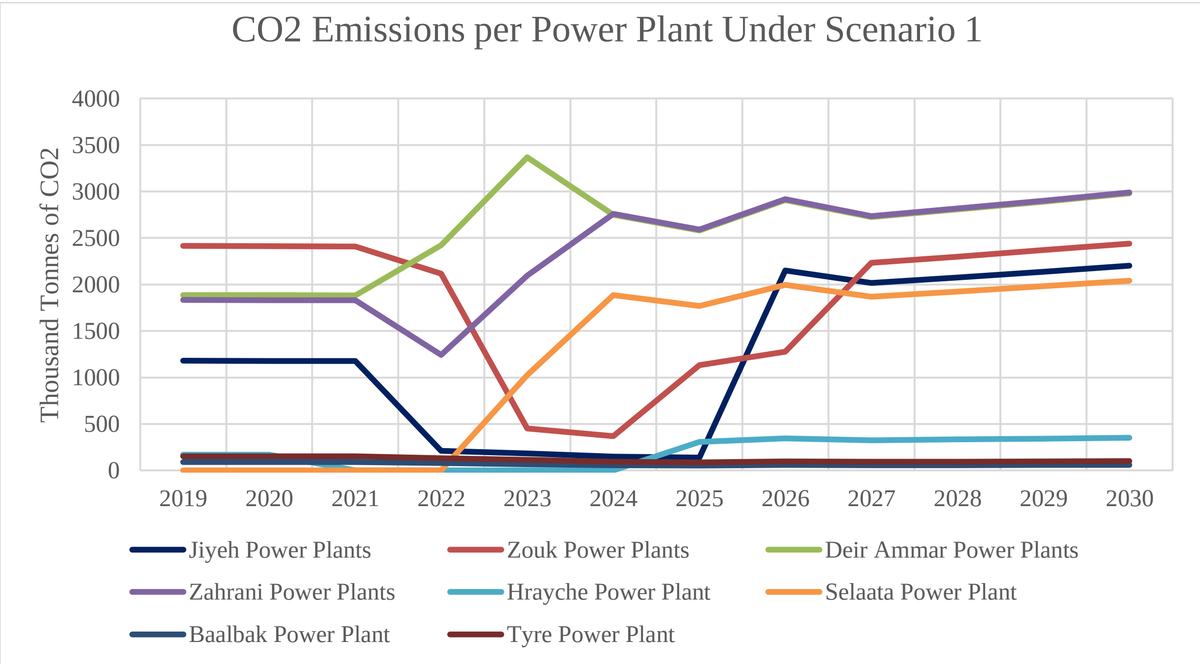

Figure 17: CO_2 emissions per power plant under the MoEW Updated Policy Paper for the Electricity Sector – 2019 Scenario

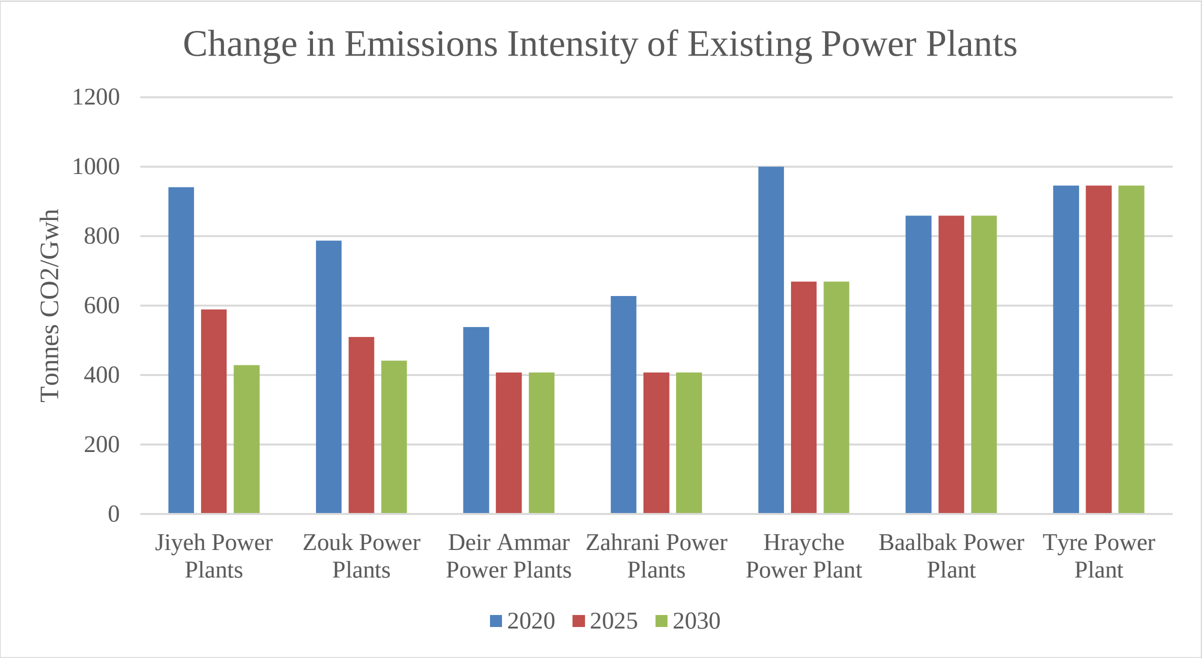

Figure 18: Emission intensity of power plants under Scenario 1

The graphs below present the forecasted CO_2 emissions and power generation rates for each power plant under scenario 1.

