AMERICAN UNIVERSITY OF BEIRUT

COST EFFECTIVE ANALYSIS OF REDUCING SO2 EMISSIONS FROM POWER PLANTS

by
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ABSTRACT
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The aim of this work is to present and assess four alternatives for reducing sulfur dioxide emissions from thermal power plants. The 4 alternatives include using low-sulfur content fuels, installing flue gas desulfurization systems, switching to natural gas, and partially shifting to PV power.

An economic model was established to assess which of the alternatives is the most feasible. The model involves all costs and revenues associated with each of the alternatives. The model was also applied to the Zouk Lebanese power plant.

As there were plenty of uncertainties associated with various parameters, one-way and multiple sensitivity analysis were carried to assess which of the parameters had the biggest effect on the choice of technology to be used.

Results revealed that the natural gas alternative is the most economical for the Lebanese case in most scenarios. This alternative would be more appealing if this natural resource is found in Lebanese offshore territories, saving millions of dollars in purchasing and transporting.

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CHAPTER 1

INTRODUCTION

1.1. Historical Remarks

For centuries, humans relied on wood as their primary source of energy. As coal emerged for electricity generation in the 19th century, it instantly became the king of power. This status did not last for long as it was dethroned by oil and gas where in 2021, fossil fuels accounted for 61% of the world's primary energy consumption [1]. While the energy sector is vital for economic growth and development of nations, its generation throughout utilizing traditional sources, such as coal, oil, and gas, has led to environmental degradation, including global warming, ozone layer depletion, air pollution, and the exhaustion of natural resources.

According to the International Energy Agency (IEA), the energy sector accounts for more than two-thirds of global greenhouse gas (GHG) emissions, with the power sector taking the largest share of 40% [2]. Furthermore, the US Energy Information Administration (EIA) forecasts revealed that the global demand on electricity will increase by 50% by 2050 [3]. This increase is associated with an increase in energy-related emissions, as most of the power plants rely on fossil fuels for electricity generation.

These fuels contain and release plenty of effluents into the atmosphere such as carbon dioxide, oxides of sulfur and nitrogen, and particulate matter. According to the World Health Organization (WHO), these emissions are responsible for the deaths of approximately 4.2 million people annually [4].

Taking the health impacts of sulfur dioxide, it can lead to inflammations and various respiratory diseases such as asthma, chronic bronchitis, and even death if found in sufficient quantities. As for its effect on the environment, it can combine with water to form acid rain which has severe consequences including deforestation, corroding building material, and acidifying water.

In Lebanon, the electricity sector has been facing chronic problems for decades due to technical, administrative, financial, and political challenges. From one side, there are the old power plants and networks that reduce the efficiency of the system, and there is the bill collection issue. Recent statistics revealed that Electricite Du Liban (EDL) has managed to increase the percentage of bill collection up to 85% [5]. This, not to mention the subsidies that the Lebanese government has imposed on tariffs for decades, which induced a debt ranging between 1 to 1.5 billion USD annually [6]. Most importantly, these power plants operate on heavy fuel oil which can have significant environmental consequences. According to the Fourth Biennial report on Climate Change, that was published in 2021, the Lebanese energy sector is responsible for around 80% of GHG emissions [7]. While consecutive governments have pledged to solve these issues, and even set a goal to diversify the sector's generation mix by achieving 30% power generation from renewables in 2030, the implementation have been slow mainly due to political factors and the current challenging economic situation. Therefore, comprehensive efforts are needed if Lebanon aims to overcome the obstacles hindering the sector's transformation. This transition into a more sustainable electric sector is critical for Lebanon's economic development, environmental sustainability, and social welfare.

1.2. Problem Statement and Objectives

Due to the increased demand for energy in Lebanon, and considering the alarming pollution levels, and the recent economic crisis, it is crucial to reduce the emissions that are being released from power plants. This purpose can be achieved in several ways, including utilizing better quality fuel with lower sulfur content, or natural gas that is regarded as the cleanest and most efficient type of fossil fuels. Another alternative is installing Flue Gas Desulfurization (FGD) systems that work to reduce the percentage of sulfur dioxide in the flue gas before being emitted. A fourth, and more appealing alternative has emerged lately which is transitioning to renewable energy that will not only reduce the amount of SO_2 being released, but also exceeds to other contaminants, and provides diversity of resources for the sector and for the whole country.

Accordingly, this thesis research will target these above-mentioned techniques for their standing and assessing their impact, as well as their economics. In such a way, not only the level of SO2 emissions will be reduced, but also Lebanon will be adopting the best economically viable option. An economic model will be developed that will evaluate all the four alternatives, followed by a case study on an established power plant in Lebanon which includes sensitivity analysis that permits assessing the impact of different parameters.

1.3. Overview of the Thesis

The methodology in this paper is as follows:

- Chapter 2: Literature review of the previously four mentioned alternatives along with an overview on the status of electricity generation in Lebanon and emission levels.
- Chapter 3,4,5,6: Developing an economical model for each of the alternatives and their parameters.
- Chapter 7: The case study on an existing power plant.
- Chapter 8: Carrying out a sensitivity analysis on the parameters with high degree of uncertainty.
- Chapter 9: Analysis, discussion of results, and conclusions.

CHAPTER 2

CURRENT STATUS OF THE ELECTRICITY SECTOR IN LEBANON AND THE POSSIBLE SOLUTIONS FOR REDUCING SO2 EMISSIONS

2.1. Introduction

The Lebanese power sector has been deteriorating for decades, specifically from the Lebanese civil war that started in 1975, up until this day. While various Lebanese governments have tried to revive the sector through a series of rehabilitation programs for the power plants, aided by power ship barges from Turkey, and more recently raising the electric tariffs to somehow lessen the financial losses and comply with the International Monetary Fund (IMF) director, the sector is still suffering from enormous financial losses, not to mention the mismanagement that led to this.

As a part of their strategies to support the sector, consecutive governments have been subsidizing electricity bills, leading to an annual debt ranging between 1.5 to 2 billion USD [8]. According to the Ministry of Energy and Water, MEW, the estimated cost of electricity generation was 0.26$ per kWh in 2020, while beneficiaries were charged at a price of 0.09$ [9]. This not to mention the technical losses, electricity thefts, and inefficiencies due to old power plants. These combined account for loosing around 42% of the electricity generated in 2021 [10].

According to the Ministry of Energy and Water, Lebanon has an installed capacity of 2,200 MW, while the demand stands at 3,500 MW [10]. And while there are various sources of electricity in the country, fossil fuels dominate the market by having a share of more than 85% from the energy generation mix [11].

While governments have pledged for improving the situation, whether by diversifying the energy mix, launching initiatives such as the net-metering schemes and feed-in tariffs, or by raising awareness amongst citizens to pay their bills and consume responsibly, they are still far from accomplishing their goals, mainly due to the lack of political will, institutional barriers, and the challenging economic situation.

2.2. Lebanese Thermal Power Plants

In Lebanon, there are seven thermal power plants (four of them operate on diesel oil, while the other three operate on heavy fuel oil). These plants all together were responsible for producing around 97% of the country's electricity in 2019 [12]. The problem with these facilities is that they became old, operating on polluting fuels, and located in highly populated areas which raises the percentage of affected people. Further information on these power plants can be found in the table 1 [13]:

Table 1: Thermal Power Plants in Lebanon

Thermal Power Plant	Fuel Type	Capacity (MW)	Year Commissioned
Zouk	Heavy fuel oil	805	1984 – 1987 – 2017
Zahrani	Diesel oil	465	1998 – 2001
Deir Ammar	Diesel oil	465	1998 – 2002
Jieh	Heavy fuel oil	418	1970 – 1981 – 2017
Hrayche	Heavy fuel oil	75	1983
Baalbeck	Diesel oil	70	1996
Tyr	Diesel oil	70	1996

2.3. Emissions from Thermal Power Plants

The increasing demand on electricity in the past few decades led to an increase in the generation, which eventually resulted in higher emissions. In a country like Lebanon, that depends heavily on fossil fuels for electricity generation, this can be problematic.

The main effluents released from power plants are carbon dioxide, oxides of sulfur and nitrogen, and particulate matter, which can all lead to severe environmental consequences and respiratory diseases.

However, the emissions being released depend on a variety of factors such as the type and quality of fuel, efficiency, and age of the power plant. Yet, a thermal power plant produces, on average, the emissions listed in table 2 [14]:

Table 2: Emissions from Power Plants

Type of pollutant	**Emission rates (g/kWh)**
CO_2	850 - 950
NO_x	4.22 - 4.38
SO_2	6.94 - 7.20

The Fourth biennial report of Lebanon to the UNFCCC that was submitted in 2021 clearly indicates that the energy sector in the country is responsible for 92% of the SO_2 emissions with values reaching around 45 Gg per year, with a projected annual increase of 3.4% [7]. These figures reflect the status where these plants were in full operation. The share of the main economic sectors is presented in Figure 1.

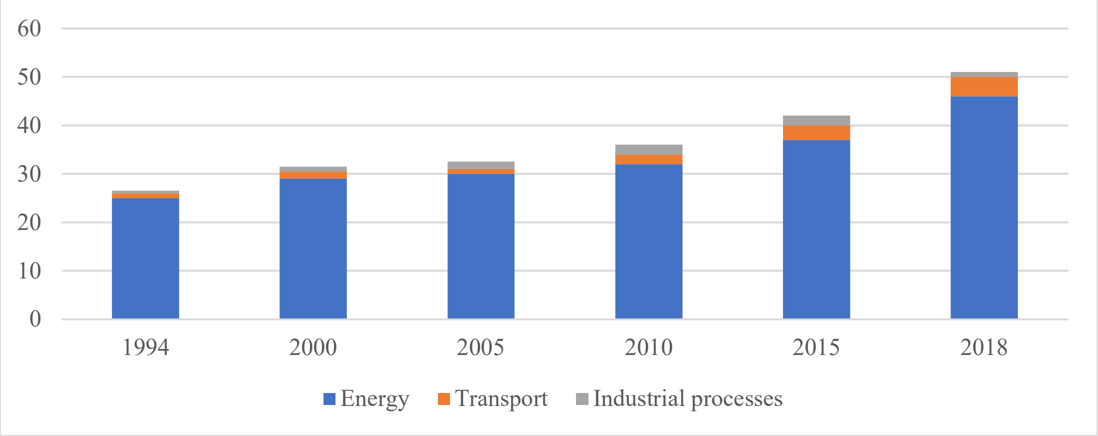

Figure 1: Emissions of SO_2 by sector in Lebanon in Gg [7]

While the Lebanese government has tried to control, or lessen, these emission by updating its standards on fuel quality, they were still far different than those introduced by World Health Organization (WHO). Table 3 shows a comparison between the standards introduced by the Lebanese government in 1996, and those of WHO [15]:

Table 3: Comparison between Sulfur dioxide standards as stated by Lebanese government and WHO

	WHO guidelines (µg/m^3)	National standards based on MoE decision 52/1 of 1996 (µg/m^3)
Sulfur dioxide	500 (10-minute mean)	350 (1 hour mean)
	20 (24 hour mean)	120 (24 hour mean)
		80 (annual mean)

2.4. Possible Solutions for Reducing SO_2 Emissions

Thermal power plants are well-known for their polluting capacities. Year after year, the level of pollutants emitted into the atmosphere has resulted in a series of climatic and health issues. Given that, governments all over the world have been keen on finding a way to reduce emissions. Research and development in the past decades have led to the invention of plenty of technologies that serve this purpose and treaties have been ratified to oblige countries to reduce these and other emissions.

2.4.1. Switching to Low-Sulfur Content Fuels

Low sulfur fuels are characterized by having an extremely low sulfur content, usually around 0.5% [16]. This pollution prevention method is regarded as one of the simplest, fastest, and sometimes the most economic ones. Even though these premium fuels cost more than regular, polluting ones, they can save enormous amounts of money in operating and environmental costs, and thus becoming more economically feasible than their counterparts. Additionally, this option is preferred for old power plants where it is not economic to install an FGD system that have a lifetime of around 20 years.

Normally, while planning a certain project such as a new power plant, the emission levels should be considered and must comply with international standards such as the World Bank Group standards. While there are plenty of specific controls present for operating a plant in an environmentally friendly way, most of them may not be required if the plant is to be operated on low-sulfur high calorific value fuels, giving this option an added advantage [17].

A study was carried out on thermal power plants in Kuwait, whereby four scenarios were considered to observe SO_2 emission levels based on the Sulphur content in the fuel. The results revealed that in the base case scenario, the emission concentration recorded was

2244.19 µg/m^3 which exceeds the national standard. On the other hand, using low-sulfur fuels (0.5% sulfur content) resulted in a maximum hourly emission of 370.62 µg/m^3 [18].

2.4.2. Installing Flue Gas Desulfurization (FGD) Systems

FGD systems are regarded as post-combustion techniques for reducing the SO_2 being emitted from power plants. There are several types of such systems, such as the wet FGD systems, the dry type systems, and the alkali scrubbers. However, the one to be considered in this study is the wet FGD system due to commercial reasons.

2.4.2.1. Wet FGD Systems

Wet FGD systems, also known as wet scrubbers, are the most utilized type of FGD systems. The process involves mixing the flue gas with a spray of water – lime (CaO), which aims to extract the SO_2 found in the gas. In some cases, limestone ($CaCO_3$) is used instead of CaO as it is economically cheaper and more abundant. Yet, this can lead to lower efficiencies in extracting SO_2.

The working principle starts by gas handling, where in this stage flue gas passes through a collection system, specifically designed for collecting and removing ash and other particulates (ESP or gravitational collector). After that, the gas is slightly heated and then transferred into a spray tower where it flows from the bottom upwards and it will be subjected to the limestone slurry, removing more than 90% of the SO_2 content. SO_2 in its turn will react with calcium carbonate ($CaCO_3$) which will yield Calcium Sulfite ($CaCO_3$) and Calcium Sulfate ($CaSO_4$).

The following equations are obtained:

$$SO_2 + H_2O \longrightarrow H_2SO_3 \text{ (1)}$$

$$CaCO_3 + H_2SO_3 \longrightarrow CaSO_3 + CO_2 + H_2O \text{ (2)}$$

$$CaSO_3 + H_2O \longrightarrow CaSO_4 \text{ (3)}$$

The first equation is called absorption, whereby SO_2 is absorbed from the flue gas. In the second equation, the mixture reacts with $CaCO_3$ producing calcium sulfite, carbon dioxide, and water. This is referred to as neutralization. The third equation, however, is called oxidation whereby $CaSO_3$ reacts with water to produce Calcium Sulfate.

It is worth mentioning that there exists a mist eliminator at the top of the spray tower, which job is to remove any spray droplets carried by the gas stream, see Figure 2. On the other hand, the slurry after mixing with the gas will return to the bottom of the tower whereby it enters a reaction tank. The purpose of this tank is to facilitate the oxidation process, turning calcium sulfate into crystalline hydrated sulfate of calcium. This happens by exposing the sulfite mixture into compressed air at pre-designated rates. Furthermore, the system is equipped with a feed and bleed system, the job of which is checking and regulating the pH of the slurry. It is worth noting that the pH of the slurry should be maintained at a value of around 6. This can be achieved by adding fresh limestone. When the pH is greater than 7, the slurry is sent up the tower, whereas if it falls below 6 then it will be circulated to a dewatering system.