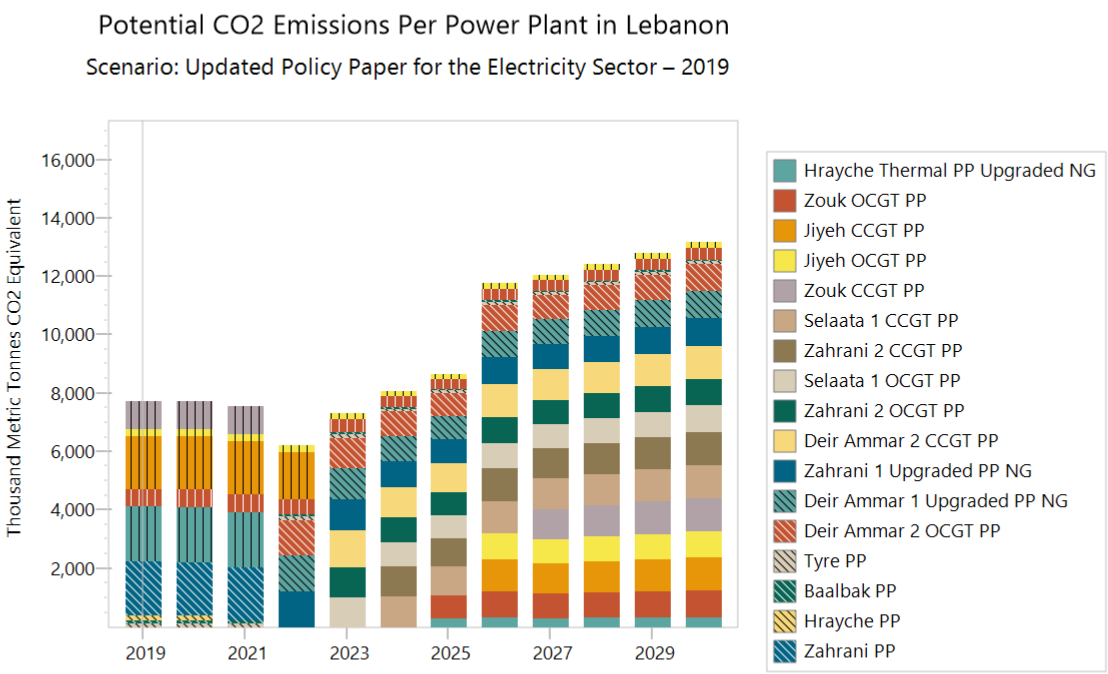

Figure 19: Potential CO_2 emissions per power plant in Lebanon under Scenario 1

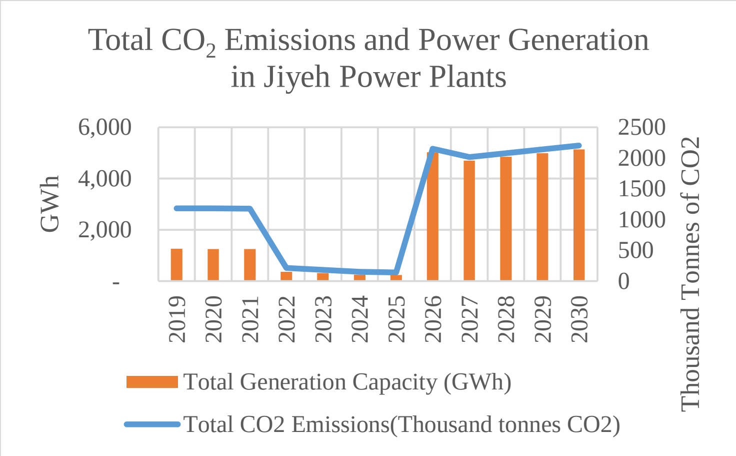

Figure 20: Forecasted CO2 emissions at Jiyeh Power Plant Under Scenario 1

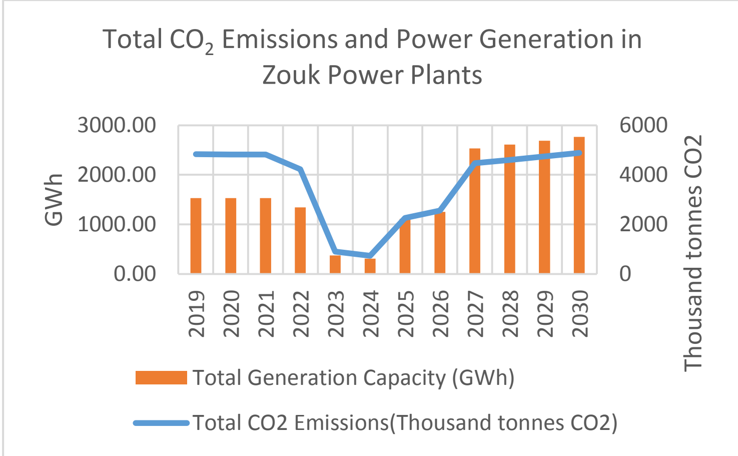

Figure 21: Forecasted CO2 emissions at Zouk Power Plant Under Scenario 1

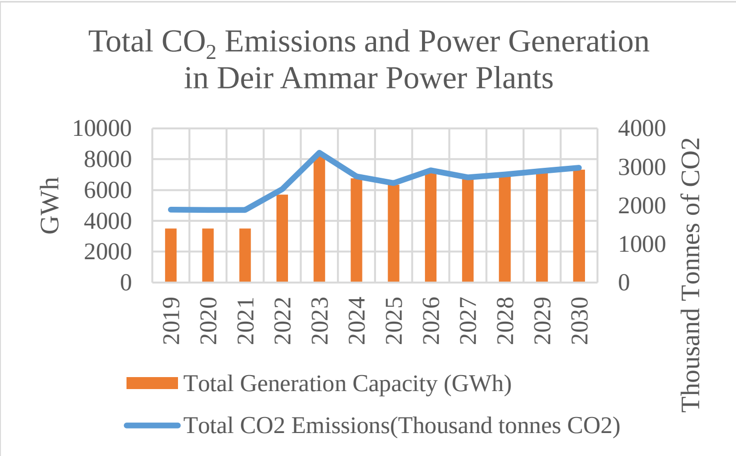

Figure 22: Forecasted CO2 emissions at Deir Ammar Power Plant Under Scenario 1

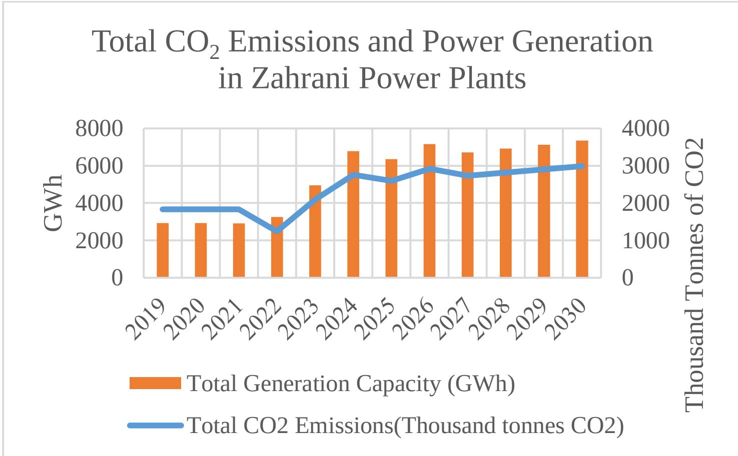

Figure 23: Forecasted CO2 emissions at Zahrani Power Plant Under Scenario 1

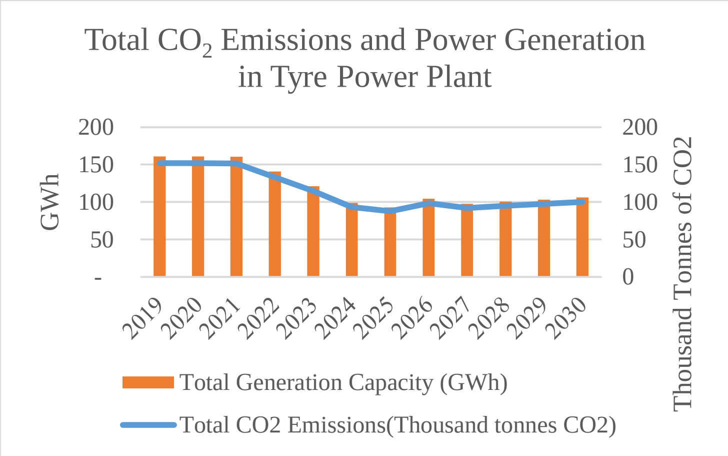

Figure 24: Forecasted CO2 emissions at Tyre Power Plant Under Scenario 1

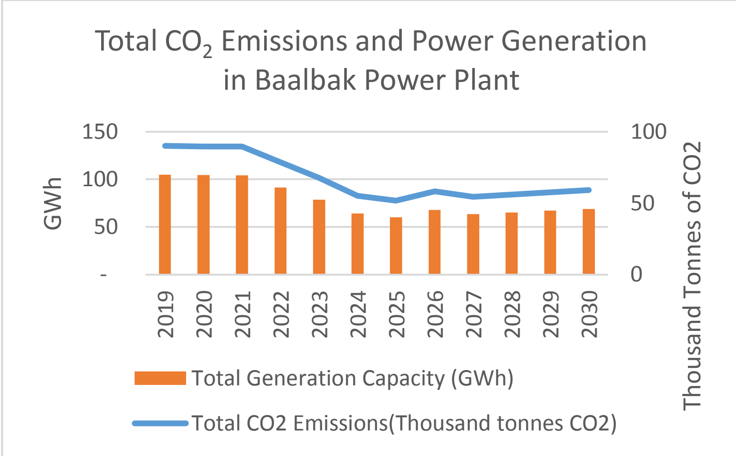

Figure 25: Forecasted CO2 emissions Baalbak Power Plant Under Scenario 1

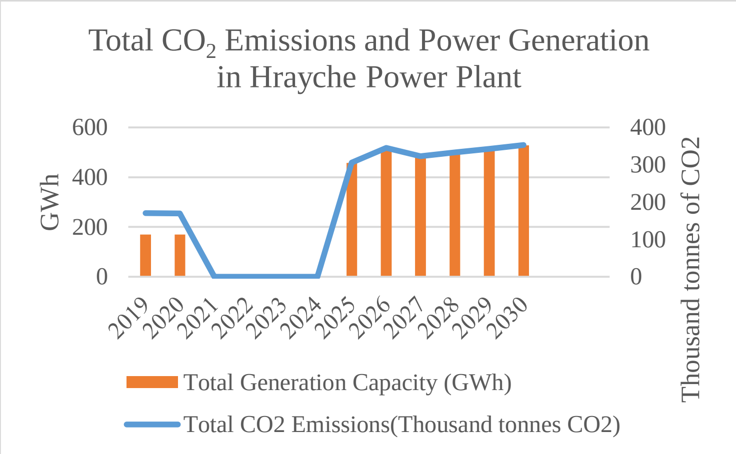

Figure 26: Forecasted CO2 emissions at Hrayche Power Plant Under Scenario 1

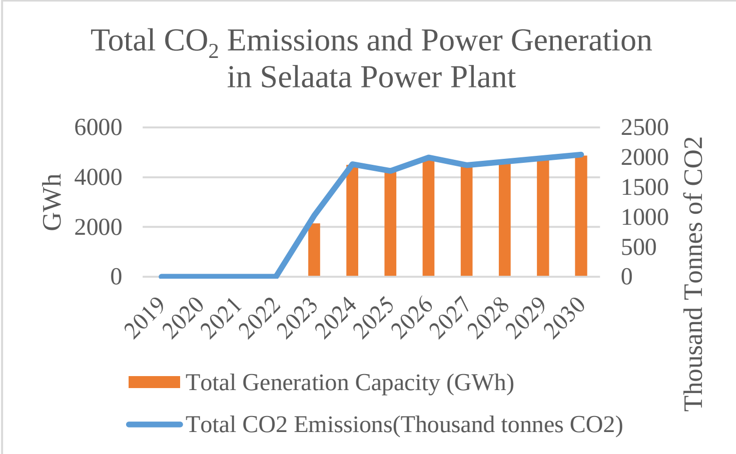

Figure 27: Forecasted CO2 emissions at Selaata Power Plant Under Scenario 1

3. *Scenario 2: Increased Share of Renewable Energy in the Lebanese Energy Mix*

In MoEW's Updated Policy Paper for the Electricity Sector - 2019, the target to increase the contribution of renewable energy in the electricity consumption mix was raised to 30% by 2030. However, the targets for the contribution of different renewable energy technologies in the electricity mix were not specified. However, in the International Renewable Energy Agency (IRENA) Report, the Renewable Energy Map (REmap) analysis complemented the MoEW's target by defining target capacities for each RE technology. The targets are summarized in the table below.

Table 12: REmap analysis RE targets by 2030 (IRENA, 2020)

Technology	**Target by 2030 (MW)**
Wind	2000
Hydropower	601
PV	3000
Biogas	13

Table 13: Generation capacity (TWh) Under Increased Share of Renewable Energy in the Lebanese Energy Mix Scenario

Source	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Jiyyeh Thermal PP	0.85	0.85	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
Jiyyeh ICE PP	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
Zouk Thermal PP	2.07	2.07	2.07	2.06	2.06	2.06	2.06	2.05	2.05	2.05	2.05	2.04
Zouk ICE PP	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Deir Ammar PP	3.51	3.50	3.50	3.50	3.50	3.49	3.49	3.49	3.49	3.49	3.49	3.48
Zahrani PP	2.92	2.92	2.92	2.92	2.91	2.91	2.91	2.91	2.91	2.91	2.91	2.90
Hrayche PP	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Baalbak PP	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Tyre PP	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Hydro	0.97	0.82	0.89	0.97	1.05	1.12	1.20	1.27	1.35	1.43	1.50	1.58
PV	0.00	0.66	1.17	1.67	2.18	2.69	3.20	3.71	4.21	4.72	5.23	5.74
Private Generators	11.26	12.15	12.09	9.68	9.60	9.55	9.52	9.52	9.55	9.61	9.69	9.80
Biogas	0.03	0.07	0.07	0.08	0.08	0.09	0.09	0.10	0.10	0.10	0.11	0.11
Barges	2.70	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95

Wind	-	0.32	0.64	0.96	1.27	1.59	1.91	2.23	2.55	2.87	3.19	3.50
Total	25.63	28.13	28.98	27.46	28.28	29.13	30.00	30.90	31.83	32.79	33.77	34.78

The proposed increased in the renewable energy share will reduce from the power deficit, reducing the percent share of private generators. This scenario will have no impact on the power output from the power plants in Lebanon and hence will not affect the quantities of CO_2 emissions generated.