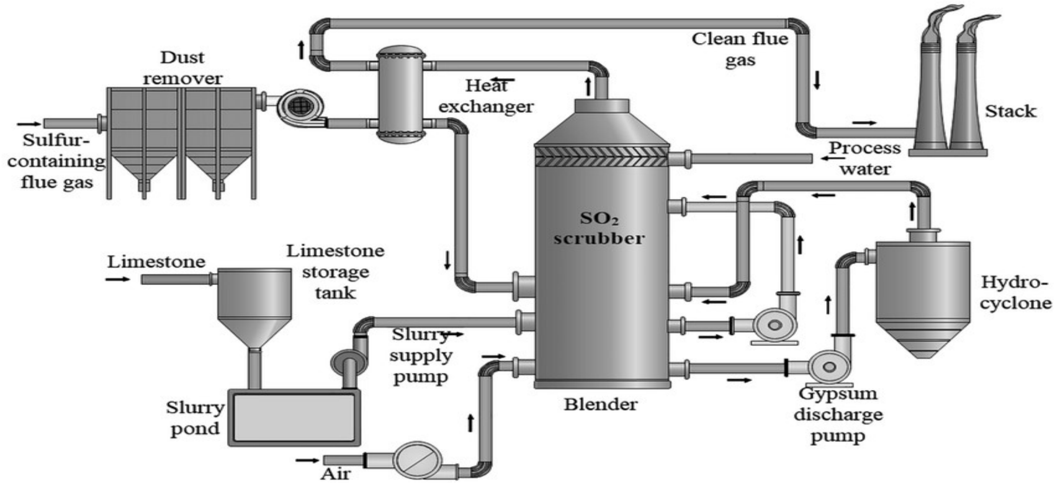

Figure 2: Diagram of wet FGD system [19]

As for the solids present in the slurry, they are normally removed using a settling tank or a thickener. The mixture is then sent to a filter and centrifuge to separate water from the precipitated salts before going back to the spray tower. The obtained solids, which are sulfates, can be used in different types of industries such as cement production, road building, or agriculture.

Wet FGD systems are highly desirable for their high SO_2 removal efficiencies which range between 90 and 97% and can even reach 99% in newer technologies [20]. On the other hand, they require enormous amounts of water and electric energy (2 to 5% of output power of the plant), plus their capital cost is significantly high.

2.4.2.2. Dry FGD Systems

Dry FGD systems, also known as dry scrubbers, use a liquid slurry with very little water content for SO_2 removal. The process starts by producing the slurry which happens in a tank equipped with a shaker. Water and lime are added to this tank so that a slaked lime mixture can be produced, which is then diluted and processed to eliminate impurities. The slurry is then injected into a spray absorber with the help of a flow control valve, as shown in Figure 3. The amount injected varies according to the concentration of SO_2.

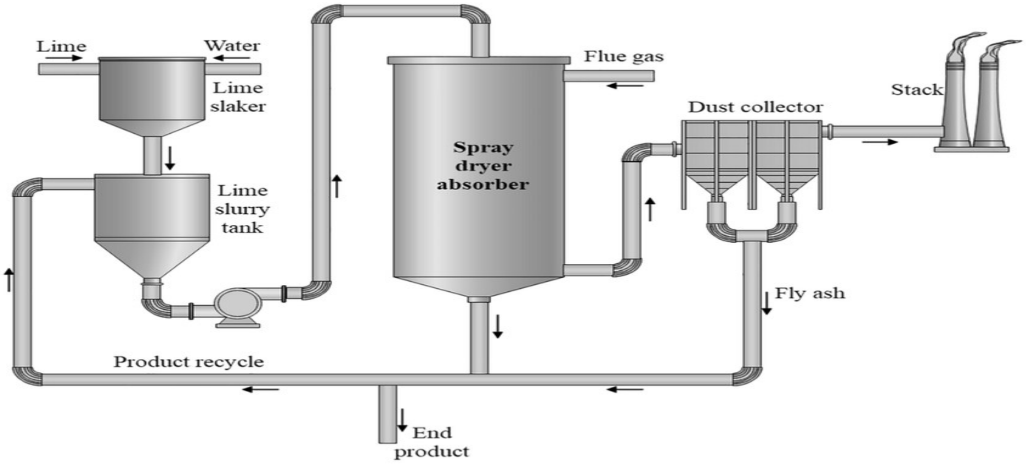

Figure 3: Diagram of dry FGD system [21]

Once the solution reaches the spray absorber, it is sprayed onto the pre-heated flue gas leading to the capture of SO_2. And due to the small size of the droplets, and the high temperature of the gas, the slurry is quickly dried, forming sulfite particles which are carried with the desulfurized gas. These particles will be collected using fabric filters or electrostatic precipitators (ESPs), leaving the de-sulfurized gas to be emitted into the atmosphere. The chemical reactions involved in this process are the same as those of wet scrubbers.

One of the privileges this system has is that the materials to be disposed are in the form of a dry powder, which reduces disposal issues. Also, the system has a lower operating cost than that of wet scrubbers. Yet, it has a much lower efficiency which ranges between 85 and 90% [20].

2.4.2.3. Single Alkali Scrubbers

Also known as the Wellman – Lord recovery, is a process that involves using water solutions of sodium or ammonia (NaOH or Na_2SO_3) to remove SO_2. The process starts by sending the flue gas from the boiler through a particulate collection system and then to the SO_2 absorber. In the latter, the water solution works to remove SO_2 from the flue gas, forming sodium bisulfite.

This formed product is taken to a surge tank that works to regulate the flow rate. After that, the mixture is sent to circulation system, commonly known as evaporatory-crystallizer that converts sodium bisulfite into a slurry by the aid of the low-pressure steam coming from the turbine exhaust. Water is then separated from SO_2 using a condenser while the sulfite slurry is recirculated into the dissolving tank and sent again to the absorber. The produced SO_2 can be used for making sulfuric acid, SO_2 liquid, or element sulfur.

Such systems are characterized by having high efficiencies varying between 90 and 95%, yet they have a high energy consumption of 6 to 8% [22].

2.4.3. Switching to Natural Gas

Natural gas is an odorless, colorless, and flammable gas that is almost entirely made from methane, with trace amounts of ethane, propane, and sulfur. Natural gas is regarded as one of the most used energy sources in the world due to the vital role it has in transitioning to low-carbon energy production.

According to the data obtained from EIA's website, natural gas power plants emit around 2.21 kg of SO_2 per 1 million kWh of energy produced [23]. While this reveals that even natural gas produces SO_2, the amount is still negligible in comparison to the amount of SO_2 produced from power plants running on oil, that is 7,070 kg per 1 million kWh [14]. Given that, utilizing natural gas for power generation is a better option for reducing SO_2 emissions. So, how does this technology work?

Normally, there are two types of gas-fired power plants: The open cycle and the combined cycle gas and steam turbine (CCGT) power plants. In the following section, each technology will be discussed.

2.4.3.1. Open-Cycle Gas Turbine

These types of plants are regarded as one of the major sources of electricity for peak power demand on grids. The reason behind their growing popularity is because they are fast-acting units that can be installed and removed at no time. They are also characterized by having good efficiencies ranging between 35% and 45% [24].

Normally, as shown in Figure 4, there are three components in such a system: a compressor, a combustor, and a power turbine. The system operates by taking fresh air from the atmosphere which will be passed through a series of compressor stages before being mixed with fuel once it is in the combustion chamber. This will yield a high-pressure hot gas, usually known as velocity gas, which is utilized to spin the turbine by hitting its blades. In its turn, the turbine is connected to the rotor of the generator, and thus electricity is generated. Emissions and excess heat will be exhausted back to the atmosphere at high temperatures, reaching nearly 5,500 degrees Celsius [26].

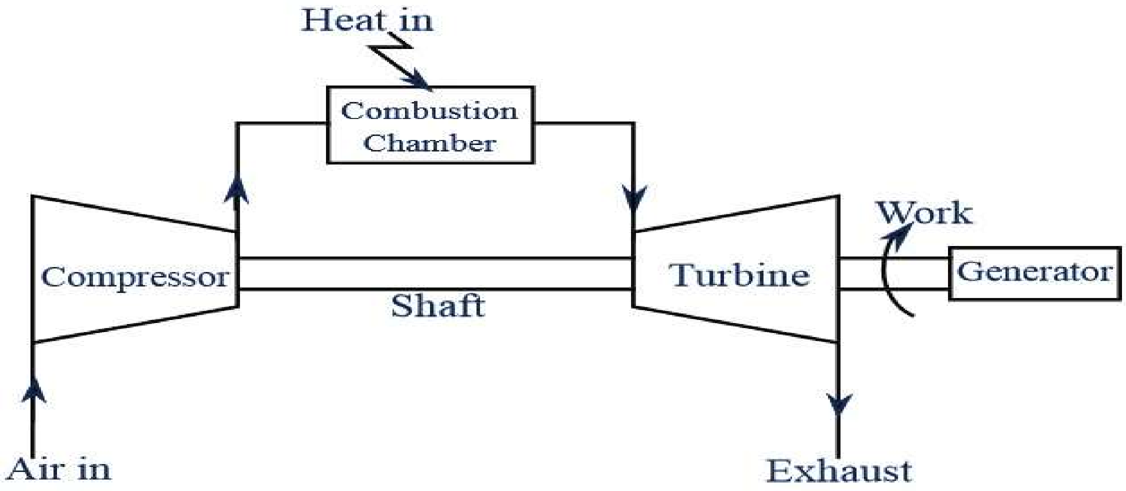

Figure 4: Diagram of open cycle gas turbine [25]

Such systems are favorable due to their short warm-up time. The turbine can be accelerated from a cold start to full operating capacity without warming up, which can be of high benefit during peak times. Additionally, they are smaller than closed-cycle power plants, and thus they occupy a much smaller area.

Furthermore, such systems do not require having a cooling medium, and any type of fuel can be used in the combustion chamber from heavy diesel oils to high octane gasoline. On the other hand, there are some drawbacks associated with utilizing open cycle systems. For a starter, they have a lower efficiency as a part of the work produced by the turbine is lost in the process since the compressor and the turbine are installed on a common shaft. Also, they have a high sensitivity to any changes in atmospheric temperature, pressure, and humidity that all can affect the efficiency of the system. Finally, the compressor and the turbine are susceptible to erosion due to the dust and depositions, which may result in lowering the efficiency of the system.

2.4.3.2. Combined Cycle Gas Turbine (CCGT) power plants

The combined cycle gas and steam turbine power plant operates by using two different types of turbines: a gas turbine and a steam one. In principle, it works by recycling the fuel being used to achieve the maximum possible electricity output with higher conversion efficiency.

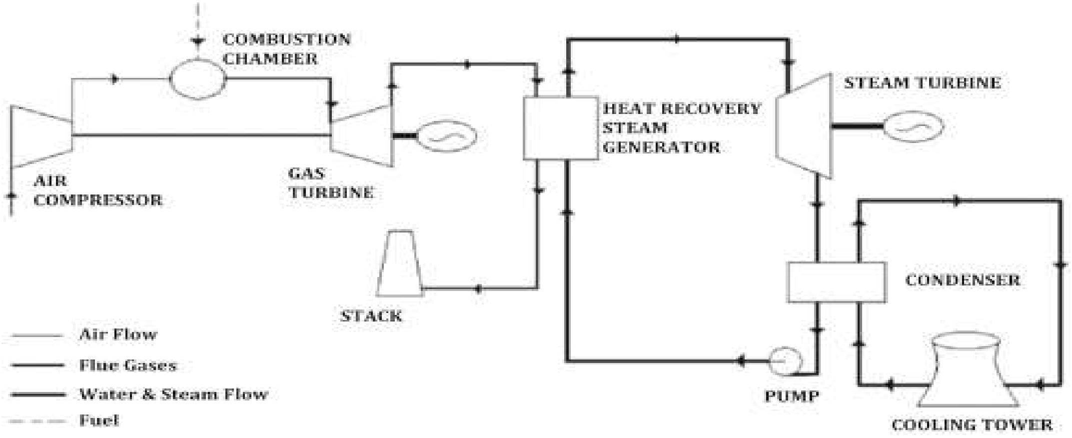

Figure 5: Diagram of combined cycle gas and steam turbines [27]

In reference to Figure 5, gas is initially fed to the plant via a pipeline, while air is drawn from the atmosphere and then it is compressed. Next stages involve mixing and burning air with gas in the combustor. The product of this operation is a high pressure, high temperature steam which is used to drive the blades of the turbine connected to a generator.

As for the exhaust gases, they are taken to a heat recovery steam generator. In this phase, the hot gases are used to boil water in pipes so that superheated steam can be produced. This superheated steam driven across a steam turbine that drives another generator and then to a condenser where it is cooled back to water and prepared for another cycle, thus increasing the efficiency of the whole system. The efficiency of such systems can range between 50% to 60% [28].

2.4.4. Switching to Renewables

Humans have been depending on fossil fuels for generating electricity for ages. With this heavy reliance comes an expensive cost: The environment. It is well known that fossil fuels utilization is a polluting process in all its stages, from extraction, to transportation and burning, and finally to the disposal of the waste coming from it. These activities produce plenty of pollutants that can affect the environment and people's health as well such as carbon dioxide, sulfur dioxide, particulate matter and more.

However, and with the risks of global warming, several conventions and treaties have been ratified in the past few decades, such as the Paris Agreement in 2015, which aims to reduce greenhouse gases (GHG) being emitted into the atmosphere. Another example is the United Nations Sustainable Development Goals (SDGs) which were introduced in 2015, and to be achieved by 2030. These 17 goals aim to achieve a better, more sustainable world for humans. Some of these goals are energy related, such as goal 7: affordable and clean energy for everyone. Other reasons behind the switch from fossil fuels is that their prices are highly unpredictable and can fluctuate depending on a variety of factors.

From there, countries all over the world saw a potential in renewable technologies, mainly hydro, wind, and solar, as they are inexhaustible, cleaner, available for everyone, and are getting much cheaper with the years. This will also create a more diversified energy mix for the country, hence enhancing its energy security. In 2021, renewable technologies scored an astonishing 13.5% of the world's power generation mix [29]. As for the types of renewable technologies present, there are many available options such as solar, wind, hydro, biomass, and geothermal. Out of these, only solar, wind, and hydro power are going to be discussed in this paper as they are the most applicable for Lebanon.

2.4.4.1. Solar Energy

Almost every location on Earth's surface receives sunlight throughout the year. However, the amount of solar radiation received varies accordingly. On average, the Earth's atmosphere receives a daily amount of 1367 W/m^2, out of which around 1050 W/m^2 will reach the Earth's surface. In other words, a panel having an area of one squared meter will receive a power of about 1kW/m^2 given that it is directed towards the sun [30]. This can be regarded as an unlimited power source which is available at almost no operating and environmental cost.

Solar power is regarded as the fastest growing renewable energy technology. By 2020, the amount of globally installed solar power has reached a value of 710 GW [31]. What made it popular is probably its ability to be installed domestically at homes and rooftops where it can provide capacities ranging between 3 to 20 kW, or it can be grouped as a powerplant, generating hundreds of megawatts. In addition, the costs of buying and installing a system have fallen drastically over the past years, where prices fell by 93% between 2010 and 2020 [31].

However, the output of a solar system depends on a variety of factors such as the system efficiency, the panel conversion efficiency, and the panel inclination angle. So, how do solar panels work?

Solar panels are made up of a group of solar cells, as shown in Figure 6. These cells, in their turn, are constituted of silicon, a semiconductor material. They are structured in a way that there is a positive layer and a negative one, thus creating an electric field. When the photons present in sunlight hit the solar cell, the electrons will be freed from their atoms. These electrons will flow in an electric circuit to generate electricity.