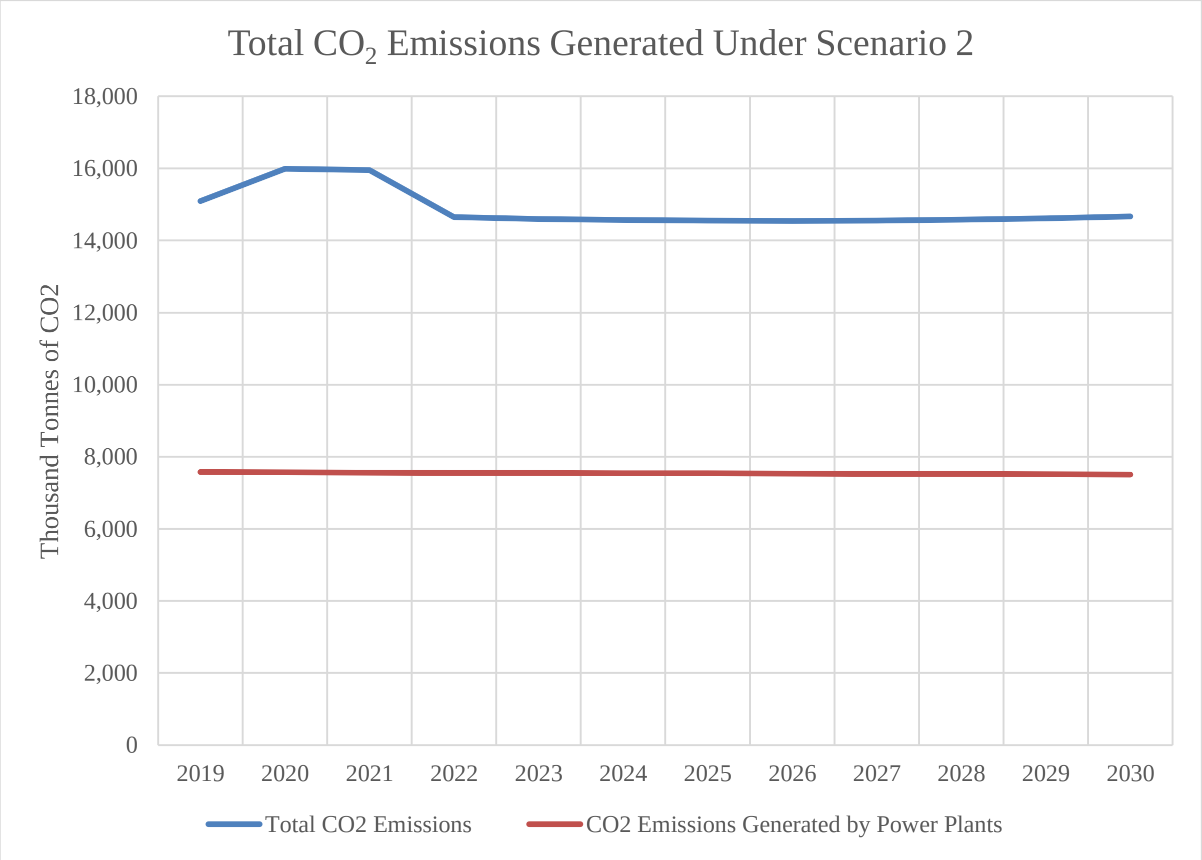

Figure 28: Total CO2 emissions generated under scenario 2

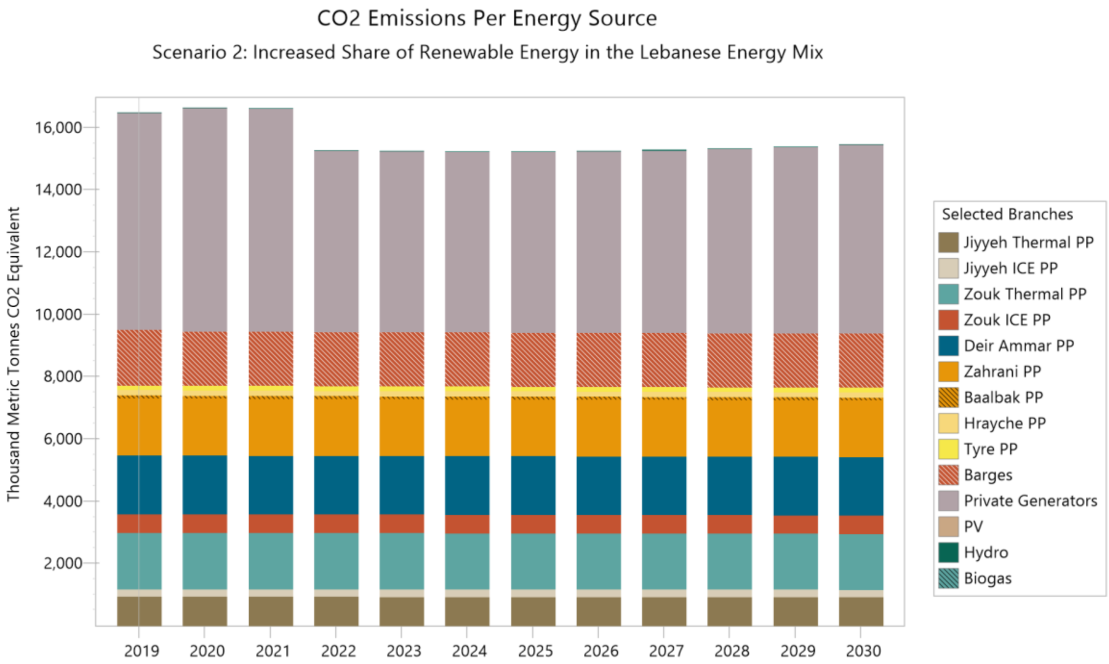

Figure 29: CO_2 emissions per power plant under Scenario 2

4. Scenario 3: Proposed Energy Structure Adjustments and Increased Share of Renewable Energy

In this Scenario, CO_2 emissions are modelled while combining the energy structure adjustments proposed by the MoEW Policy Paper for the Electricity Sector 2019 and the increased share of RE proposed by the IRENA report (2020).

Table 14: Generation capacities (TWh) under Scenario 3

Source	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Jiyyeh Thermal PP	0.85	0.85	0.84	-	-	-	-	-	-	-	-	-
Jiyyeh ICE PP	0.41	0.41	0.41	0.35	0.29	0.23	0.21	0.23	0.21	0.20	0.20	0.20
Zouk Thermal PP	2.07	2.07	2.07	1.75	-	-	-	-	-	-	-	-
Jiyeh OCGT PP	-	-	-	-	-	-	-	1.59	1.43	1.41	1.41	1.38
Jiyeh CCGT PP	-	-	-	-	-	-	-	2.49	2.23	2.20	2.20	2.15
Zouk ICE PP	1.00	0.99	0.99	0.84	0.72	0.57	0.51	0.56	0.50	0.49	0.49	0.48

Zouk CCGT PP	-	-	-	-	-	-	-	-	2.23	2.20	2.20	2.15
Zouk OCGT PP	-	-	-	-	-	-	1.44	1.59	1.43	1.41	1.41	1.38
Deir Ammar PP	3.51	3.50	3.50	-	-	-	-	-	-	-	-	-
Deir Ammar 1 Upgraded PP NG	-	-	-	3.10	2.64	2.10	1.86	2.05	1.84	1.82	1.82	1.77
Deir Ammar 2 OCGT PP	-	-	-	2.41	2.05	1.63	1.44	1.59	1.43	1.41	1.41	1.38
Deir Ammar 2 CCGT PP	-	-	-	-	3.20	2.54	2.26	2.49	2.23	2.20	2.20	2.15
Zahrani PP	2.92	2.92	2.92	-	-	-	-	-	-	-	-	-
Zahrani 1 Upgraded PP NG	-	-	-	3.14	2.67	2.12	1.88	2.08	1.86	1.84	1.84	1.79
Zahrani 2 OCGT PP	-	-	-	-	2.05	1.63	1.44	1.59	1.43	1.41	1.41	1.38
Zahrani 2 CCGT PP	-	-	-	-	-	2.54	2.26	2.49	2.23	2.20	2.20	2.15
Hrayche PP	0.17	0.17	-	-	-	-	-	-	-	-	-	-
Hrayche Thermal PP Upgraded NG	-	-	-	-	-	-	0.79	0.79	0.79	0.79	0.79	0.79
Baalbak PP	0.11	0.10	0.10	0.09	0.08	0.06	0.05	0.06	0.05	0.05	0.05	0.05
Tyre PP	0.16	0.16	0.16	0.14	0.12	0.09	0.08	0.09	0.08	0.08	0.08	0.08
Selaata 1 OCGT PP	-	-	-	-	2.05	1.63	1.44	1.59	1.43	1.41	1.41	1.38
Selaata 1 CCGT PP	-	-	-	-	-	2.54	2.26	2.49	2.23	2.20	2.20	2.15
Barges	2.70	2.95	14.38	12.20	8.28	6.58	5.83	-	-	-	-	-
Private Generators	10.73	11.80	0.58	-	-	-	-	-	-	-	-	-
Hydro	0.97	0.82	0.89	0.97	1.05	1.12	1.20	1.27	1.35	1.43	1.50	1.58
PV	0.00	0.15	0.49	0.49	1.07	1.64	2.21	2.79	3.55	4.51	5.27	5.74
Biogas	0.03	0.07	0.07	0.08	0.08	0.09	0.09	0.10	0.10	0.10	0.11	0.11
Wind	-	0.39	0.39	0.39	0.39	0.39	1.09	1.26	1.44	1.61	1.70	2.63
Total	25.63	27.34	27.81	25.94	26.72	27.52	28.34	29.19	30.07	30.97	31.90	32.86

Similar to Scenario 1, as shown in Figure 30 and Figure 31, the total CO_2 emissions in 2022 dropped due to the halt in the operations of Jiyeh Thermal, Zouk Thermal and Zahrani power plants and a decrease in energy demand. Total CO_2

emissions remain to decrease with the years due to increase in the generation capacity of power plants and renewable energy sources and a decrease in the use of private diesel generators. On the other hand, emissions from power plants started to increase again due to the addition of new thermal power plants. However, the emission intensity (tonnes of CO_2/GWh) was decreasing due to the improvement in the efficiency of the power plants and the use of Natural Gas instead of HFO and DO (Figure 32). Emission intensity of Baalbak and Tyre didn't improve as no adjustments were suggested to be implemented in these two industries by the MoEW Updated Policy Paper for the Electricity Sector.

By the Year 2025, the potential CO2 emissions generated by the power plants in Lebanon are expected to account for 7,857 thousand tonnes, with the majority being emitted by Deir Ammar, Zahrani and Selaata Power Plants. However in Year 2030, with all the MoEW's proposed energy structure adjustments being implemented, and RE share increased to 30%, the total CO_2 emissions generated by power plants are expected to be around 10,189 thousand tonnes of CO_2 with the majority being emitted from Zouk, Deir Ammar and Zahrani power plants. The emission intensity of the power plants under Scenario 3 is the same as Scenario 1. However, comparing Scenario 1 to Scenario 3, the increase in RE share will reduce the CO_2 emissions generated by power plants by 9.5% in 2025 and 22.6% in 2030. This decrease in emissions is mainly due to reducing the generation capacity of the power plants.