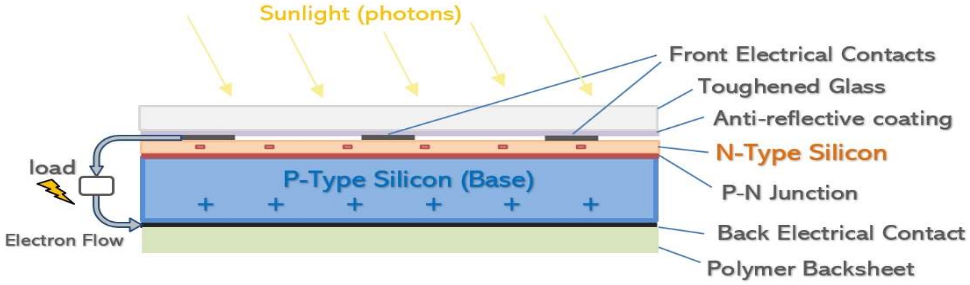

Figure 6: Illustration of a PV cell [32]

Conveniently, as the number of panels increases, more energy will be generated. However, PV panels produce a direct current (DC), and therefore inverters are used to obtain an alternating current (AC). Inverters also serve other purposes, such as ground fault protection and provide statistics about the system like the voltage, current, and energy production. Most systems use central inverters, yet new technologies such as the micro-inverter are becoming popular as it enables each solar panel to perform at its maximum potential [33]. The system also includes batteries for storage purposes. This can be of high benefit so that solar power can be used at peak times or at night.

As for the weather condition, and opposite to what is believed by the public, solar panels efficiency increases in cold weather, just like any other electronic, allowing the panel to generate more electricity in the same time frame. However, this does not mean that solar panels perform better in winter. One should consider that in summer the day is longer, which means more sun hours, and there are no clouds to block the sunlight. Hence, solar panels are more likely to produce more electricity in summer than in winter.

According to Pierre El Khoury, the director of the Lebanese Center for Energy Conservation (LCEC), Lebanon has witnessed solar installations of around 100 MW between 2010 and 2020. This value was matched in 2021 alone and in 2022 solar installations exceeded 250 MW [34].

2.4.4.2. Wind Power

Humans have always been keen on harnessing the power of wind throughout their lives. From windmills and sailing by ships thousands of years ago, to electricity generation in the 20th century. To understand the working principle of this technology, one should know where wind comes from. The origin of wind is radiation from the sun, where at the local level there is a variation in the solar absorption between land and water, leading to convection currents and pressure winds. This is also affected by the position and rotation of the Earth with respect to the sun. On the global scale, the high intensity solar flux found at the equator causes the warmer air to rise upwards, which creates areas of low pressure, and cooler air to flow in from the North and South. It is estimated that 0.5% of the incident solar power (1.37 kW/m^2) is converted into wind, yielding a 7 W/m^2 power [35]. Thus, wind power depends on the sunlight heating the atmosphere, the rotation of the Earth, and the irregularities found on Earth's surface.

Normally, generating electricity through wind demands having a wind turbine. The wind turbine primary constituents are the rotor blades, generator, and a computer. The system works by converting wind energy into mechanical one. As the wind hits the rotor blades, the pressure will decrease on one side of the blade, creating a pressure difference between the two sides causing the blade to spin. These forces are called the lift and drag. In its turn, the rotor is connected to a generator that works in converting the obtained mechanical energy into electrical one. As for the computer, if found, it is used to control the direction of the blades to have better efficiency.

Wind turbines can vary in size, from less than 100 kW (used for residential applications) to several megawatts (used in industries and utility powerplants) [36]. It is worth noting that larger wind turbines are more cost effective, especially if grouped together into a wind plant. The wind turbine output power can be calculated using the following equation:

$$P = 0.5 \text{ x } D \text{ x } A \text{ x } Cp \text{ x } V^3 \text{ x } Ng \text{ x } Nb \text{ [36]}$$

Where, P is the power in Watts (W)

D = air density (1.225 kg/m^3 at sea level)

A = rotor swept area exposed to the wind (m^2)

Cp = coefficient of performance (0.35 is considered good)

V = wind speed (m/s).

Ng = generator efficiency

Nb = gearbox efficiency

The advantages of wind turbines are plenty, from producing clean energy without any emissions, to being economically viable, and do not require any type of fuel or water to operate. Yet, there are some limitations associated with wind turbines as their power density is considered practically low, and thus many of them are needed to generate enough energy. Also, there is an environmental cost for their production and maintenance, not to mention the noise pollution. Yet, one feature of wind turbines is that they can be installed offshore as well, which eliminates the noise pollution problem. In this technique, the turbines can be more efficient as they are subjected to the powerful ocean winds. However, this may create difficulties in delivering the generated electricity to the grid, plus it may cause some navigation issues for the ships.

2.4.4.2. Hydropower

For thousands of years, humans have been relying on the power of water to accomplish certain tasks. From irrigation purposes at the ancient Egyptians times, to wheat grinding 2,000 years ago, and finally to electricity generation [37]. Hydropower, also called hydroelectric power, is a form of renewable energy source that generates electricity through the flow of water. It is regarded as one of the most desirable renewable energy sources, and in 2020 the world generated around 4,335,820 GWh of hydroelectric power [38]. Taking Norway as an example, which is an oil and gas exporter country, it depends highly on hydropower for electricity generation whose share reached 92% in 2020 [39].

Generally, to generate electricity using the power of water a dam is needed to control the water flow, as well as a turbine and a generator, see Figure 7. The working principle of such a technique is quite simple, as the dam creates a reservoir behind it which will cause a high-pressure flow of water when the gates are opened. This flowing water will pass through a pipe, normally known as penstock, to hit the placed turbines at the bottom. This will cause the blades of the turbine to spin, which in turn spins the shafts to the generators. As for the water, it continues its flow normally into the river. It is worth noting that the electricity generated depends on the volume of water and the elevation. The greater these two are, the more energy can be generated. Utilizing this will also give the operator an option to store energy to be used during peak hours. This is done by closing the gates, stopping electricity generation, and preserving water for high demand hours. Nevertheless, hydropower can be used without building a dam or having a reservoir, but such an option is used for small scale applications [37].

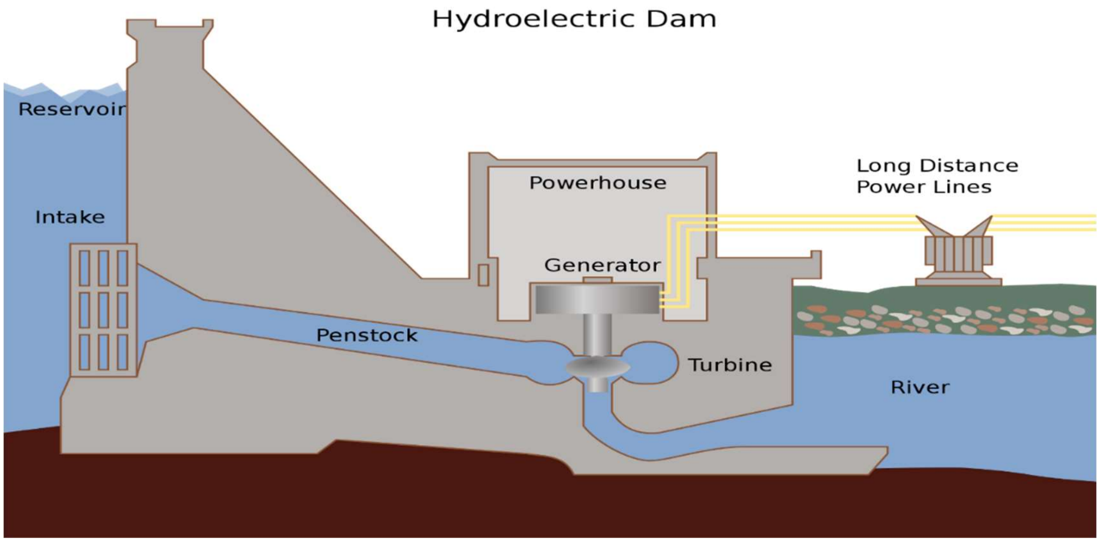

Figure 7: A scheme for a hydro powerplant [40]

Other than producing electricity, hydropower has plenty of advantages such as being a long-term sustainable solution, where dams are designed to stay for decades. Additionally, the created lakes can be used for irrigation or holding sports, cultural, and touristic events. On the other hand, the building process can be of a very high cost and should be done according to the best standards possible. Also, the flooding of large areas of land means that the natural environment is lost, not to mention that building dams may trigger earthquakes.

CHAPTER 3

THE LOW SULFUR FUEL ALTERNATIVE

Generally, the fuel used in power plants that are fitted with FGD systems is that which has 2.2% or higher sulfur content. While the FGD system works to remove more than 90% of the sulfur content, another alternative to reduce SO_2 emissions is using low-sulfur content fuel.

3.1. Fuel Oil Prices

Fuel prices are highly influenced by the political events occurring globally, and can change accordingly, not to mention the stretch in the supply and demand, making this option a risky one especially for long-term projects. This is illustrated in Figure 8 [41], where it represents the major events that made an infliction on crude oil prices between 1968 and 2022.

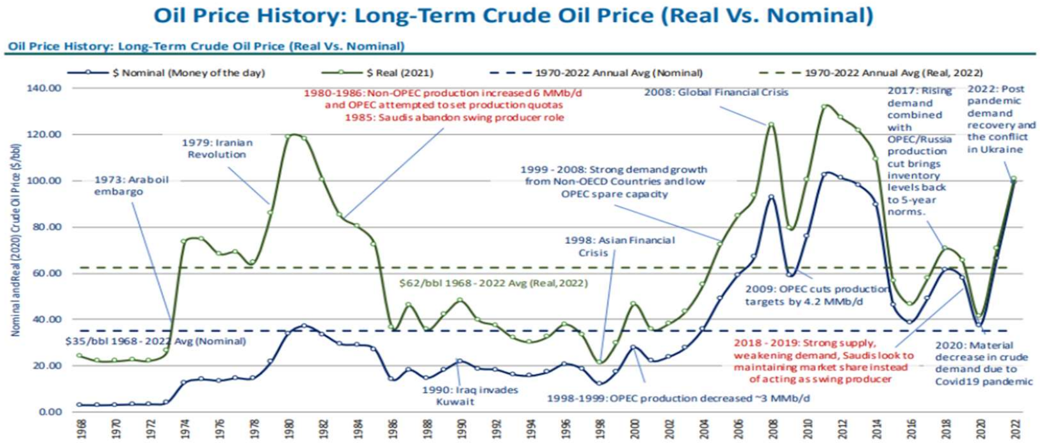

Figure 8: Historical Changes in Crude Oil Prices for years 1968 – 2022

The data on premium fuels prices are obtained from the website of the Organization of the Petroleum Exporting Countries (OPEC). Note that the fuel prices were taken from the United States East coast market – New York, as this chart has the prices of both the fuel with 0.3% sulfur content and that which has 3% sulfur content [42].

Table 4: US East Coast Market - spot cargoes, New York $/barrel, duties and fees included

Year	**Month**	**Regular gasoline unleaded 87**	**Gasoil**	**Jet kerosine**	**Fuel oil (0.3% S)**	**Fuel oil (3% S)**
2021	November	100.78	100.43	97.55	92.28	69.91
	December	91.80	94.33	92.12	88.45	66.37
2022	January	102.81	109.86	107.23	101.02	79.27
	February	115.43	121.00	119.03	112.79	85.91
	March	134.68	158.55	158.01	149.32	100.95
	April	135.92	172.32	238.78	148.24	97.19
	May	161.70	190.63	224.38	155.83	102.26
	June	172.02	182.90	177.23	162.70	103.26
	July	145.90	154.69	153.38	144.45	91.34
	August	124.36	151.06	146.74	130.55	87.69
	September	110.26	143.93	147.65	121.67	68.18
	October	132.91	182.33	179.98	122.15	65.00
	November	120.38	172.17	157.91	115.52	67.01

Using the data of table 4, specifically the February 2022 \$/barrel value it is found that:

- The average price of 0.3% sulfur content fuel oil is \$112.79/barrel.
- The average price of 3% sulfur content fuel oil is \$85.91/barrel.

These values shall be converted to \$/tonne, and for that the density of the fuel oil should be considered. EDL requires a fuel oil density of around 0.98Kg/L or less. And thus, by using the appropriate conversion factors we obtain:

- \$112.79/barrel. 1 barrel/42 US gallons. 1 US gallons/3.785L. 1 L/0.98Kg. 1000 Kg/tonne = **\$724/tonne.**
- \$85.91/barrel. 1 barrel/42 US gallons. 1 US gallons/3.785L. 1 L/0.98Kg. 1000 Kg/tonne = **\$551/tonne.**

3.2. Net Present Value

Let LSFCi be the low-sulfur fuel oil cost at year i (\$/tonne), and HSFCi be the high-sulfur fuel oil cost at year i (\$/tonne). Assuming that the power plant consumes an amount of D (tonne/year) of fuel oil, r is the minimum attractive rate of return (MARR), or the interest rate, and N is the plant lifetime. Then, the Net Present Value (NPV) of this alternative can be written as [42]:

$$\text{NPV} = \sum_{i=0}^{N} \frac{(LSFCi - HSFC\ )x\ D}{(1+r)^{i}} \qquad (3\text{-}1)$$

CHAPTER 4

THE FLUE GAS DESULFURIZATION ALTERNATIVE

The FGD system removes sulfur dioxide from the flue gas in an absorption process. While there are various types of such systems, the most used one is the wet FGD system, as discussed earlier. The cost of the system includes various components such as the land cost, unit installation costs, staff wages, utilities costs, raw materials costs, and maintenance. Nevertheless, there are some benefits behind utilizing this alternative. This can be represented by the revenues generated from selling gypsum and the land salvage value after the project ends.

4.1. Land Cost

The cost of land, paid at year 0, can be expressed as:

$$C_L(0) = S. L \qquad (4\text{-}1)$$

Where S is the land area required (m^2) and L is the cost of land in the power plant area ($\$/m^2$).

4.2. Unit Installation Cost

The unit installation cost includes the price of the FGD system, its shipping and installation costs, as well as insurance. However, several FGD units are needed, where each generating unit at the power plant must be coupled with a FGD system. Let n be the number of these units, j is the generating unit, having a power rating of Pj, and y is the time needed to install one FGD unit. Therefore, for any year i in the construction period (from year zero to year n) the cost of installation can be written as:

$$C_I = \frac{I.\ \sum_{j=1}^{n} Pj}{(n.y)} \qquad (4\text{-}2)$$

4.3. Staff Wages

Operating the FGD systems demands having qualified operators, working in multiple shifts. Let z be the number of qualified personnel per shift, n the number of generating units, s the number of shifts per day, and A the annual salary of each operator. Inflation rates should be considered, and thus the total staff wages paid annually can be expressed as:

$$C_W\ (i) = n.\ z.\ s.\ A.\ (1 + f)^{i} \qquad (4\text{-}3)$$

4.4. Utilities Cost

As previously discussed, the FGD system will consume a percentage of the power plant's output (P_{out}) to operate, noting that the power plant has a load factor If. Let e% be this percentage (usually between 2% and 5%). Assuming that the power plant consumes β kWh/ton of fuel, the annual cost of utilities paid is:

$$C_u\ (i) = \frac{If.8760.\ P_{out}.\ e}{\beta}\ .\ HSFC_i \qquad (4\text{-}4)$$

4.5. Raw Materials Cost

Moving to the chemistry of SO_2, every 64g of it will produce 82g of sulfurous acid which will later react with 100g of calcium carbonate.

If S tons of SO_2 are produced during the combustion process, then around 95% of them will be involved and absorbed in the reaction. Thus, the consumption of calcium carbonate can be expressed as 1.483 * S tons/day. If the calcium carbonate to be used has 85% limestone content, then the limestone yearly consumption will be 636.8 S tons/year.