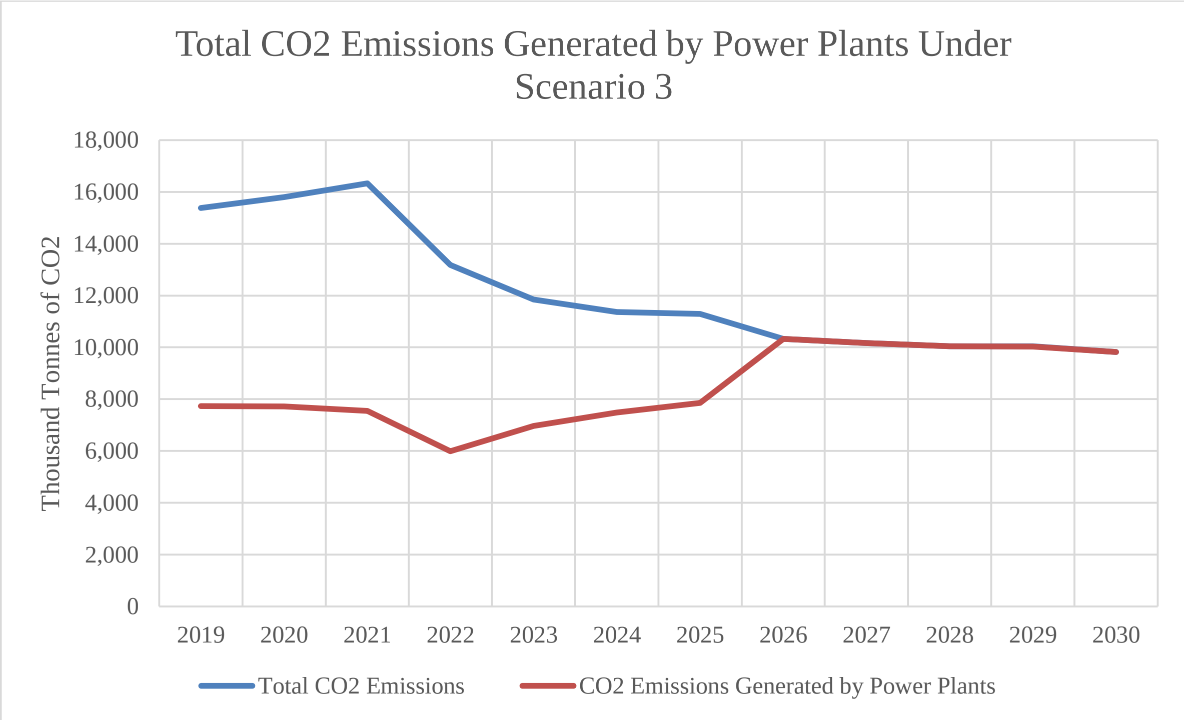

Figure 30: Total CO2 emissions under Scenario 3

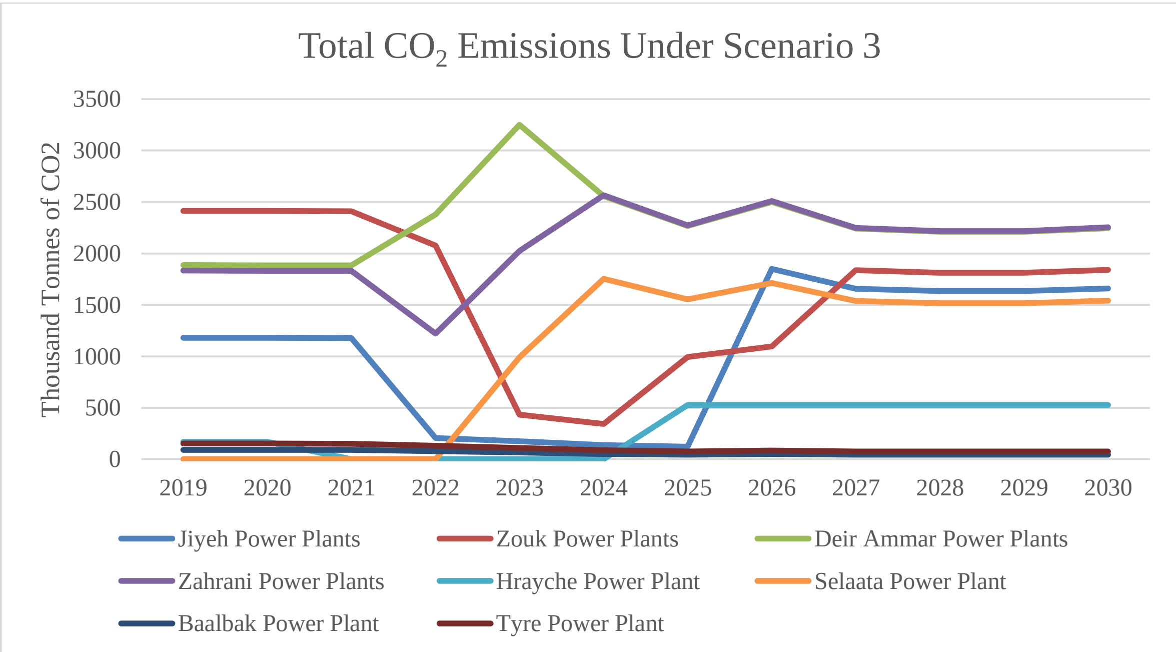

Figure 31: CO2 emissions per power plant under Scenario 3

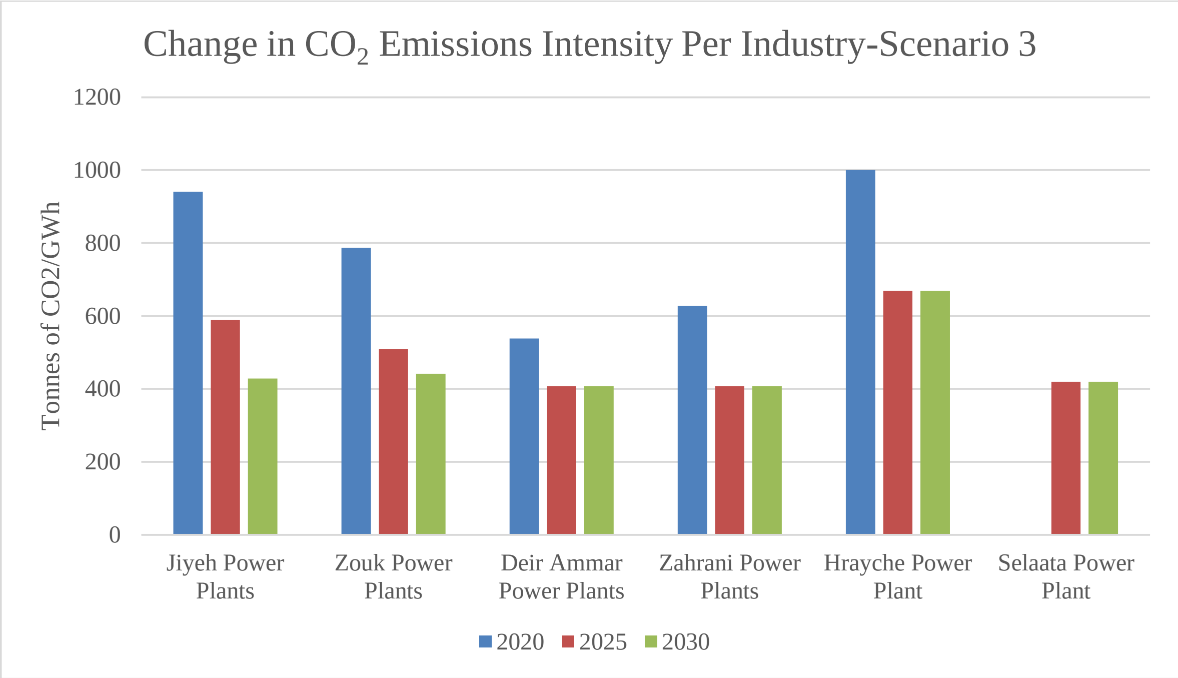

Figure 32: Change in emissions intensity per industry under Scenario 3

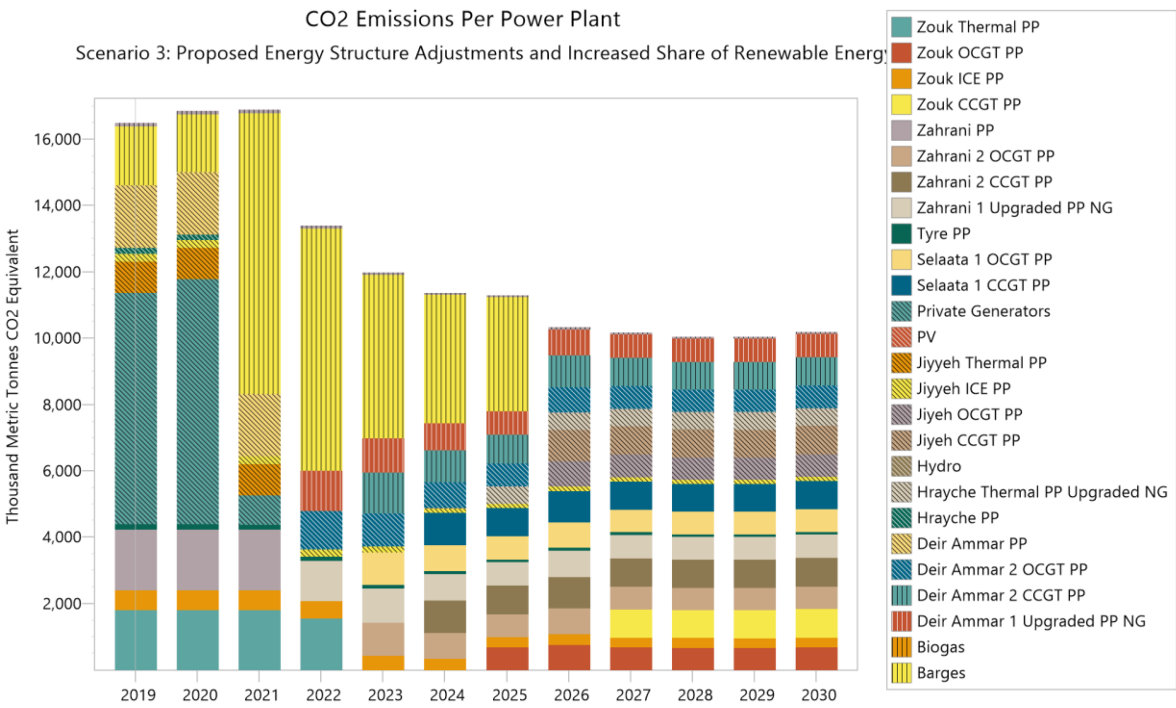

Figure 33: CO_2 emissions per industry under Scenario 3

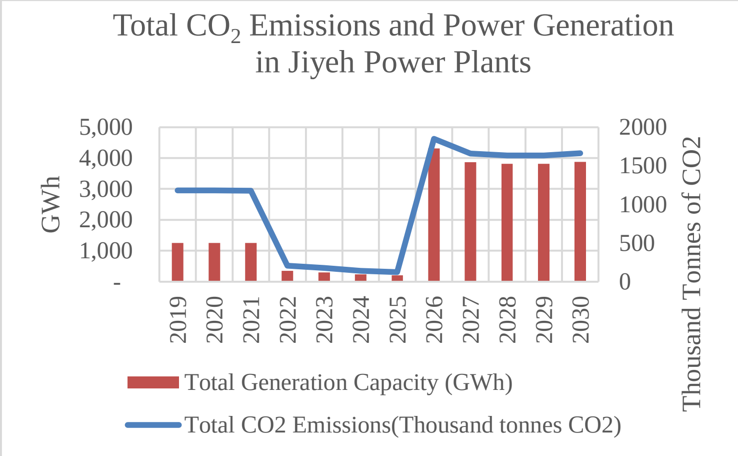

Figure 34: Forecasted CO2 emissions at Jiyeh Power Plant Under Scenario 3

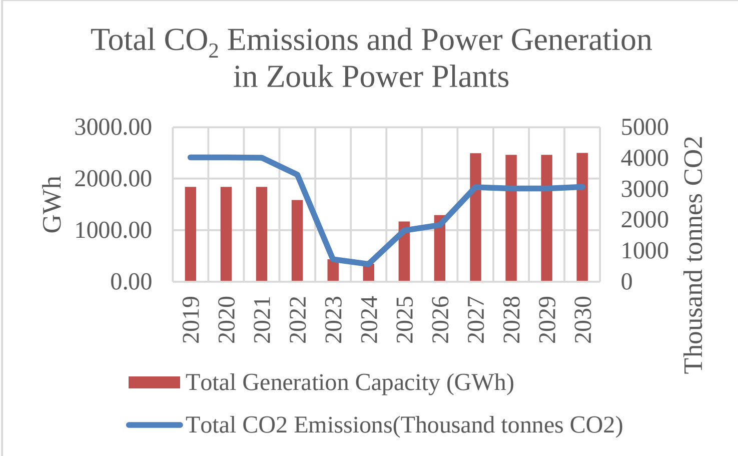

Figure 35: Forecasted CO2 emissions at Zouk Power Plant Under Scenario 3

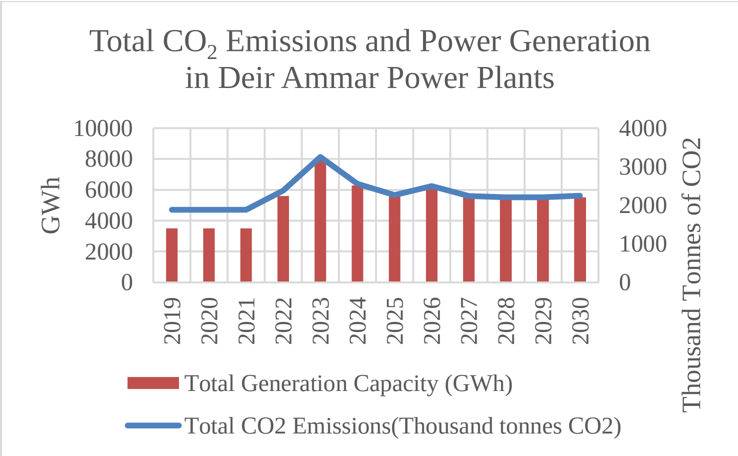

Figure 36: Forecasted CO2 emissions at Deir Ammar Power Plant Under Scenario 3

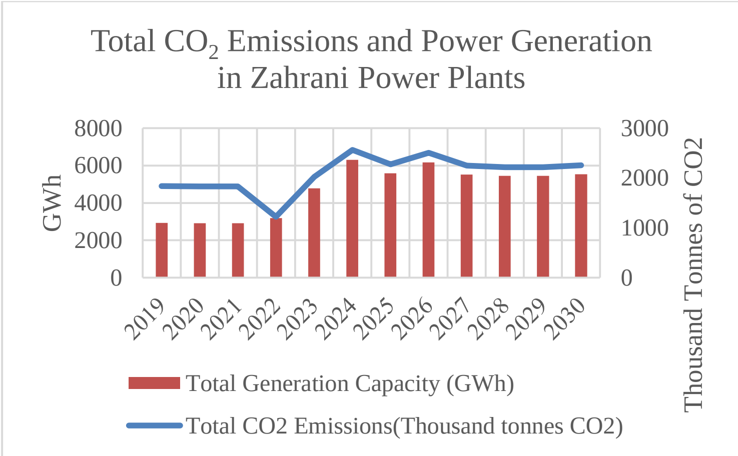

Figure 37: Forecasted CO2 emissions at Zahrani Power Plant Under Scenario 3

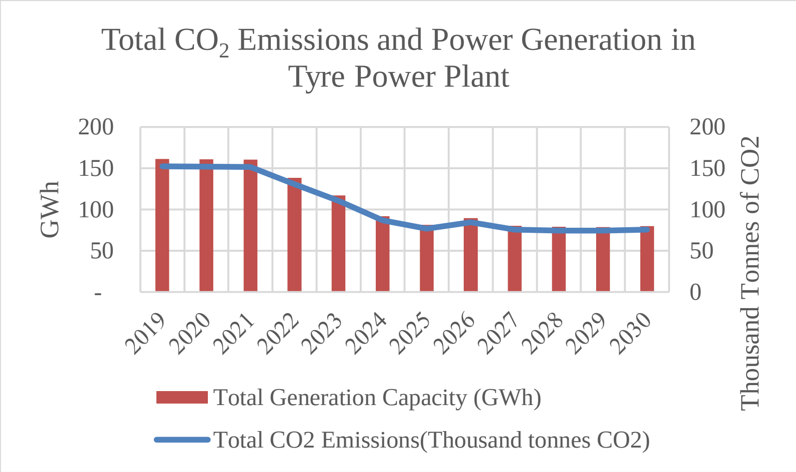

Figure 38: Forecasted CO2 emissions at Tyre Power Plant Under Scenario 3

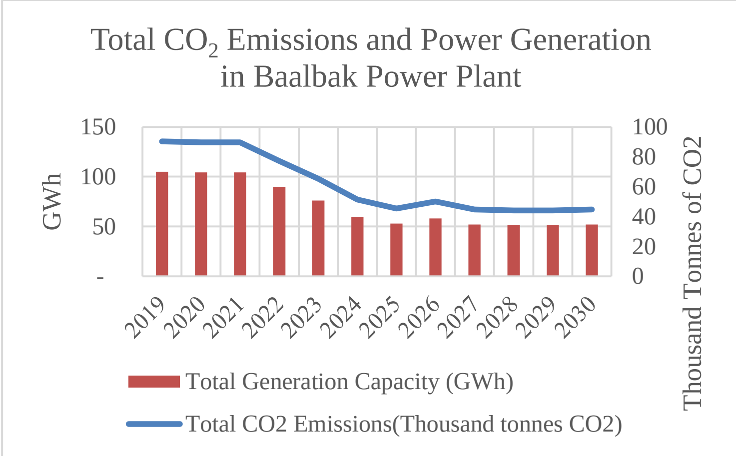

Figure 39: Forecasted CO2 emissions Baalbak Power Plant Under Scenario 3

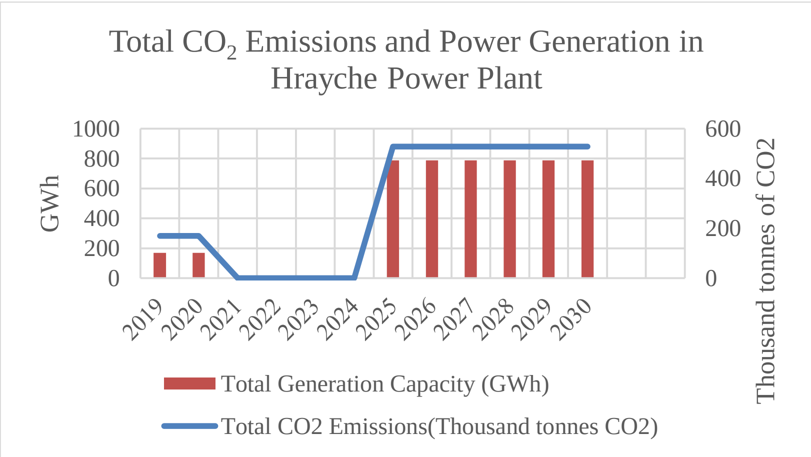

Figure 40: Forecasted CO2 emissions at Hrayche Power Plant Under Scenario 3

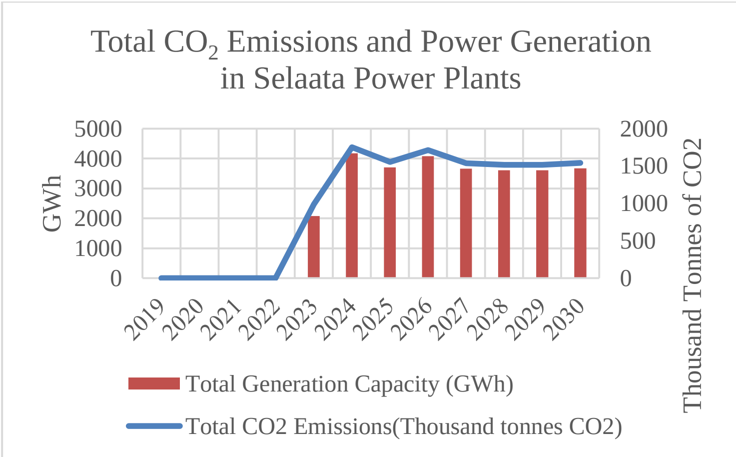

Figure 41: Forecasted CO2 emissions at Selaata Power Plant Under Scenario 3

5. *Scenario 4: Proposed Energy Structure Adjustments and Different Fuel Type Utilization*

Due to the remaining uncertainty related to the supply of natural gas in Lebanon, this scenario assumes the use of diesel oil in the power plants in Lebanon, taking into account the proposed energy structure adjustments proposed by the MoEW's Updated Policy Paper for the Electricity Sector - 2019.

The use of diesel oil in power plants will result in an increase of emissions by 28.5% in 2030 compared to Scenario 1, where natural gas is used. The emission intensity of the power plants will increase by 25-30% when diesel oil is utilized instead of natural gas.

In 2025, the total CO_2 emissions generated by power plants is expected to be 11,074 thousand tonnes of CO_2 per year, while in 2030 with all the adjustments in the energy sector being implemented, the total CO_2 emissions are expected to be 16,905 thousand tonnes of CO_2 per year. Compared to other scenarios, scenario 4 resulted in the highest level of CO_2 emissions.