Therefore, the annual consumption of the raw materials can be calculated by using the following equation:

$$C_R\,(i) = 636.8.\ S.\ E.\ (1+f)^i \qquad (4\text{-}5)$$

Where E is the cost of one ton of limestone ($/ton).

4.6. Maintenance Cost

Like every other system out there, the FGD system should be constantly maintained, which will induce further costs. Since this process is occurring on a yearly basis, inflation should be taken into consideration.

The annual maintenance cost is expressed as m% (usually around 2.5% for most FGD systems). And the full equation is as follows:

$$C_M\,(i) = m.\ I.\ (\textstyle\sum_{j=1}^{n} Pj).\ (1+f)^i \qquad (4\text{-}6)$$

4.7. Revenues from Gypsum Sale

As discussed in previous sections, the product of this process is gypsum that can be utilized in plenty of other industries. Let G be the quantity of gypsum produced (in tons) for every ton of SO_2 removed, usually around 2.4 tonnes, and B is the selling price of gypsum.

If S_0 is the daily amount of SO_2 produced, then 95% of it will be removed by the system and the annual revenue from gypsum sales can be calculated as:

$$R_G\ (i) = 365.\ 0.95.\ S_0.\ G.\ B.\ (1+f)^i$$

$$R_G\ (i) = 346.75.\ S_0.\ G.\ B.\ (1+f)^i \qquad (4\text{-}7)$$

4.8. Land Salvage Value

At the end of the project, the land can be salvaged taking inflation into account. The amount received at year N is equal to:

$$R_L\ (N) = C_L\ (1+f)^N \qquad (4\text{-}8)$$

4.9. Net Present Value

Taking all the components into account, the net present value of this alternative can be expressed as:

$$NPV_{FGD} = C_L + \sum_{i=0}^{n.y-1} \frac{C_I(i)}{(1+r)^i} + \sum_{i=1}^{N} \frac{C_W\ (i)+C_u(i)+C_R(i)+C_M(i)-R_G(i)}{(1+r)^i} - \frac{R_L}{(1+r)^N} \qquad (4\text{-}9)$$

CHAPTER 5

THE NATURAL GAS ALTERNATIVE

Natural gas has proven to be a tough contender against traditional fossil fuels. This has to do with its less polluting effects, especially when it comes to SO_2, and the high efficiency this technology provides, which can reach up to 60% in certain cases [44]. However, switching to natural gas demands adjusting the power plant so that it can be compatible, and this will impose an initial capital cost or investment cost and fuel shipping costs.

On the other hand, there are some benefits associated with this alternative, such as the O and M savings for the power plant, the differential fuel cost (could be an expense), and savings due to longer power plant lifetime.

5.1. Investment Cost

The investment represents the amount of money required to modify the power plant. These include the price of equipment and installation costs, to be paid at year 0. This cost can be expressed as:

$$C_{\text{modification}} = P.IMC \qquad (5\text{-}1)$$

Where P is the capacity of the power plant (kW), and IMC is the investment cost of natural gas boilers and other systems ($/kW).

5.2. Shipping Cost

Gas transportation can be made either by pipelines or via shipping vessels. If the first is chosen for the purpose of this study, and the pipeline must pass onshore, then the country or operator should secure a right-of-way as it passes through other countries. However, if the pipeline is offshore, then there is no need for a right-of-way. This model considers transporting natural gas via a vessel (natural gas tankers) which can be calculated according to the following equation:

$$C_T = C_{shipping}\ x\ Annual\ consumption\ of\ natural\ gas \qquad (5\text{-}2)$$

5.3. Land Cost

Converting the power plant to natural gas will demand having a storage facility for this resource. The facility will be situated next to the plant and will be assumed to have the same area of 5000 m^2.

The cost of land can be calculated using equation 5-3:

$$C_L = S * L \qquad (5\text{-}3)$$

5.4. Differential Fuel Cost/Benefit

Switching from regular fossil fuels to natural gas has its implications on the fuel price as well. This can result in a spike in the prices or lead to some savings, depending on the case. Mainly this is based on the fuel prices, consumption rates of the fuels, and the efficiency of natural gas fired power plants is normally higher. The costs of the fuel change can be calculated using:

$$C_{FC}(i) = D_{NG}.\ NGC_i - D_O.\ OC_i \qquad (5\text{-}4)$$

Where; D_O is the power plant consumption of either fuel oil (high/low sulfur) for steam plants or gas oil for gas turbine or combined cycle plants (ton/year), D_{NG} is the power plant consumption of natural gas (m^3/year), NGC_i is the cost of natural gas at year i (\$/m^3), and OC_i is the fuel oil (high/low sulfur) or gas oil price at year i (\$/ton).

5.5. Reduction in Operations and Maintenance (O & M) Cost

Utilizing natural gas will result in a noticeable decrease in maintenance and operations costs at the power plant, as it is far cleaner than fuel oil or gas oil. This revenue can be estimated after the first year by using the following equation:

$$B_M(i) = r_m.\ OMC.\ P.\ IC_{plant}.\ (1+f)^i \qquad (5\text{-}5)$$

Where IC_{plant} is the investment cost of the power plant in \$/kW, r_m is the percentage of savings in the operations and maintenance cost (usually ranges between 5 and 25%), and OMC is the operations and maintenance percentage cost from the power plant initial investment cost (4-5%).

5.6. Longer Power Plant Lifetime Effects

The usage of natural gas will result in a longer power plant lifetime. To express this increase economically, the annuity factor for the initial lifetime of the power plant and that for the increased lifespan should be considered. The money paid for fuel oil or gas oil over the span of a year can be obtained from:

$$A_1 = P.\ IC_{plant}.\ \frac{r.(1+r)^N}{(1+r)^N-1} \qquad (5\text{-}6)$$

And that for natural gas is:

$$A_2 = \text{P}.\ IC_{plant}.\ \frac{r.(1+r)^{N+s}}{(1+r)^{N+s}-1} \qquad (5\text{-}7)$$

Where s is the increase in the lifetime of the power plant (in years).

The difference between these two equations (6 and 7) will yield the annual benefit, gained from year 1 to year N + s:

$$B_L(i) = \text{P}.\ IC_{plant}.\ \text{r}.\ [\frac{(1+r)^N}{(1+r)^N-1} - \frac{(1+r)^{N+s}}{(1+r)^{N+s}-1}] \qquad (5\text{-}8)$$

5.7. Land Salvage Value

At the end of the project, the land bought for storing, or any other purpose, can be sold at a discount price. This benefit can be calculated by using equation 5-9:

$$\text{R}_\text{L}\ (\text{N}) = \text{C}_\text{L}\ (1 + \text{f})^\text{N} \qquad (5\text{-}9)$$

5.7. Net Present Value

The total NPV of this alternative can be written as:

$$\text{NPV}_{\text{NG}} = \text{IC}\ (0) + \text{C}_\text{L} + \sum_{i=1}^{N} \frac{(C_T)}{(1+r)^i} - \sum_{i=1}^{N} \frac{(C_{FC}(i))}{(1+r)^i} - \sum_{i=1}^{N} \frac{(B_M(i))}{(1+r)^i} - \sum_{i=1}^{N} \frac{(B_L(i))}{(1+r)^i} - \sum_{i=1}^{N} \frac{(R_L(N))}{(1+r)^N} \qquad (5\text{-}10)$$

CHAPTER 6

THE PV ALTERNATIVE

As mentioned earlier, there are various types of renewable energy technologies. However, this paper will discuss the economics of implementing one alternative only. The chosen technology is that the most compatible for the case of Lebanon, that is, solar photovoltaic (PV) panels.

Solar power is regarded as one of the fastest growing renewable energy technologies. The shift towards solar can be justified due to their decreasing price over the years, plus they are suitable for residential projects as they occupy a small area. According to Pierre Khoury, president of the Lebanese Center for Energy Conservation (LCEC), Lebanon witnessed a total of 250 MW of solar installations between 2021 and 2022 to be added over the existing 100 MW projects [45]. As promising as it seems, this number is still far from achieving the 30% electricity generation goal which was set by the government, and to be achieved by the year 2030.

6.1. Land Cost

The first thing to consider is the cost of land which can be calculated using equation 6-1, noting that the area needed for a solar power plant is much larger than that needed for a similar major thermal one:

$$C_L(0) = S.\ L \qquad (6\text{-}1)$$

6.2. Investment Cost

The capital costs of equipment should be considered, which includes the price of panels, inverters, mounting equipment, and a monitoring system. The capital investment cost can be calculated as:

$$C_I = \sum C_{PV} + C_{Inv} + C_M + C_{MT} + C_B \qquad (6\text{-}2)$$

Where C_I is the capital investment cost, C_{PV} is the cost of panels, C_{Inv} is the cost of inverters, C_M is the cost of monitoring system, C_{MT} is the cost of metal structures, and C_B is the batteries cost.

6.3. Maintenance Cost

Maintenance costs are to be paid annually. For that, the time value of money should be taken into consideration. These costs can be calculated by using the following equation:

$$C_M = M_{PV} \, . \, C_I \, (1+f)^i \qquad (6\text{-}3)$$

6.4. Staff Wages

The cost of wages for personnel can be calculated using equation (6-4), noting that operating a solar power plant demands having n number of workers, divided over z number of shifts, while each of them is getting an annual salary of A.

$$C_W\,(i) = n.\ z.\ A.\ (1+f)^i \qquad (6\text{-}4)$$

6.5. Differential Fuel Cost

As there are no fuel costs in this alternative, then all of the money used for purchasing fuel in other alternatives will be regarded as revenue. The price to be considered is that of the high sulfur fuel, \$551, and the equation is as follow:

$$C_{FC} = \text{HSFCi x D} \qquad (6\text{-}5)$$

6.6. Land Salvage Value

After the project ends, any bought piece of land can be sold at a salvaged value, taking inflation into consideration.

$$\mathrm{R_L}\ (\mathrm{N}) = C_L.\,(1+f)^N \qquad (6\text{-}6)$$

6.7. Net Present Value

The net present value of this alternative can be calculated accordingly:

$$NPV_{PV} = C_L + C_I + \sum_{i=1}^{n} \frac{C_M+C_W}{(1+r)^i} - \frac{C_{FC}}{(1+r)^i} \frac{R_L}{(1+r)^N} \qquad (6\text{-}7)$$

CHAPTER 7

ECONOMIC FEASIBILITY STUDY

7.1. Power Plant Parameters

In the purpose of comparing the costs of the above created model, it will be applied to the 805 MW Zouk thermal power plant which is currently operating on fuel oil. The lifetime of the project is 20 years, while the inflation rate and the interest rate are set at 3% and 8%, respectively. As for the minimum attractive rate of return, it is set at 8%. Other factors and power plant parameters can be found in the Table 5:

Table 5: Power Plant Case Study Parameters

Plant power rating	805 MW
Plant load factor	75%
Annual fuel oil consumption	1,250,000 tons
Annual gas consumption (estimate)	2,000,000,000 m^3
Land area	5000 m^2
Land cost	$200/$m^2$
FGD Installation cost	$450/kW
FGD electricity requirement	3.5% of the output
Annual salaries for FGD operators	$24,000/operator
FGD installation time	6 month/unit
High- sulfur fuel cost	$551/ton
Low- sulfur fuel cost	$724/ton
Limestone purchase cost	$50/ton
Gypsum sale price	$50/ton
Natural Gas Cost	$6.67/MBtu or $0.25/$m^3$

7.2. NPV for the BAU Scenario

The BAU scenario can be evaluated in a way like that of low sulfur fuel alternative with a sulfur content of 1%, the price of which was valued around $708/tonne last year. Also, in this case, a sulfur tax of $1,500 per ton will be applied.

Computing the sulfur tax addition is made according to the following equation:

Sulfur tax = Annual fuel oil consumption * sulfur content * sulfur tax

Sulfur tax = 1,250,000 x 0.01 x 1,500

Sulfur tax = $18,750,000

Table 6: BAU Cash Flow

Year	Incremental cost at year i	NPV
1	215,000,000.0	199,074,074.1
2	215,000,000.0	184,327,846.4
3	215,000,000.0	170,673,931.8
4	215,000,000.0	158,031,418.4
5	215,000,000.0	146,325,387.4
6	215,000,000.0	135,486,469.8
7	215,000,000.0	125,450,435.0
8	215,000,000.0	116,157,810.2
9	215,000,000.0	107,553,527.9
10	215,000,000.0	99,586,599.9
11	215,000,000.0	92,209,814.7
12	215,000,000.0	85,379,458.1
13	215,000,000.0	79,055,053.8
14	215,000,000.0	73,199,123.9
15	215,000,000.0	67,776,966.5
16	215,000,000.0	62,756,450.5
17	215,000,000.0	58,107,824.5
18	215,000,000.0	53,803,541.2
19	215,000,000.0	49,818,093.7
20	215,000,000.0	46,127,864.6
	Total NPV	**2,110,901,692**

7.3. NPV for the Low Sulfur Fuel Alternative

Using the needed given from above, and the following equation, the cash flow for the 20 years is generated and displayed in the table below:

$$\text{NPV} = \sum_{i=0}^{N} \frac{(LSFCi - HSFCi) x\ D}{(1+r)^{i}} \qquad (7\text{-}1)$$

Table 7: Low Sulfur Fuel Oil Alternative Cash Flow

Year	Incremental cost at year i	NPV
1	216,250,000.0	200,231,481.5
2	216,250,000.0	185,399,520.0
3	216,250,000.0	171,666,222.1
4	216,250,000.0	158,950,205.7
5	216,250,000.0	147,176,116.4
6	216,250,000.0	136,274,181.8
7	216,250,000.0	126,179,798.0
8	216,250,000.0	116,833,146.3
9	216,250,000.0	108,178,839.1
10	216,250,000.0	100,165,591.8
11	216,250,000.0	92,745,918.3
12	216,250,000.0	85,875,850.3
13	216,250,000.0	79,514,676.2
14	216,250,000.0	73,624,700.2
15	216,250,000.0	68,171,018.7
16	216,250,000.0	63,121,313.6
17	216,250,000.0	58,445,660.7
18	216,250,000.0	54,116,352.5
19	216,250,000.0	50,107,733.8
20	216,250,000.0	46,396,049.8
	Total NPV	**2,123,174,377**

7.4. NPV for the FGD Alternative

By referring to the data in table 5, the cash flows for different components can be calculated and added to represent the NPV for the whole system.

7.4.1. Land Cost

The FGD systems generally demand an area similar, or close, to that of the power plant. In this case, the area of the Zouk power plant is nearly 5000 m^2. As for the land cost, it is estimated to be around 200$/$m^2$. Thus, the cost of land can be calculated using the following equation:

$C_L(0) = S.\ L$

$C_L(0) = 5000\ m^2 \text{ x } 200\$/m^2 = \$1{,}000{,}000$

$NPV_1 = \$1{,}000{,}000$

7.4.2. Unit Installation Cost

The installation of the FGD system takes generally about 6 months per each generating unit. The Zouk power plant has 4 units and thus the time needed is 2 years.

The total installation cost can be calculated by using the following equation:

$C_I = \frac{I.\ \sum_{j=1}^{n} Pj}{(n.y)} = 362{,}250{,}000$ USD

However, it should be noted that this amount shall be paid over the period of two years, making the cost per year: $\frac{322{,}000{,}000}{2} = 181{,}125{,}000$ USD.

Using a MARR of 8%, the net present value of this component is NPV_2 = $348,833,333

7.4.3. Staff Wages

Using equation 4-3, the wages of staff can be calculated over the years:

$$C_W\ (i) = n.\ z.\ s.\ A.\ (1+f)^i$$

Where n is 4 (as there are 4 generating units), z is one personnel per shift, s is 3 shifts per day, and A is equal to $24,000 per year. The inflation rate is set at 3%, while the MARR is 8%.