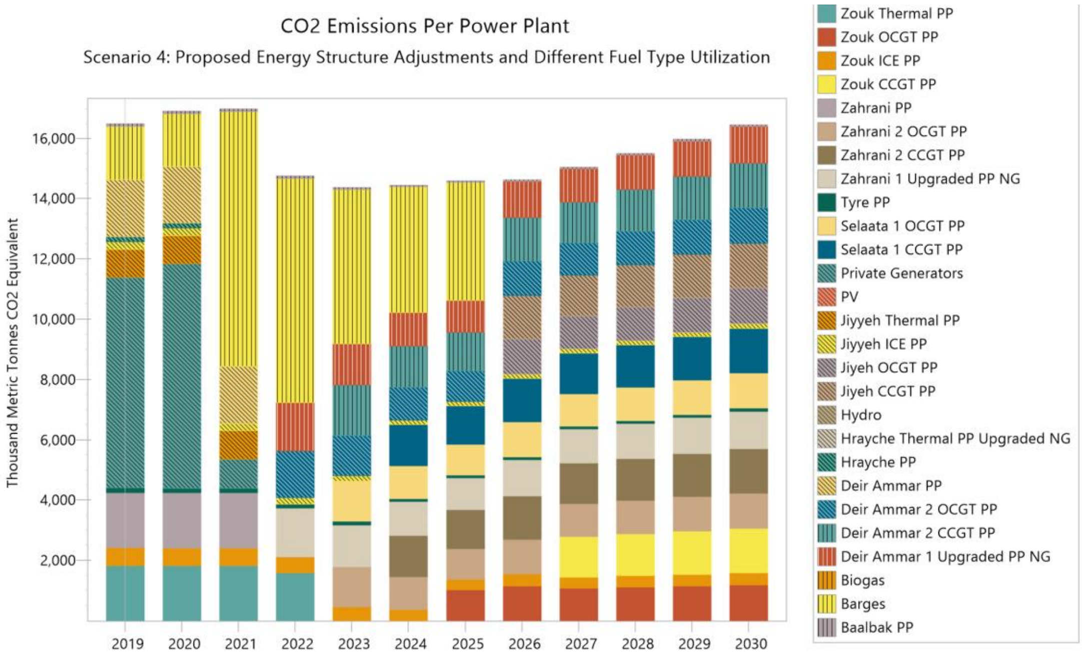

Figure 42: CO_2 emissions per power plant under scenario 4

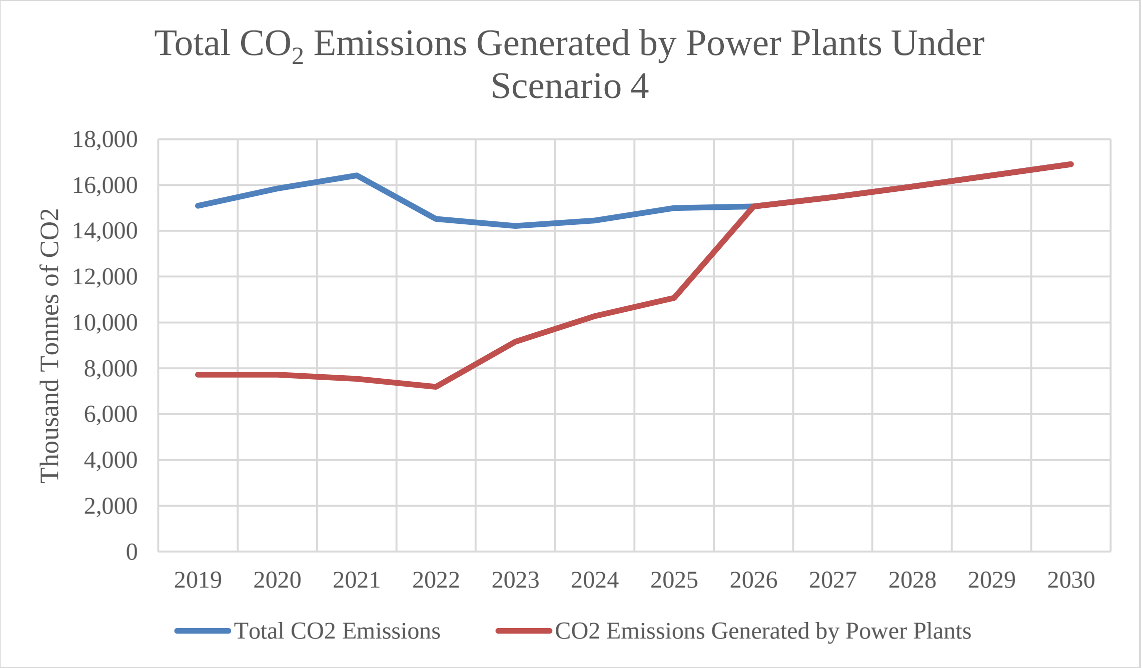

Figure 43: Total CO_2 emissions under Scenario 4

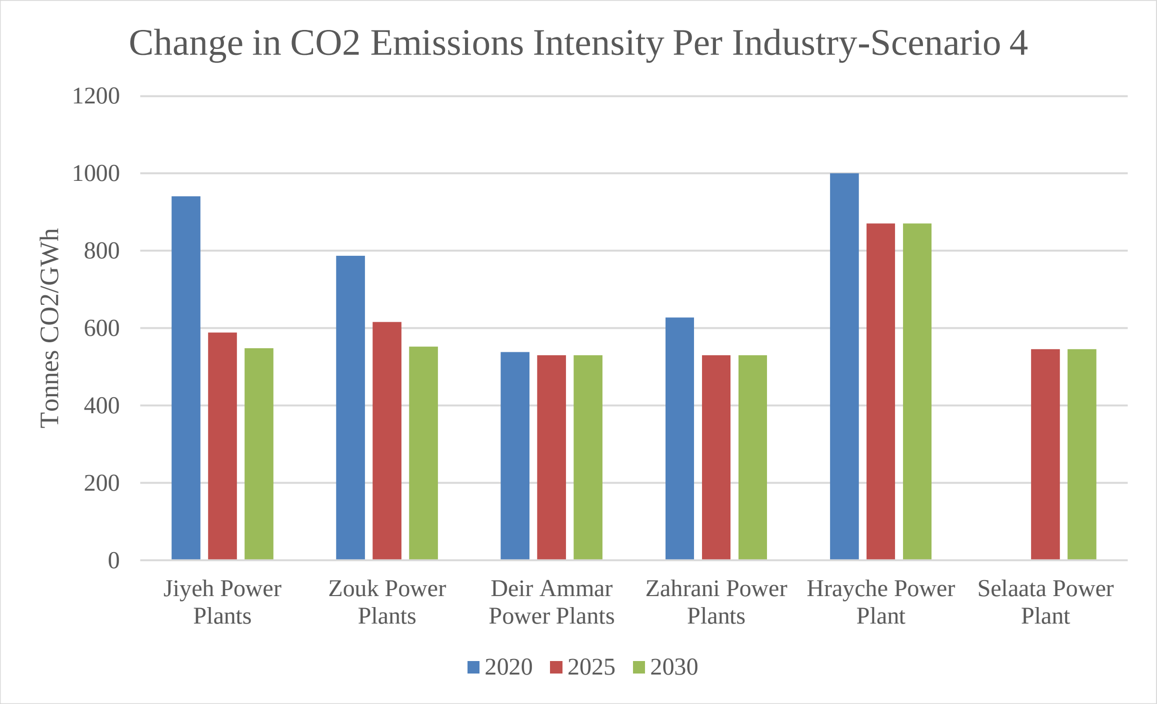

Figure 44: Change in emissions intensity per industry under Scenario 4

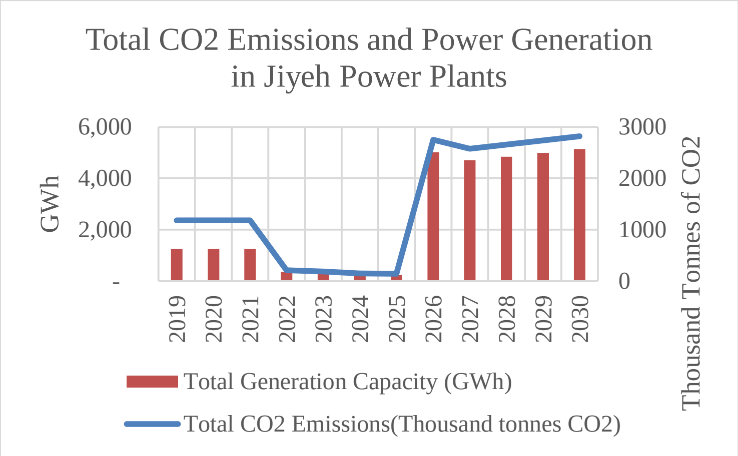

Figure 45: Forecasted CO2 emissions at Jiyeh Power Plant Under Scenario 4

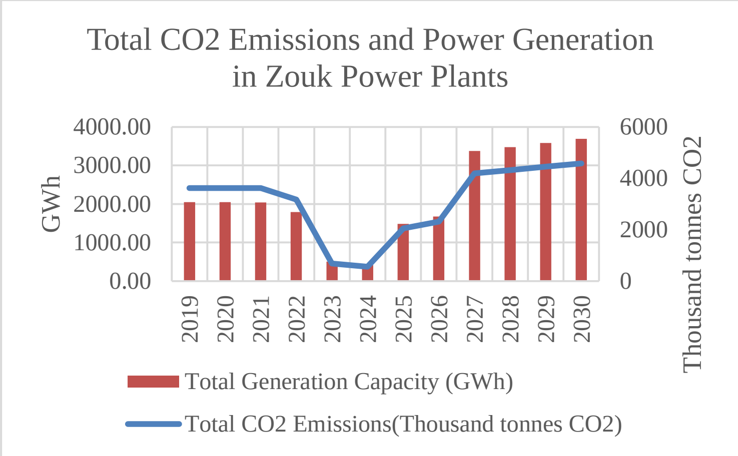

Figure 46: Forecasted CO2 emissions at Zouk Power Plant Under Scenario 4

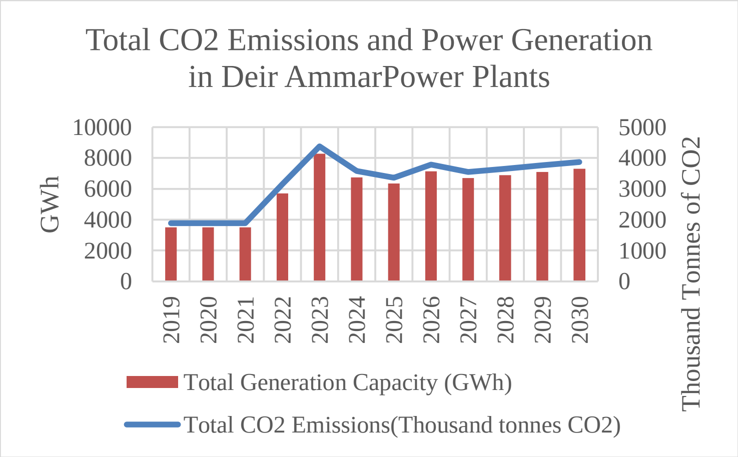

Figure 47: Forecasted CO2 emissions at Deir Ammar Power Plant Under Scenario 4

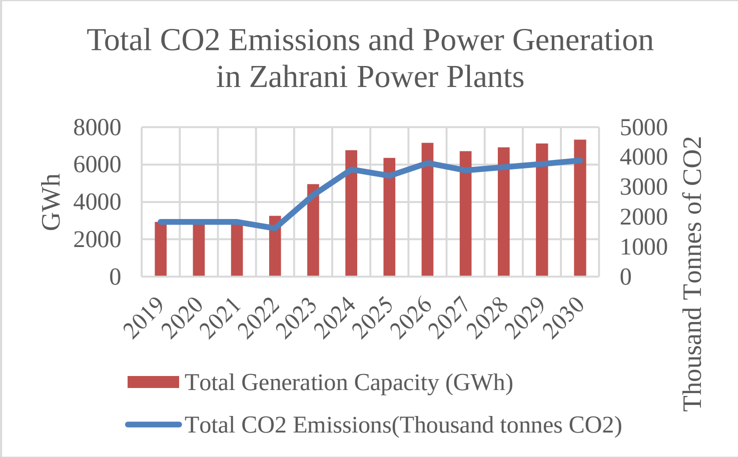

Figure 48: Forecasted CO2 emissions at Zahrani Power Plant Under Scenario 4

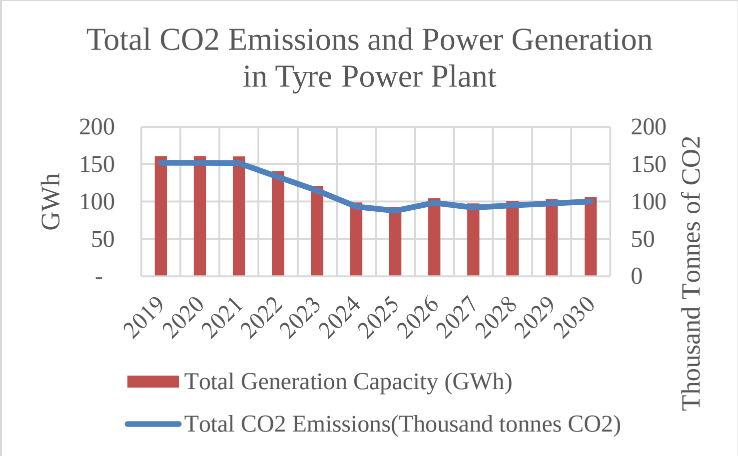

Figure 49: Forecasted CO2 emissions at Tyre Power Plant Under Scenario 4

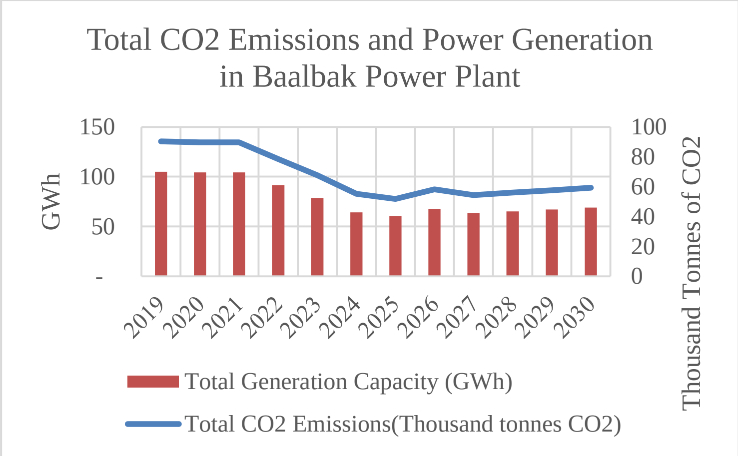

Figure 50: Forecasted CO2 emissions Baalbak Power Plant Under Scenario 4

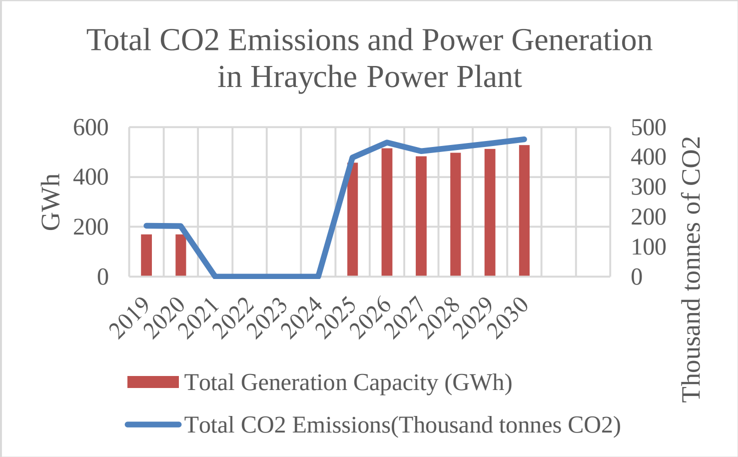

Figure 51: Forecasted CO2 emissions at Hrayche Power Plant Under Scenario 4

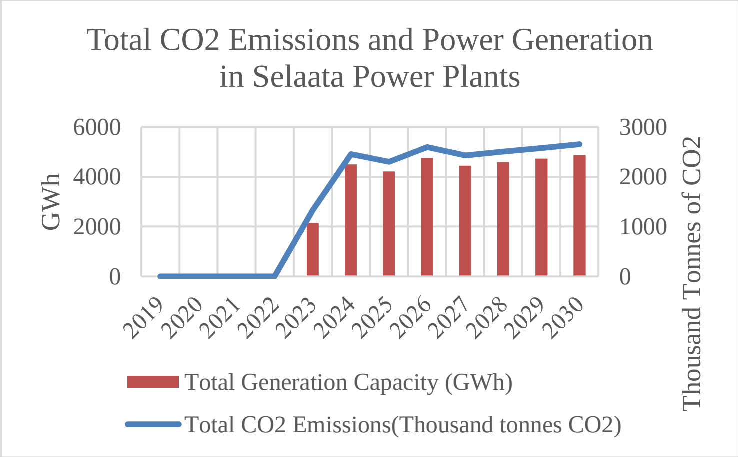

Figure 52: Forecasted CO2 emissions at Selaata Power Plant Under Scenario 4

6. *Summary of Scenario Analysis*

The forecasted CO_2 emissions under the BAU and four modelled scenarios are presented in the graph and table below. Results showed that the forecasted CO_2 emissions are expected to be the highest, 16,905 thousand tonnes of CO_2 by 2030, under the implementation of proposed energy structure adjustments by the MoEW's Updated Policy Paper for the Electricity Sector (2019), with the use of Diesel Oil instead of Natural Gas in the energy industries (Scenario 4). The implementation of proposed energy structure adjustments, with the use of Natural Gas (Scenario 1), will generate the second highest CO_2 emissions, around 13,162 thousand tonnes of CO_2 by 2030. Increasing the share of Renewable Energy, coupled with the implementation of the proposed energy structure adjustments, will reduce CO_2 emissions to 10,187 thousand tonnes of CO_2 by 2030. On the other hand, increasing the Renewable Energy share without implementing adjustments in the energy sector will not impact CO_2 generated by power plants, but will reduce the energy deficit and hence the reliance on private power generation.

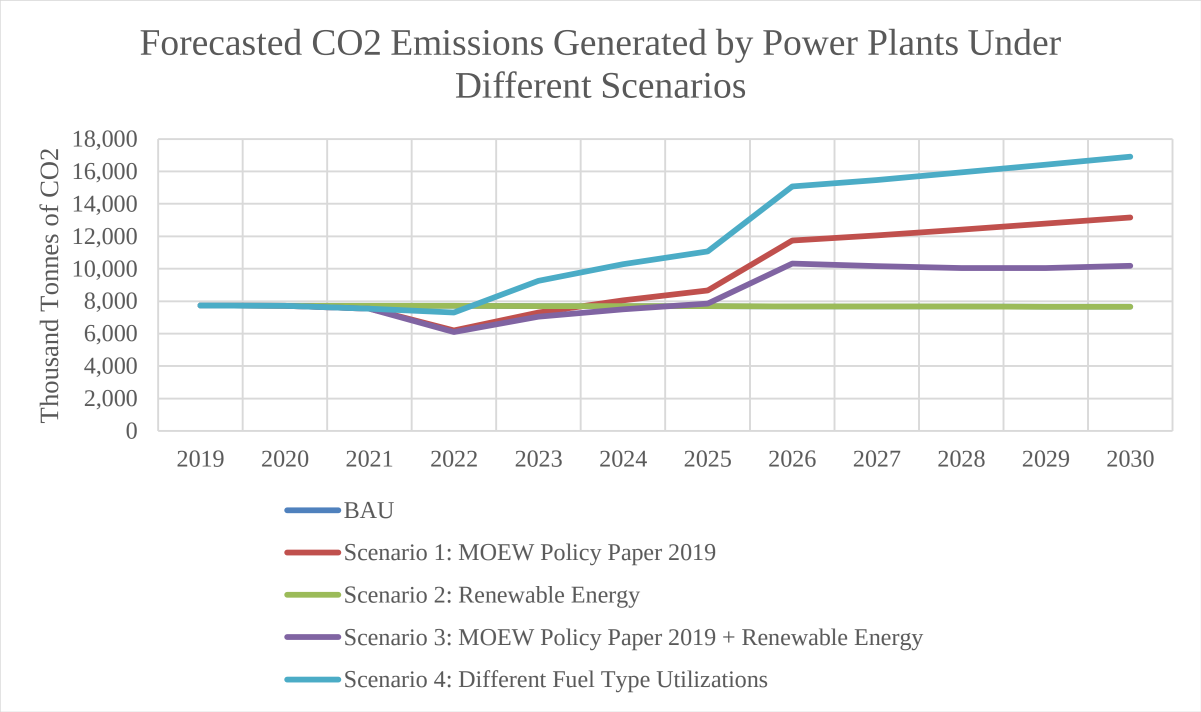

Figure 53: Forecasted CO2 emissions generated by power plants under different modelled scenarios

Under Scenario 2, the emission intensities of the power plants will be the highest, as the industries will be running as the BAU. The increase in renewable energy share will only affect the use of private power generation sources and not the power plants. The second highest emission intensities will be under Scenario 4–the implementation of Electricity Policy Paper (2019) using Diesel Oil instead of Natural Gas. The replacement of diesel oil by natural gas, Scenario 1, will result in a decrease in CO2 emissions by 20-23%.