The net present value for this component is calculated and shown in the following table:

Table 8: Staff Wages Cash Flow for the FGD Alternative

Year	Staff Wages	NPV
1	296,640.0	274,666.6
2	305,539.2	261,950.6
3	314,705.3	249,823.2
4	324,146.5	238,257.3
5	333,870.9	227,226.9
6	343,887.0	216,707.1
7	354,203.6	206,674.4
8	364,829.7	197,106.1
9	375,774.6	187,980.8
10	387,047.9	179,278.0
11	398,659.3	170,978.1
12	410,619.1	163,062.5
13	422,937.7	155,513.3
14	435,625.8	148,313.6
15	448,694.6	141,447.2
16	462,155.4	134,898.7
17	476,020.1	128,653.4
18	490,300.7	122,697.2
19	505,009.7	117,016.8
20	520,160.0	111,599.4
	Total NPV	**3,633,851**

7.4.4. Utilities Cost

The utilities cost is paid on a yearly basis, and it depends on the price of the fuel to be used. In this alternative, the high sulfur fuel is chosen and the cash flow for each year can be calculated by using the following equation:

$$C_u\ (i) = \frac{If.8760.\ P_{out}.\ e}{\beta}\ .\ HSFC_i$$

While the load factor (If), the FGD electricity requirement (e), and the price of high sulfur fuel oil are given, the rate of fuel consumption (kWh/ton) should be calculated.

The electricity produced per day is 805,000 x 24 = 19,320,000 kWh, and the power plant fuel consumption per day is 3,424 tonnes. Thus, the rate of power production per tonne of fuel oil is:

$\beta = \frac{19320000}{3424} = 5{,}642.5$ kWh/tonne.

Now, by using equation 4-4, and a MARR of 8%, the net present value of the utilities cost can be calculated and is shown in the following table:

Table 9: Utilities Cost Cash Flow for the FGD Alternative

Year	Utilities Cost	NPV
1	18,076,291	16,737,306.4
2	18,076,291	15,497,506.0
3	18,076,291	14,349,542.6
4	18,076,291	13,286,613.5
5	18,076,291	12,302,419.9
6	18,076,291	11,391,129.5
7	18,076,291	10,547,342.1
8	18,076,291	9,766,057.5
9	18,076,291	9,042,645.9
10	18,076,291	8,372,820.2
11	18,076,291	7,752,611.3
12	18,076,291	7,178,343.8
13	18,076,291	6,646,614.6
14	18,076,291	6,154,272.8
15	18,076,291	5,698,400.8
16	18,076,291	5,276,297.0
17	18,076,291	4,885,460.2
18	18,076,291	4,523,574.2
19	18,076,291	4,188,494.7

20	18,076,291	3,878,235.8
	Total NPV	**177,475,688**

7.4.5. Raw Materials Cost

In order to calculate the cost of raw materials, which depends mainly on the consumption of limestone, the amount of sulfur dioxide emitted should be calculated. For a fuel oil with 3% sulfur content, 0.03 x 3424 x 2 = 205.5 tonnes of sulfur oxide are emitted per year.

Now, using the following equation, with inflation rates and MARR of 3% and 8% respectively, the net present value for this component can be calculated:

$$\mathrm{C_R}\ (\mathrm{i}) = 636.8.\ \mathrm{S.\ E.}\ (1+f)^{i}$$

Table 10: Raw Materials Cost Cash Flow for the FGD Alternative

Year	Raw Materials Cost	NPV
1	6,739,413.6	6,240,197.7
2	6,941,596.0	5,951,299.7
3	7,149,843.8	5,675,776.5
4	7,364,339.2	5,413,009.1
5	7,585,269.3	5,162,406.8
6	7,812,827.4	4,923,406.5
7	8,047,212.2	4,695,471.0
8	8,288,628.6	4,478,088.1
9	8,537,287.5	4,270,769.2
10	8,793,406.1	4,073,048.4
11	9,057,208.3	3,884,481.4
12	9,328,924.5	3,704,644.2
13	9,608,792.3	3,533,132.9
14	9,897,056.0	3,369,561.9
15	10,193,967.7	3,213,563.7
16	10,499,786.8	3,064,787.6
17	10,814,780.4	2,922,899.3
18	11,139,223.8	2,787,579.9
19	11,473,400.5	2,658,525.3
20	11,817,602.5	2,535,445.4
	Total NPV	**82,558,094**

7.4.6. Maintenance Cost

Maintenance costs can be calculated using the following equation:

$$C_M (i) = m. I. (\sum_{j=1}^{n} Pj). (1+f)^i$$

Knowing that the total installation cost is 362,250,000 and m is 0.025. Using an inflation rate of 3% and an MARR of 8%, the following data is obtained and presented in the below table:

Table 11: Maintenance Cost Cash Flow for FGD Alternative

Year	Raw Materials Cost	NPV
1	9,327,937.5	8,636,979.1
2	9,607,775.6	8,237,118.9
3	9,896,008.8	7,855,770.8
4	10,192,889.1	7,492,077.7
5	10,498,675.8	7,145,222.3
6	10,813,636.1	6,814,425.0
7	11,138,045.2	6,498,942.4
8	11,472,186.5	6,198,065.4
9	11,816,352.1	5,911,117.9
10	12,170,842.7	5,637,455.0
11	12,535,967.9	5,376,461.7
12	12,912,047.0	5,127,551.5
13	13,299,408.4	4,890,164.8
14	13,698,390.7	4,663,768.3
15	14,109,342.4	4,447,853.1
16	14,532,622.7	4,241,934.0
17	14,968,601.3	4,045,548.1
18	15,417,659.4	3,858,254.3
19	15,880,189.2	3,679,631.4
20	16,356,594.8	3,509,278.0
	Total NPV	**114,267,619**

7.4.7. Revenues from Gypsum Sale

The revenues from gypsum sale can be estimated by using the following equation:

$$R_G(i) = 346.75.\ S_0.\ G.\ B.\ (1+f)^i$$

Where S_0 = 205.5 tonnes for 3% sulfur content fuel, G = 2.4 tonnes, and B = $50/tonne.

Using the previously mentioned parameters, an inflation rate of 3%, and an MARR of 8%, the revenues and the NPV of this component can be calculated and presented in the following table:

Table 12: Revenues from Gypsum Sale Cash Flow for FGD Alternative

Year	Revenues from Gypsum Sale	NPV
1	8,807,380.6	8,154,982.0
2	9,071,602.0	7,777,436.5
3	9,343,750.1	7,417,370.0
4	9,624,062.6	7,073,973.2
5	9,912,784.5	6,746,474.5
6	10,210,168.0	6,434,137.7
7	10,516,473.0	6,136,260.9
8	10,831,967.2	5,852,174.8
9	11,156,926.3	5,581,240.8
10	11,491,634.0	5,322,850.0
11	11,836,383.1	5,076,421.8
12	12,191,474.6	4,841,402.3
13	12,557,218.8	4,617,263.3
14	12,933,935.4	4,403,501.1
15	13,321,953.4	4,199,635.3
16	13,721,612.0	4,005,207.7
17	14,133,260.4	3,819,781.4
18	14,557,258.2	3,642,939.7
19	14,993,976.0	3,474,285.1
20	15,443,795.2	3,313,438.5
	Total NPV	**107,890,776**

7.4.8. Land Salvage Value

The land salvage value can be calculated using the following equation:

$$R_L\ (N) = C_L\ (1+f)^N$$

$$R_L\ (N) = 1{,}000{,}000 \times (1+0.03)^{20} = \$1{,}806{,}111$$

This amount will be received at the end of the project, that is year 20. Discounting it to year 0 yields:

NPV = 387,497

NPV_8 = $387,497

7.4.9. Net Present Value

To obtain the net present value for the FGD alternative, the whole 8 components should be added according to the following equation:

$$NPV_{FGD} = C_L + \sum_{i=0}^{n.y-1} \frac{C_I(i)}{(1+r)^i} + \sum_{i=1}^{N} \frac{C_W\,(i)+C_u(i)+C_R(i)+C_M(i)-R_G(i)}{(1+r)^i} - \frac{R_L}{(1+r)^N}$$

Table 13: Net Present Value of the FGD Alternative

NPV #	**Cost Component**	**NPV**
NPV1	Land Cost	1,000,000
NPV2	Unit Installation Cost	348,833,333
NPV3	Staff Wages	3,633,851
NPV4	Utilities Cost	177,475,688
NPV5	Raw Materials Cost	82,558,094
NPV6	Maintenance Cost	114,267,619
NPV7	Revenues from Gypsum Sales	107,890,776
NPV8	Land Salvage Value	387,497
Total NPV	**FGD**	**619,490,313**

7.5. NPV for the Natural Gas Alternative

By referring to the data in table 5, the cash flows for different components can be calculated and added to represent the NPV for the whole system.

7.5.1. Investment Cost

The investment cost of the power plant includes the cost of converting the power plant to use natural gas. This modification cost is typically for the boilers to be installed at the plant and can be calculated by using the following equation, noting that the boilers can cost up to 200$/kW:

$$C_{modification} = \text{P.IMC}$$

$$C_{modification} = 805{,}000 \text{ x } 200 = \$161{,}000{,}000$$

7.5.2. Shipping Cost

Shipping costs can vary and are regarded as highly unpredictable, depending on the market forces, political situations, and demand and supply. However, recent figures revealed that it approximately costs around 0.12 $\$/m^3$ to transport natural gas via a vessel.

$$C_T = C_{shipping} \text{ x annual consumption of natural gas}$$

Table 14: Shipping Cost Cash Flow for Natural Gas Alternative

Year	Shipping Cost	NPV
1	240,000,000	222,222,222.2
2	240,000,000	205,761,316.9
3	240,000,000	190,519,737.8
4	240,000,000	176,407,164.7
5	240,000,000	163,339,967.3
6	240,000,000	151,240,710.5

7	240,000,000	140,037,694.9
8	240,000,000	129,664,532.3
9	240,000,000	120,059,752.1
10	240,000,000	111,166,437.1
11	240,000,000	102,931,886.2
12	240,000,000	95,307,302.0
13	240,000,000	88,247,501.9
14	240,000,000	81,710,649.9
15	240,000,000	75,658,009.2
16	240,000,000	70,053,712.2
17	240,000,000	64,864,548.3
18	240,000,000	60,059,766.9
19	240,000,000	55,610,895.3
20	240,000,000	51,491,569.7
	Total NPV	**2,356,355,377**

7.5.3. Land Cost

The area needed for the storing facilities is close to those of the power plant, that is, 5000 m^2. The price of land in this area is taken as \$200/m^2. Therefore, land cost can be expressed as follows:

$$C_L = 5000 * 2000 = \$1,000,000$$

7.5.4. Differential Fuel Cost/Benefit

The differential fuel cost can be a benefit or cost, depending on the prices of natural gas and fuel oil globally. If a negative sign is obtained from this equation, this means that the power plant will save money by switching fuel type. Using the data from table 5:

$$\mathrm{C_{FC}}(i) = (0.25 \text{ x } 2{,}000{,}000{,}000) - (551 \text{ x } 1{,}250{,}000)$$

$$\mathrm{C_{FC}} = -188{,}750{,}000$$

Table 15: Differential Fuel Cost Cash Flow for Natural Gas Alternative

Year	Differential Fuel Cost/Benefit	NPV
1	188,750,000	174,768,518.5

2	188,750,000	161,822,702.3
3	188,750,000	149,835,835.5
4	188,750,000	138,736,884.7
5	188,750,000	128,460,078.4
6	188,750,000	118,944,517.1
7	188,750,000	110,133,812.1
8	188,750,000	101,975,751.9
9	188,750,000	94,421,992.5
10	188,750,000	87,427,770.8
11	188,750,000	80,951,639.7
12	188,750,000	74,955,221.9
13	188,750,000	69,402,983.2
14	188,750,000	64,262,021.5
15	188,750,000	59,501,871.8
16	188,750,000	55,094,325.7
17	188,750,000	51,013,264.6
18	188,750,000	47,234,504.2
19	188,750,000	43,735,652.0
20	188,750,000	40,495,974.1
	Total NPV	**$1,853,175,322**

7.5.5. Reduction in Operations and Maintenance (O & M) Cost

Switching to natural gas has its benefits on the power plant itself. This can be reflected in the operations and maintenance savings that are gained starting from year 1. The savings can go as high as 25% of the O and M of the power plant, that is usually around 4% of the initial investment of the power plant ($750/kW for steam turbine power plants)

$$\mathrm{B_M(i) = r_m.\ OMC.\ P.\ IC_{plant}}.\ (1+f)^{i}$$

$$\mathrm{B_M(i)} = 0.25 \times 0.04 \times 805{,}000 \times 750 \times (1+0.03)^{i}$$

Table 16: O & M Savings Cash Flow for Natural Gas Alternative

Year	O & M Savings	NPV
1	6,218,625.0	5,757,986.1
2	6,405,183.7	5,491,412.6
3	6,597,339.2	5,237,180.5
4	6,795,259.4	4,994,718.5
5	6,999,117.2	4,763,481.5
6	7,209,090.7	4,542,949.9
7	7,425,363.4	4,332,628.2
8	7,648,124.3	4,132,043.5
9	7,877,568.0	3,940,745.2
10	8,113,895.1	3,758,303.3
11	8,357,311.9	3,584,307.8
12	8,608,031.3	3,418,367.6
13	8,866,272.2	3,260,109.8
14	9,132,260.4	3,109,178.8
15	9,406,228.2	2,965,235.4
16	9,688,415.1	2,827,956.0
17	9,979,067.5	2,697,032.1
18	10,278,439.6	2,572,169.5
19	10,586,792.8	2,453,087.6
20	10,904,396.5	2,339,518.7
	Total NPV	**$76,178,412**

7.5.6. Longer Power Plant Lifetime Effects

Another benefit from switching to natural gas is longer power plant lifetime. This can extend the lifetime of the power plant for a duration varying between 2 to 5 years (taken as 5 in this case). The annual benefits can be gained after the first year of the project according to the following equation:

$$B_L(i) = \text{P}.\ IC_{plant}.\ \text{r}.\ \left[\frac{(1+r)^N}{(1+r)^N-1} - \frac{(1+r)^{N+s}}{(1+r)^{N+s}-1}\right]$$

$$\text{B}_\text{L}(\text{i}) = 805{,}000 \text{ x } 750 \text{ x } 0.08 \text{ x } 0.102 = \$4{,}926{,}600$$

Table 17: Longer Lifetime Savings Cash Flow for Natural Gas Alternative

Year	Longer Lifetime Savings	NPV
1	4,926,600.0	4,561,666.6
2	4,926,600.0	4,223,765.4
3	4,926,600.0	3,910,893.9
4	4,926,600.0	3,621,198.0
5	4,926,600.0	3,352,961.1
6	4,926,600.0	3,104,593.6
7	4,926,600.0	2,874,623.7
8	4,926,600.0	2,661,688.6
9	4,926,600.0	2,464,526.5
10	4,926,600.0	2,281,969.0
11	4,926,600.0	2,112,934.3
12	4,926,600.0	1,956,420.6
13	4,926,600.0	1,811,500.6
14	4,926,600.0	1,677,315.3
15	4,926,600.0	1,553,069.7
16	4,926,600.0	1,438,027.5
17	4,926,600.0	1,331,507.0
18	4,926,600.0	1,232,876.8
19	4,926,600.0	1,141,552.6
20	4,926,600.0	1,056,993.2
	Total NPV	**$48,370,084**

7.5.7. Land Salvage Value

The land salvage value can be calculated using the following equation:

$$R_L(N) = C_L\,(1+f)^N$$

$$R_L(N) = 1{,}000{,}000 \text{ x } (1+0.03)^{20} = \$1{,}806{,}111$$

This amount will be received at the end of the project, that is year 20. Discounting it to year 0 yields:

NPV_7 = \$387,497

7.5.8. Net Present Value

To obtain the net present value for the natural gas alternative, all of the components are added and presented in the following table:

Table 18: Net Present Value of the Natural Gas Alternative

NPV #	Cost Component	NPV
NPV1	Investment Cost	161,000,000
NPV2	Shipping Cost	2,356,355,377
NPV3	Land Cost	1,000,000
NPV4	Differential Fuel Cost/Benefit	-1,853,175,322
NPV5	O & M Savings	-76,178,412
NPV6	Longer Lifetime Savings	-48,370,084
NPV7	Land Salvage Value	-387,497
Total NPV	**Natural Gas**	**547,057,533**

7.6. NPV for the PV Alternative

By referring to the data in table 5, and the equations introduced earlier, the cash flows for different components can be calculated and added to represent the NPV for the whole system.

7.6.1. Land Cost

Calculating the land area for an 805 MW solar power plant can be a little challenging as there are plenty of uncertainties and factors that need to be considered. Starting off with the number of solar panels needed to generate this amount of power, and assuming that the power rating of solar panels is 540 Wp, then the number of panels needed is:

$$\frac{805{,}000{,}000\ \text{W}}{540} = 1{,}490{,}740 \text{ panels}$$

Next up is taking the size of the panel and spacing into consideration. Assuming that the panels will be of the standard utility scale size, that is having a length of 2.3 m^2 and a width of 1.1 m^2. The spacing between the rows of solar panels will be 1.5*Length of the panel to avoid shading and maximize sunlight.

Thus, the total area needed can be calculated as:

Total panel area = number of panels x panel area x spacing

Total panel area = 1,490,740 x 6.325

Total panel area = 9,428,930 m^2

Finally, there is the area needed for inverters and batteries. This space depends on the technologies being used, but usually it is estimated to be around 10 - 15% of the total panel area. Thus, the total area needed is 9,428,930 x (1+0.15) = 10,843,270 m^2.

However, since the project will occupy a relatively large area, especially for a small country like Lebanon, then it will be deployed as smaller units situated on mountains, far from population where obstacles may be present, preventing the implementation and increasing shading. Thus, the land price will be significantly lower than that of establishing a thermal power plant, which is close to the city and sea. Taking a land price of \$100/m^2, then the cost of land needed can be estimated at:

$$C_L = 10{,}843{,}270 \times 100 = \$1{,}084{,}327{,}000$$

Thus, NPV_1 = \$1,084,327,000

7.6.2. Investment Cost

Now that the number of solar panels is calculated, next up is estimating the cost of these panels, the number of inverters needed, and their prices, as well as mounting equipment, and monitoring system.

The cost of solar panels in utility scale projects differs from those in residential or commercial projects, where on average the cost is estimated at \$0.35/W [46]. Thus, the cost of solar panels can be estimated at:

$$C_{PV} = 0.35 \text{ x } 805{,}000{,}000 = \$281{,}750{,}000$$

The cost of inverters in utility scale projects is proportional to the power generated and it costs, on average, around \$0.1/W. That being said, the cost of inverters is estimated at:

$$C_{Inv} = 805{,}000{,}000 \text{ x } 0.1 = \$80{,}500{,}000$$

As for the cost for monitoring systems, the prices can vary according to the project size. According to the US Department of Energy, the sophisticated and detailed monitoring of a utility scale project can cost up to \$50,000 for a 100 MW project [47]. So, for an 805 MW project the cost will be estimated at \$402,500.

As for the costs of batteries, first the number of batteries needed should be calculated. Assuming an energy storage capacity of 14 hours, 805 MW x 14 hours = 11,270 MWh.

Assuming a large battery size of 1 MWh, the number of batteries needed is 11,270 batteries. As for their cost, it can vary depending on the type of technology, but it usually ranges between \$200/kWh and \$300/kWh. Assuming a price of \$250/kWh, the costs of batteries will be \$250/kWh x 1,000 = \$250,000 per battery. Having a total of 11,270 batteries, the total cost will be \$2,817,500,000.

Finally, there is the cost of mounting equipment. These metal structures can cost up to \$0.12/W, and thus the cost can be estimated at:

$$C_{MT} = 0.12 \times 805{,}000{,}000 = \$96{,}600{,}000$$

Adding all of these components together will yield the investment cost needed for the project:

$$C_I = \sum C_{PV} + C_{Inv} + C_M + C_{MT} + C_B$$

$$C_I = \$3{,}276{,}752{,}500$$

7.6.3. Installation Cost

Installation costs can vary depending on the size and the location of the project. However, on average, installation costs are estimated between \$1.5 to \$2 per watt of installed capacity. Therefore, the installation costs can be calculated as:

$$C_{Inst} = 2 \times 805{,}000{,}000 = \$1{,}610{,}000{,}000$$

However, the installation period can take up to 3 years to be completed, making the cost per year \$536,666,666.7.

Using a MARR of 8%, the NPV of this component is:

NPV_3 = \$1,493,685,414

7.6.4. Maintenance Cost

Over the years, the efficiency of the systems, as well as metal structures are going to degrade. For that, regular maintenance is required. The cost of maintenance can be calculated by using the equation:

$$C_M = M_{PV} \; . \; C_I \; (1 + f)^i$$

Noting that the maintenance cost is usually around 6% of the capital cost the NPV for this component is:

$$C_M = 0.06.\; 3{,}276{,}752{,}500.\; (1 + 0.03)^i$$

Table 19: Maintenance Costs Cash Flow for the PV Alternative

Year	Maintenance Cost	NPV
1	202,503,304.5	187,503,059.7
2	208,578,403.6	178,822,362.5
3	214,835,755.7	170,543,549.4
4	221,280,828.4	162,648,014.7
5	227,919,253.3	155,118,014.1
6	234,756,830.9	147,936,624.5
7	241,799,535.8	141,087,706.7
8	249,053,521.9	134,555,868.5
9	256,525,127.5	128,326,430.1
10	264,220,881.3	122,385,391.6
11	272,147,507.8	116,719,401.3
12	280,311,933.0	111,315,725.3
13	288,721,291.0	106,162,219.5
14	297,382,929.7	101,247,301.9
15	306,304,417.6	96,559,926.8
16	315,493,550.2	92,089,559.8
17	324,958,356.7	87,826,154.3
18	334,707,107.4	83,760,128.6
19	344,748,320.6	79,882,344.9
20	355,090,770.2	76,184,088.2
	Total NPV	**$2,480,673,872**

7.6.5. Staff Wages

Operating a solar power plant on such a big scale demand having a team of operators that are present around the clock to check for any failures. For that, 6 workers are needed per shift, for 3 shifts a day. Each operator will take a salary of $30,000 per year.

The cash flow of this component is calculated and represented in the table below:

$$C_W\ (i) = n.\ z.\ A.\ (1 + f)^i$$

Table 20: Staff Wages Cash Flow for the PV Alternative

Year	Staff Wages	NPV
1	556,200.0	515,000.0
2	572,886.0	491,157.4
3	590,072.5	468,418.5
4	607,774.7	446,732.5
5	626,008.0	426,050.5
6	644,788.2	406,325.9
7	664,131.8	387,514.5
8	684,055.8	369,574.0
9	704,577.5	352,464.1
10	725,714.8	336,146.3
11	747,486.3	320,584.0
12	769,910.8	305,742.1
13	793,008.2	291,587.4
14	816,798.4	278,088.0
15	841,302.4	265,213.6
16	866,541.4	252,935.1
17	892,537.7	241,225.2
18	919,313.8	230,057.3
19	946,893.2	219,406.5
20	975,300.0	209,248.8
	Total NPV	**$6,813,471**

7.6.6. Differential Fuel Benefit

Shifting from steam power plants will eliminate the costs of fuel, which will be regarded as a benefit for this alternative.

The price of the fuel to be used is that of the high sulfur fuel content, and the net present worth of this component is as follows:

$$C_{FC} = \text{HSFCi x D}$$

Table 21: Differential Fuel Benefit Cash Flow for the PV Alternative

Year	Differential Fuel Benefit	NPV
1	688,750,000	637,731,481.5
2	688,750,000	590,492,112.5
3	688,750,000	546,751,956.0
4	688,750,000	506,251,811.1
5	688,750,000	468,751,677.0
6	688,750,000	434,029,330.5
7	688,750,000	401,879,009.7
8	688,750,000	372,110,194.2
9	688,750,000	344,546,476.1
10	688,750,000	319,024,514.9
11	688,750,000	295,393,069.4
12	688,750,000	273,512,101.3
13	688,750,000	253,251,945.6
14	688,750,000	234,492,542.2
15	688,750,000	217,122,724.3
16	688,750,000	201,039,559.5
17	688,750,000	186,147,740.3
18	688,750,000	172,359,018.8
19	688,750,000	159,591,684.1
20	688,750,000	147,770,077.8
	Total NPV	**$6,762,249,026**

7.6.7. Land Salvage Value

After the project ends, any bought piece of land can be resold. At an inflation rate of 3%, the land cost in 20 years will be:

$$R_L(N) = C_L . (1+f)^N$$

$$R_L(N) = 1{,}084{,}327{,}000. (1+0.03)^{20}$$

$$R_L(N) = \$1{,}958{,}415{,}177$$

Discounting the price to the present time using an MARR of 8% gives the NPV of this component:

$NPV_7 = \$420{,}174{,}465$

7.6.8. Net Present Value

To obtain the net present value for the PV alternative, all the components are added and presented in the following table:

Table 22: Net Present Value of the PV Alternative

NPV #	**Cost Component**	**NPV**
NPV1	Land Cost	1,084,327,000
NPV2	Investment Cost	3,276,752,500
NPV3	Installation Costs	1,493,685,414
NPV4	Maintenance Costs	2,480,673,872
NPV5	Staff Wages	6,813,471
NPV6	Differential Fuel Benefits	-6,762,249,026
NPV7	Land Salvage Value	-420,174,465
Total NPV	**PV**	**1,159,828,766**

7.7. Comparison of the Alternatives

After conducting the necessary calculations, the net present values of the four alternatives, low sulfur fuel, FGD system, natural gas, and the PV alternative are presented in Table 23:

Table 23: NPVs of the Alternatives

Alternative	**NPV**
BAU	2,110,901,692
Low-sulfur fuel	2,123,174,377
FGD	619,490,313
Natural gas	547,057,533
PV	1,159,828,766

Clearly, the natural gas alternative is the most economical one for the Zouk power plant under the discussed conditions, while installing an FGD system comes in second place, followed by the PV alternative.

CHAPTER 8

SENSITIVITY ANALYSIS

8.1. Choice of Parameters

One of the main issues associated with this model is the presence of uncertainties within some parameters. This necessitates carrying out a sensitivity analysis for those components with high degree of uncertainty. These parameters are:

- Minimum attractive rate of return (MARR).
- Inflation rate.
- Lifetime of the power plant.
- Incremental fuel oil prices.
- Natural gas prices.
- Natural gas shipping price.
- Installation cost of the FGD system.
- Boiler modification cost.
- PV panels cost.
- Batteries cost.
- Land costs.

8.2. Sensitivity Analysis on MARR

This parameter is associated with a high level of uncertainty as it depends on various factors such as the time frame of the project, the supply and demand in the market, and the government's share of dollars at the Central Bank. Therefore, the MARR can vary between 5% and 20% and the results are shown in Figure 9:

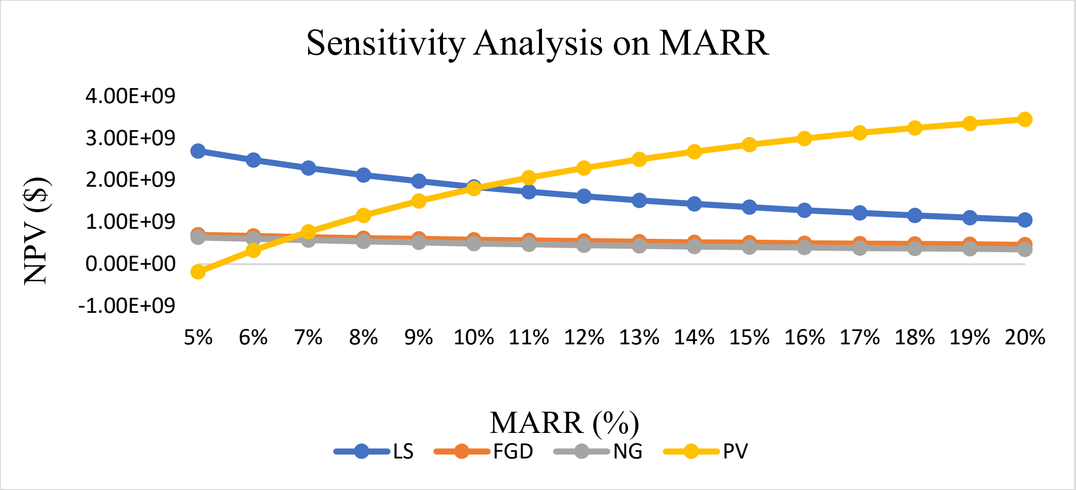

Figure 9: Sensitivity Analysis on MARR

It is obvious how the MARR affects the results as it changes between 5% and 20%. While the NPV for the three alternatives, the low sulfur fuel, FGD, and natural gas will decrease as the MARR increases, that of the PV will increase. The changes in the NPV of the PV alternative are significant mainly due to the changes in the differential fuel benefits that will decrease as the MARR increases. Other factors in this alternative show little or no changes at all as they are paid in year 0 as a capital cost. In conclusion, for a MARR less than 6%, the PV alternative is the most economic one. At 7% the natural gas alternative becomes the most feasible option.

8.3. Sensitivity Analysis on Inflation Rate

The inflation rate is a crucial parameter that is included in three of the four alternatives (FGD, natural gas, and PV). There are lots of uncertainties associated with the inflation rate, and that's why it is changed between 1% and 16% as shown in figure 10:

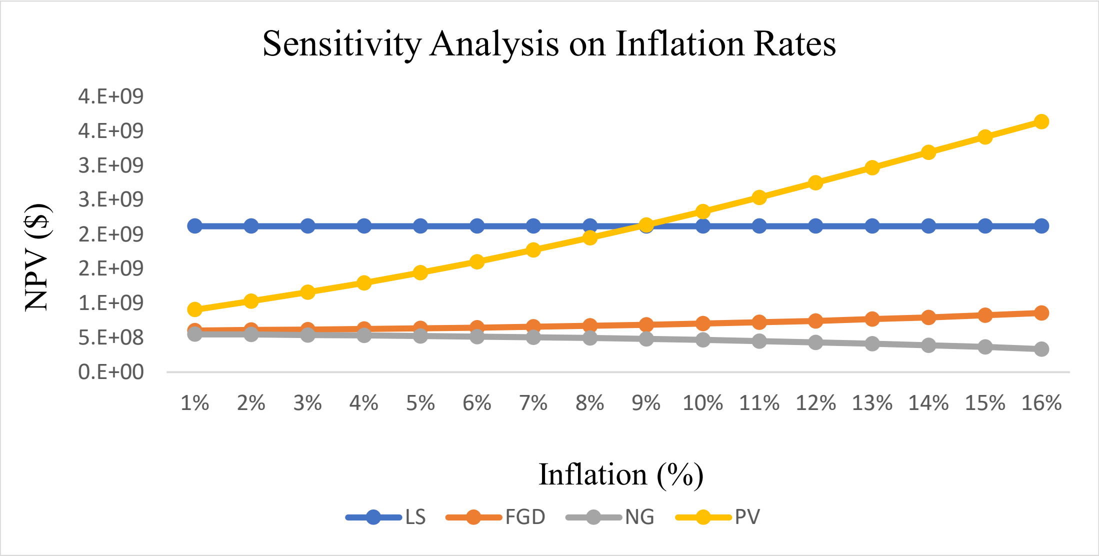

Figure 10: Sensitivity Analysis on Inflation Rate

Like MARR's case, the changes in inflation rates will highly affect the NPVs of some alternatives. For the low sulfur fuel alternative, the results are intact. As for the natural gas alternative, the NPV decreases as inflation rate increases, especially after a rate of 12%. This is mainly due to the increase in revenues from the operation and maintenance savings from switching to natural gas fired power plants.