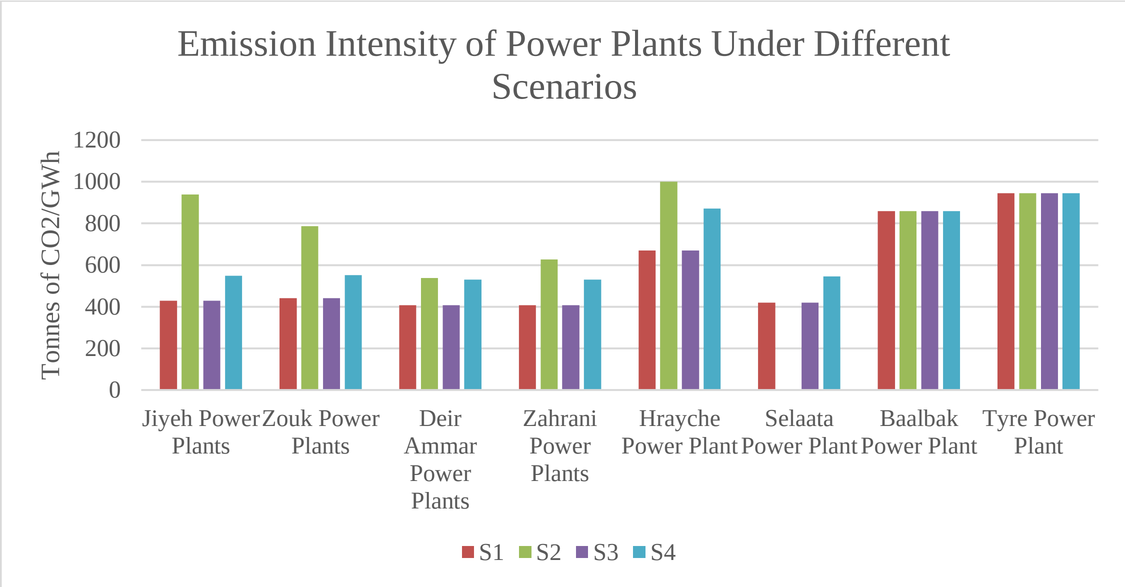

Figure 54: Comparison between emission intensities of power plants under different scenarios

Table 15: Forecasted CO_2 emissions under different scenarios

Forecasted CO_2 Emissions (Thousand Tonnes of CO_2)															
	2020					**2025**					**2030**				
	BAU	**S1**	**S2**	**S3**	**S4**	**BAU**	**S1**	**S2**	**S3**	**S4**	**BAU**	**S1**	**S2**	**S3**	**S4**
Jiyeh Power Plants	1178.8	1178.9	1,178.88	1178.8	1179	1172.8	139.08	1,172.87	122	139	1166.8	2202.5	1,166.85	1660	2816
Zouk Power Plants	2411.6	2412	2,411.65	2412	2412	2399.8	1132	2,399.87	993	1369	2388.1	2440	2,388.15	1840	3054
Deir Ammar Power Plants	1884.3	1884	1,884.3	1884	1884	1879.4	2582	1,879.4	2265	3358	1874.3	2978	1,874.3	2246	3874
Zahrani Power Plants	1832.3	1835	1,832.3	1832	1835	1827.5	2590	1,827.5	2273	3369	1822.6	2988	1,822.6	2253	3887
Hrayche Power Plant	169.6	169.6	169.6	169	169.6	168.5	306	168.5	527	398	167.4	353	167.4	527	459
Selaata Power Plant	0	0	0	0	0	0	1770	0	1553	2302	0	2042	0	1540	2656
Baalbak Power Plant	89.7	90	89.7	90	90	89.1	52	89.1	45	52	88.5	59	88.5	45	59
Tyre Power Plant	151.9	152	151.9	152	152	150.9	87	150.9	77	87	149.9	100	149.9	76	100
Total	**7718.2**	**7721.5**	**7718.33**	**7717.8**	**7721.6**	**7688**	**8658.08**	**7688.14**	**7855**	**11074**	**7657.6**	**13162.5**	**7657.7**	**10187**	**16,905**

C. Shadow Price of Carbon

Considering that the Carbon Tax or Shadow Price of Carbon (SPC) are absent in Lebanon, the SRC was assumed to be in the range of US$40-80 per ton of CO2 in 2020, rising to US$50-100 per ton of CO2 by 2030, consistent with the High-Level Commission on Carbon Prices (World Bank, 2017). Results showed that SPC are expected to be the highest, 845-1690 million USD by 2030, under the implementation of proposed energy structure adjustments by the MoEW’s Updated Policy Paper for the Electricity Sector (2019), with the use of Diesel Oil instead of Natural Gas in the energy industries (Scenario 4). The implementation of proposed energy structure adjustments, with the use of Natural Gas (Scenario 1), will have the second highest SPC, around 657-1315 million USD by 2030. Increasing the share of Renewable Energy, coupled with the implementation of the proposed energy structure adjustments, will reduce SPC to 509-1018 million USD by 2030. On the other hand, increasing the Renewable Energy share without implementing adjustments in the energy sector will result in the SPC of 383-765 million USD by 2030.

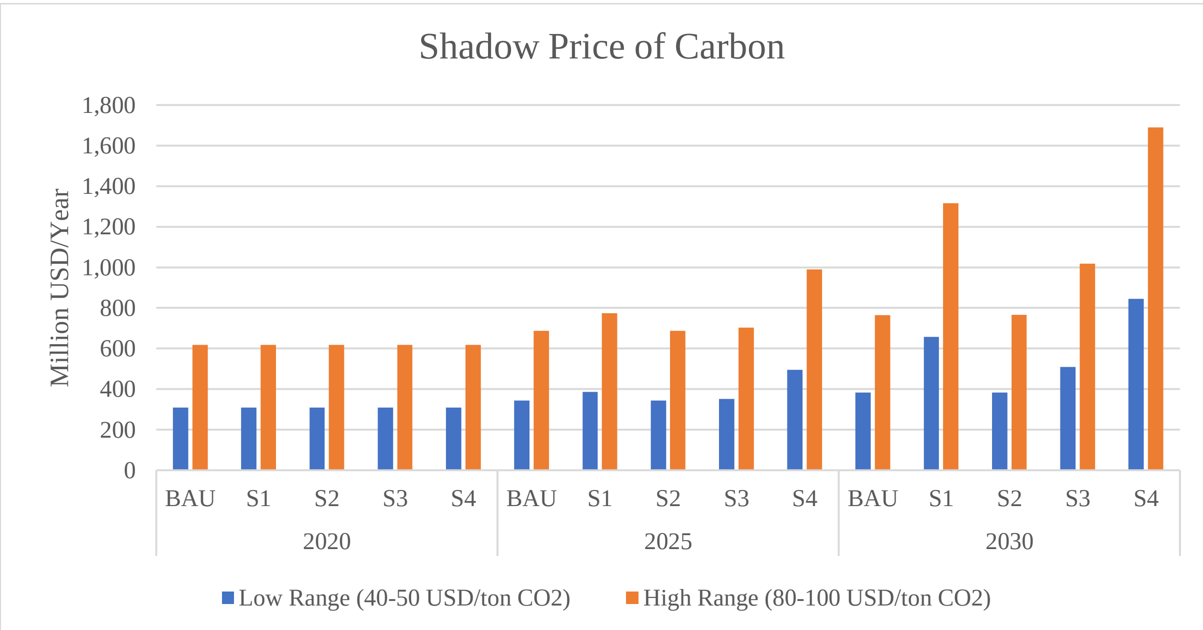

Figure 55: Shadow price of carbon per scenario

Table 16: Shadow price of carbon

Shadow Price of Carbon (Thousand USD/Year)															
	2020					2025					2030				
	BAU	**S1**	**S2**	**S3**	**S4**	**BAU**	**S1**	**S2**	**S3**	**S4**	**BAU**	**S1**	**S2**	**S3**	**S4**
Low Range (40-50 USD/ton CO2)	308,728	308,860	308,733	308,712	308,864	343,708	387,078	343,715	351,174	495,087	382,636	657,706	382,641	509,025	844,711
High Range (80-100 USD/ton CO2)	617,456	617,720	617,466	617,424	617,728	687,416	774,155	687,429	702,349	990,173	765,272	1,315,411	765,282	1,018,051	1,689,423

CHAPTER VII

CONCLUSION AND RECOMMENDATIONS

In the context of assessing the potential of CCS deployment in Lebanon, this research has focused on carbon source characterization, the first component of the CCS value chain.

This study has updated the CO2 emissions inventory for the energy industries in Lebanon, which was lastly updated in 2015. CO2 emissions generated by the seven power plants were calculated based on the fuel consumption in each industry and country-specific emission factors. For the first time in Lebanon, CO2 emissions from the energy sector were calculated using Tier 2 approach of the IPCC, which relies on calculated country-specific emission factors. The results indicate that the difference between country-specific emission factors and default emission factors is less than 1%. Considering that the emission factors depend primarily on the quality of fuel being used, the Lebanese government should include Carbon Content (% C by mass) and Net Calorific Value in the list of parameters to be tested when receiving fuel barges in the country. Accordingly, emission factors should be reviewed on regular basis.

Based on the baseline data collected and on future development trends of influencing factors, CO2 emissions were studied, using Long Range Energy Alternatives Planning System, under five different scenarios including: (i) Business-as-usual, (ii) Scenario 1 – proposed energy structure adjustments by the MoEW's Updated Policy Paper for the Electricity Sector (2019), (iii) Scenario 2 – increased share of renewable energy in the Lebanese energy mix, (iv) Scenario 3 – proposed energy structure adjustments and increased share of renewable energy, and (v) proposed energy structure adjustments and different fuel type utilization.

Results showed that the forecasted CO_2 emissions are expected to be the highest, 16,905 thousand tonnes of CO_2 by 2030, under the implementation of proposed energy structure adjustments by the MoEW's Updated Policy Paper for the Electricity Sector (2019), with the use of Diesel Oil instead of Natural Gas in the energy industries (Scenario 4). The implementation of proposed energy structure adjustments, with the use of Natural Gas (Scenario 1), will generate the second highest CO_2 emissions, around 13,162 thousand tonnes of CO_2 by 2030. Increasing the share of Renewable Energy, coupled with the implementation of the proposed energy structure adjustments, will reduce CO_2 emissions to 10,187 thousand tonnes of CO_2 by 2030. On the other hand, increasing the Renewable Energy share without implementing adjustments in the energy sector will not impact CO_2 generated by power plants, but will reduce the energy deficit and hence the reliance on private power generation.

The study's outcomes are expected to inform policy making and allow for the development of strategic environmental planning for Lebanon based on detailed energy analysis and updated data. It shall also pave the way for the development of a CCS/CCUS road map in Lebanon. Moreover, the quantities of CO_2 emissions generated under the different scenario will be essential for the assessment of the technical and financial feasibility of potential CCS projects. A detailed feasibility study will be needed to evaluate the soundness of implementing CCS in Lebanon. Nevertheless, future studies should also focus on assessing the quality of CO_2 and the potential presence of impurities which might impact the identification of the optimal combination of separation technologies, transportation infrastructure, and safe and efficient geological sequestration mechanisms.

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