As for the other alternatives, the FGD's NPV will witness a slight increase, while that of the PV alternative will increase steadily mainly due to the increase in the cost of maintenance.

8.4. Sensitivity Analysis on Power Plant Lifetime

The decommissioning of a power plant usually varies between projects. However, it is in the range of 20 years. Figure 11 shows the net present values of the four alternatives for a power plant lifetime varying between 1 year and 16 years:

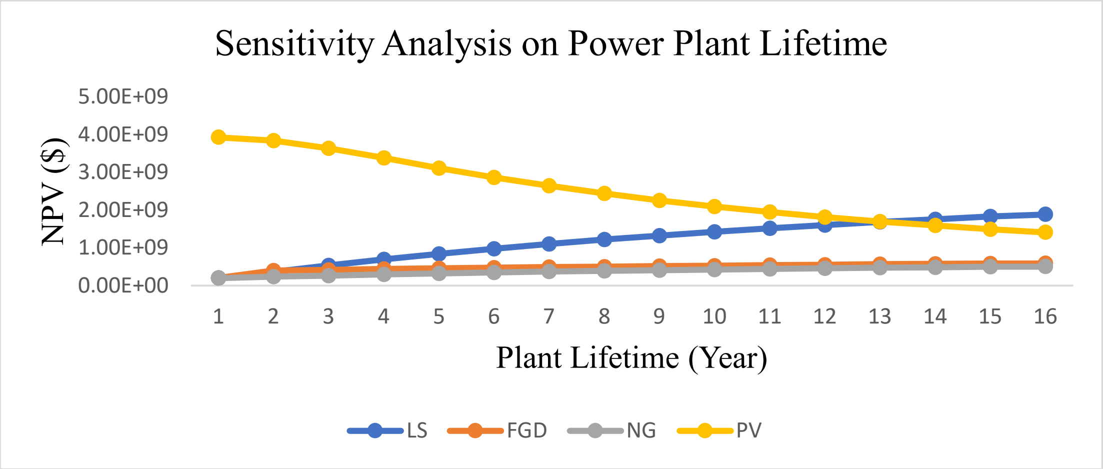

Figure 11: Sensitivity Analysis on Power Plant Lifetime

From this graph, the natural gas alternative appears to be always the most economical, although if the duration is less than 2 years, the difference between low-sulfur fuel, FGD, and natural gas alternatives is slight. It is obvious as well that the NPV of the PV alternative decreases with time, mainly because the capital cost is paid at first and then revenues will start to flow in due to the differential fuel benefits.

8.5. Sensitivity Analysis on Incremental Fuel Oil Prices

Oil prices are highly unpredictable and are subjected to regular changes due to wars and politics. However, the high and low sulfur fuel oil prices are correlated so the sensitivity analysis is done on the incremental fuel oil price.

For that reason, the NPVs for the FGD, natural gas, and PV alternatives most likely will not change, in opposition to that of the low sulfur fuel alternative. Results are shown in Figure 12:

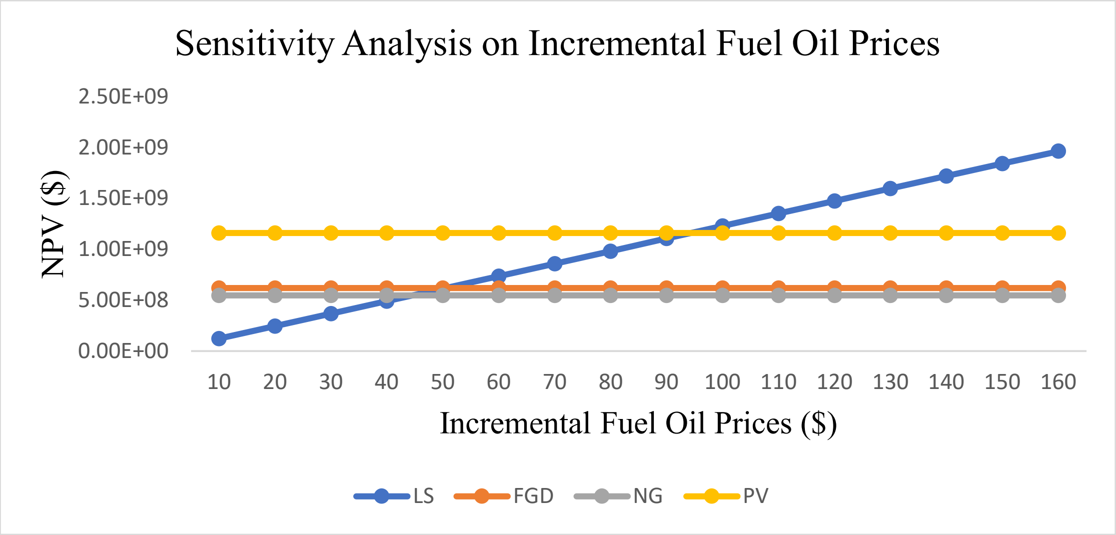

Figure 12: Sensitivity Analysis on Incremental Fuel Oil Prices

Clearly, below $40, the low sulfur fuel is the most economical. However, as the incremental fuel oil prices increase, so does the NPV of this alternative. It can be noticed as well that the NPVs for other alternatives are not altered as they use only one type of fuel.

8.6. Sensitivity Analysis on Natural Gas Prices

Natural gas prices can vary for the same reasons as oil prices. Usually, the prices range between \$0.17/m^3 and \$0.47/m^3. This will affect only the natural gas alternative, while the other alternatives will remain intact.

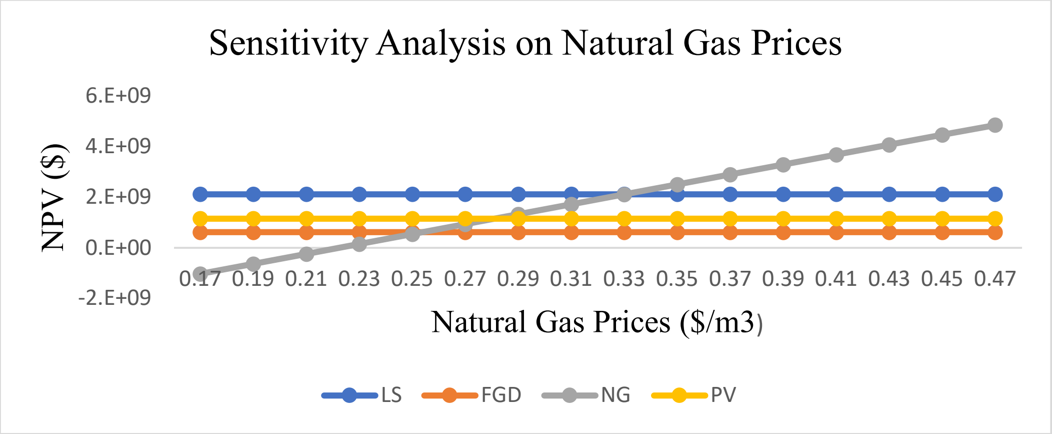

Figure 13: Sensitivity Analysis on Natural Gas Prices

For natural gas prices of less than \$0.25/m^3, this alternative is the most economic one. However, as the price of natural gas increases, the NPV will increase as well until it becomes the less feasible after a value of \$0.33/m^3.

8.7. Sensitivity Analysis on FGD Installation Cost

The FGD installation costs can vary depending on various factors such as the type of technology used, the size of the units, and existing infrastructure. By varying the installation costs between \$90/kW and \$540/kW, the sensitivity analysis is generated and presented in Figure 14:

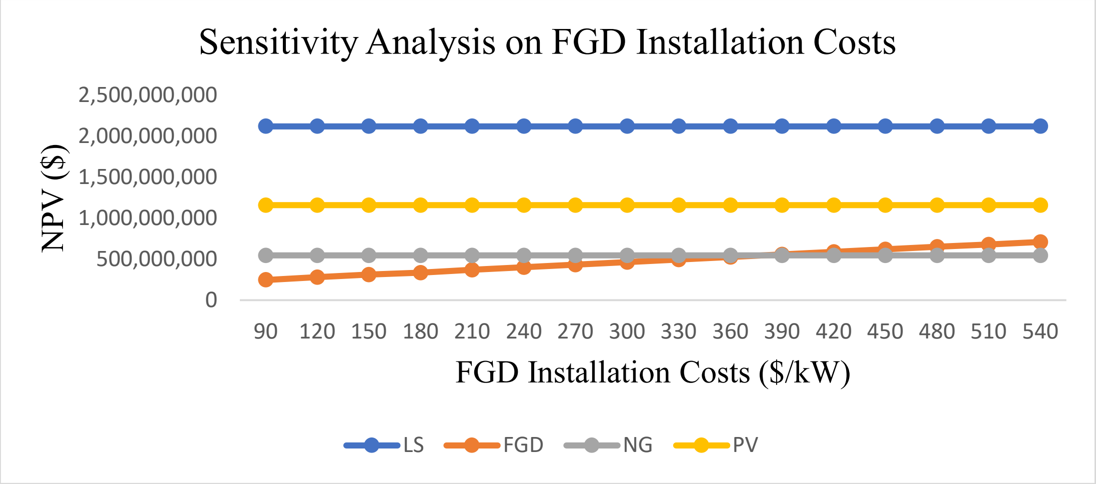

Figure 14: Sensitivity Analysis on FGD Installation Costs

For values less than $360/kW, the FGD alternative will be the most economical one to implement. However, it is unlikely for a system to be this cheap and higher prices are often more common.

8.8. Sensitivity Analysis on Natural Gas Shipping Cost

This component is associated with lots of uncertainties such as the distance, volume being transported, market conditions, type of vessel, and much more. The costs are varied between $\$0.1/m^3$ and $\$0.25/m^3$ and the results are represented in Figure 15:

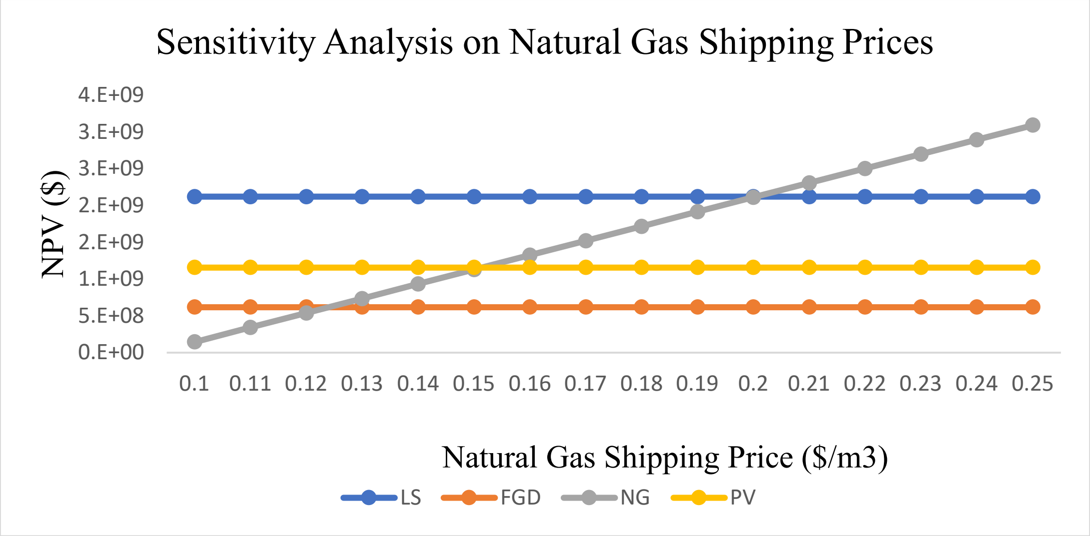

Figure 15: Sensitivity Analysis on Natural Gas Shipping Prices

For values less than $\$0.13/m^3$, the natural gas alternative is the most feasible, however, as the price increases the FGD alternative will become the most economical one.

8.9. Sensitivity Analysis on PV Panel Prices

The price of solar panels is dictated by the materials costs, manufacturing scales, governmental incentives, and market demand. However, in recent years the prices are witnessing a huge decrease especially with the technological advancements and the global shift towards green energy.

The prices are varied between $0.24/kW and $0.84/kW and the results are shown in Figure 16:

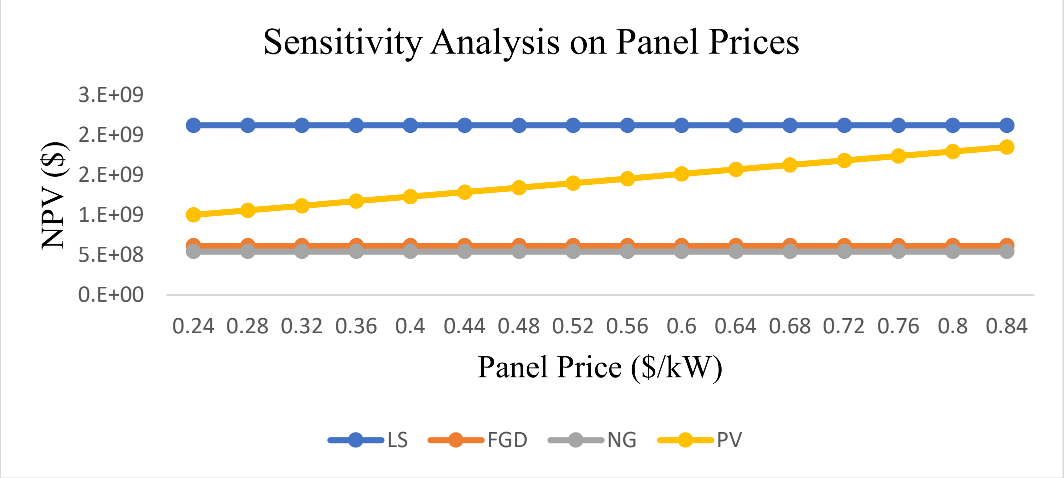

Figure 16: Sensitivity Analysis on Panel Prices

While these changes do not affect the results, as natural gas remains the most economical one, it is possible with years to witness lower panel prices that can further lower the NPV of this alternative.

8.10. Sensitivity Analysis on Battery Prices

While the price of batteries takes a big portion of the capital investment costs in solar projects, lots of research and development is being undertaken in the field of energy storage which may, eventually, lower the price of batteries. The prices are varied between $150/kW and $375/kW and the results are shown in the Figure 17:

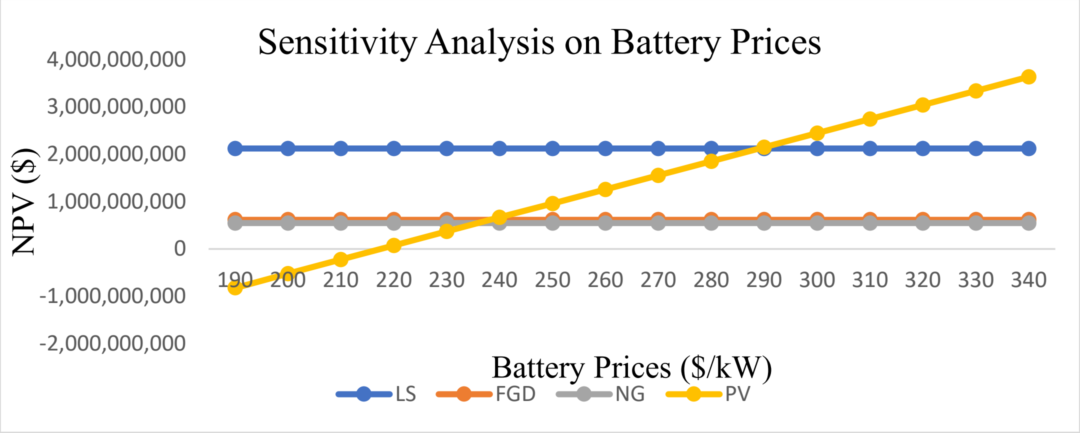

Figure 17: Sensitivity Analysis on Battery Prices

It is obvious that for battery prices less than $240/kW, the PV alternative will be the most economical one. However, the prices today stand in the vicinity of $250/kW, but they are expected to decrease with years especially with all the advancements being made.

8.11. Sensitivity Analysis on Land Cost

Land costs can change depending on the location, political situations, and the terrain. For instance, one square meter of land close to the sea can cost around $\$250/m^2$. This value can decrease significantly if the chosen piece of land is on a mountain, reaching values as low as $\$50/m^2$.

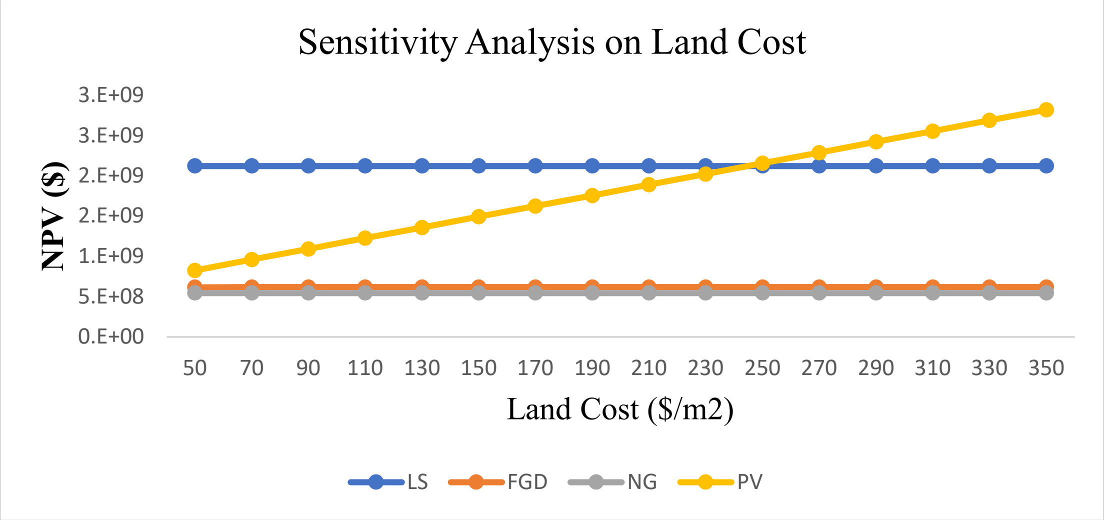

Figure 18: Sensitivity Analysis on Land Cost

While this does not affect the low-sulfur fuel and natural gas alternatives, the PV alternative will witness a high increase in its NPV as the cost of land increases. This can be related to the big area needed to establish a solar power plant.

8.12. Sensitivity Analysis on Sulfur Tax Cost

Another parameter that has lots of uncertainties is the tax imposed on sulfur as an externality cost. This analysis will not affect any of the alternatives, only the BAU scenario.

The tax is varied between $500/ton and $3000/ton, and the results are presented in Figure 19:

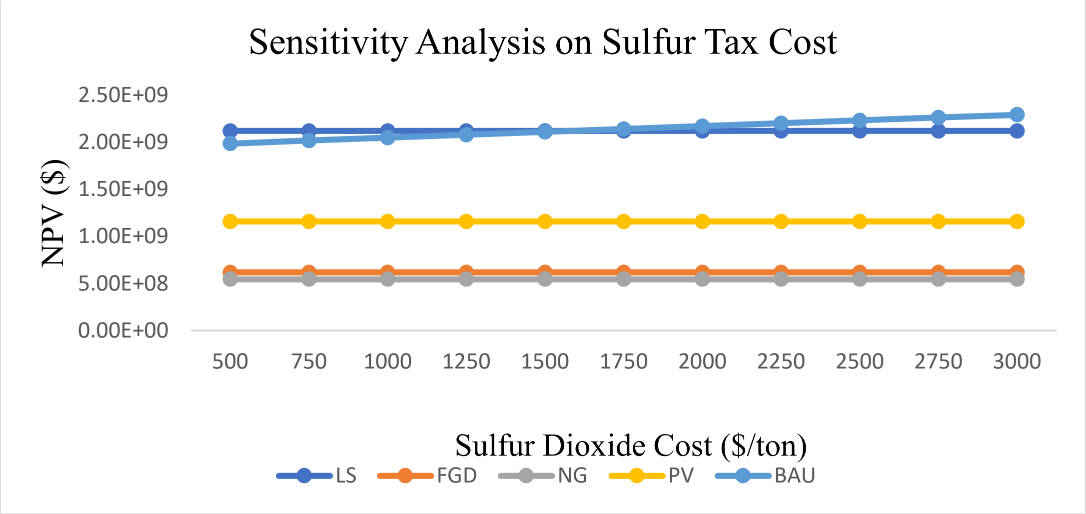

Figure 19: Sensitivity Analysis on Sulfur Tax Cost

This analysis reveals that if the sulfur tax is $1,500/tonne or less, then the BAU scenario is more economic than the low sulfur fuel alternative. Other alternatives are not altered as the sulfur tax is not considered while calculating their NPVs.

8.13. Multiple Parameter Sensitivity Analysis

In each of the previously performed sensitivities, one parameter was tackled at a time. This may reduce the accuracy of the results, and so, a multiple parameter sensitivity analysis will be carried out to provide more feasible analysis.

Figures 20, 21, and 22 represent the net present values of the four alternatives for different lifetimes of the project at different MARR and inflation rates. The rates are set at MARR of 5% and inflation rate of 5% for Figure 20, a MARR of 15% and inflation rate of 10% for Figure 21, and finally in Figure 22 the MARR is set at 20% and an inflation rate of 20%.

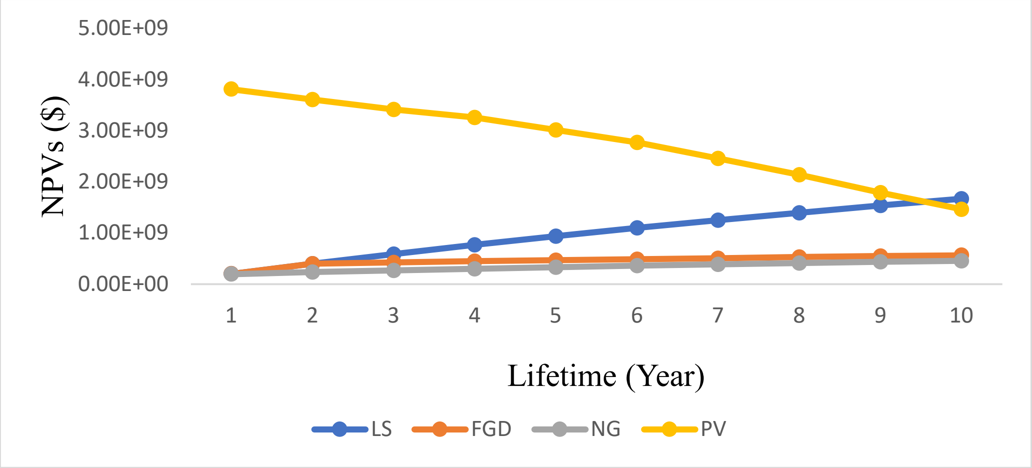

Figure 20: Sensitivity Analysis on Lifetime with MARR 5% & inflation rate 5%

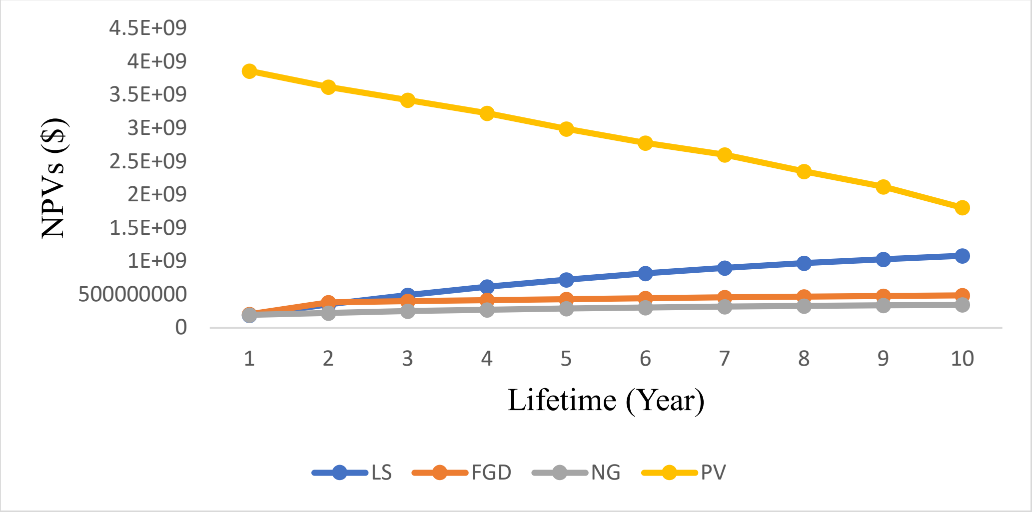

Figure 21: Sensitivity Analysis on Lifetime with MARR 15% and inflation rate 10%

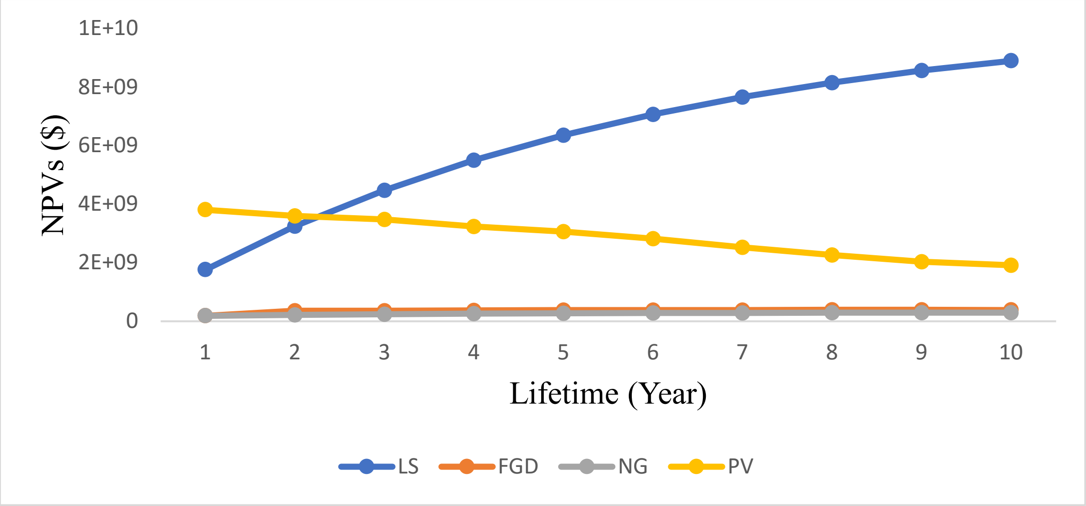

Figure 22: Sensitivity Analysis on Lifetime with MARR 20% and inflation 20%

As seen in the figures, the natural gas alternative is still the most feasible one despite the changes in MARR and inflation rates. It is worth noting, however, that the NPV for the PV alternative is decreasing with time because it has a high capital cost and is associated with huge fuel savings that increase with time.

CHAPTER 9

CONCLUSION

Anthropogenic activities have been deteriorating the Earth's climate for decades. With global warming becoming a reality, it is time to step-up and deal with these issues. Reducing sulfur dioxide emissions from thermal power plants is regarded as a crucial step in mitigating air pollution and its associated health and environmental hazards. Various alternatives are proposed such as utilizing low-sulfur fuels, installing flue-gas desulfurization systems, switching to natural gas or solar energy.

In this thesis, an economic model was developed to assess the economic feasibility of each of the above-mentioned alternatives, taking the Zouk thermal power plant in Lebanon as a case study. While most of the case studies revealed that natural gas is currently the most feasible option, other alternatives are better suited under specific circumstances, like if the natural gas shipping prices increase, or the price of PV batteries decreases over time.

The sensitivity analysis performed on a variety of parameters revealed that for MARR values of 6% and under, the PV alternative will be the most feasible one. Whereas after 6% and up until 20%, the natural gas alternative is regarded as the most economic. Sensitivity analysis on inflation rate, which varied between 1% and 16%, and on power plant lifetime showed no significant changes as natural gas remained as the best option.

Nevertheless, varying natural gas prices, natural gas shipping prices, and boiler modification cost had their toll on the results. If natural gas prices go higher than $\$0.25/m^3$, which is the price used in the study, then the FGD alternative will be more economic. As for the natural gas shipping prices, if they exceed the $\$0.12/m^3$ boundary, then the natural gas alternative will not be regarded as the most feasible anymore. As for the boiler modification costs, they will not have a significant alteration unless the value exceeds \$300/kW, which is 1.5 times the current price and unlikely to happen.

Finally, with the PV alternative, it will be regarded as the most economic if battery prices fell to \$210/kW or less. This is expected to happen in the near future, especially with all of the technological advancements taking place in this domain, and with the global shift towards renewables.

Additionally, multiple-parameter sensitivity analysis was conducted as some parameters were correlated. However, this had no effect on the choice of alternative as natural gas remained the most economic while varying the MARR and inflation rates between 5% and 20%, along with the project lifetime.

The conducted analysis revealed that in certain cases, the natural gas alternative will not be regarded as the most feasible option for the Zouk power plant and may induce further losses on EDL. However, the conversion is still deemed as the most feasible one under ordinary conditions, especially if natural gas was found in the Lebanese offshore territories. Exploration and drilling activities are being conducted by Total, Eni, and Qatar gas, and if commercial quantities were found, then these will induce more savings as there will not be any cost for purchasing natural gas, and the cost of transporting gas will be significantly less.

A suggestion would be to conduct a national feasibility analysis on the Lebanese energy mix, whereby the country can maximize its benefits from the natural resources. This step would diversify and strengthen the energy mix, which would result in preventing monopolies in the sector, securing electricity for citizens, and reducing pollution. Another suggestion would be introducing updated and more inclusive social taxes on emissions from power plants and industries in the country. These would exceed sulfur dioxide to include nitrous oxides and carbon dioxide as well.

One limitation in this research lies in the assumptions taken for some parameters, such as the inflation rate. Taking the rate as 3% in the base case is far from real, where inflation rates in Lebanon have exceeded 240% in one of the worst economic crises as described by the world bank. This necessitates conducting extensive research to take these values into account. Moreover, further analysis should be done to examine the health impacts of electricity generation in Lebanon, especially that the power plants are situated in densely populated areas, and most of the power lines passes above residential areas.

In conclusion, the natural gas alternative is deemed as the most economic option for Lebanon and should be accomplished in the near future. This resource can be found in most of neighboring countries, and potentially could be found in Lebanon as well. Shifting towards natural gas has plenty of benefits as it is better for the environment and has much higher efficiencies than oil.

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