Optimal Integration of Renewable Energy Sources in Oil Refinery Operations

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Petroleum refining is one of the energy intensive sectors of the oil and gas (O&G) industry. With increase in global energy demand and declining energy return on energy invested (EROEI) of crude oil, global energy consumption by the O&G industry has increased drastically over the past few years. In addition, this energy increase has led to an increase in GHG emissions, resulting in adverse environmental effects. On the other hand, electricity generation through renewable resources have become relatively cost competitive to fossil based energy sources in a much 'cleaner' way. In this study, renewable energy is integrated optimally into a refinery considering costs and CO_2 emissions. Using Aspen HYSYS, a refinery in the Middle East was simulated to estimate the energy demand by different processing units. An LP problem was formulated based on existing solar energy systems and wind potential in the region. The multi-objective function, minimizing cost as well as CO_2 emissions, was solved using GAMS to determine optimal energy distribution from each energy source to units within the refinery. Additionally, economic feasibility studies were carried out to determine the viability of renewable energy technology project implementation to overcome energy requirement of the refinery. Weights, α, were assigned to carbon dioxide emissions constraint and a Pareto front was constructed based on different scenarios. For α=0 (i.e. minimizing CO_2 emissions), the total carbon dioxide emissions as well as the cost of producing electricity were 7.92×10^7 gCO_2 and US$ 7.58×10^7, respectively. 56% of the electricity is generated through renewable energy technologies where Solar CSP, Solar PV and wind technologies contribute by 51%, 4% and 1%, respectively. The remainder of electricity demand is met by purchasing it from the national grid. For α=1 (minimizing cost), electricity is purchased solely from the grid with CO_2 emissions and a cost of 5.43×10^8 gCO_2 and US$ 2.96×10^7, respectively. From the feasibility studies, electricity generation through all renewable energy sources considered (i.e. solar PV, solar CSP and wind) were found feasible their low levelized cost of electricity (LCOE). The payback period for a Solar CSP project, with an annual capacity of about 411 GWh and a lifetime of 30 years, was found to be 10 years. In contrast, the payback period for Solar PV and Wind were calculated to be 7 and 6 years, respectively. This opens up possibilities for

integrating renewables into the refining sector as well as optimizing multiple energy carrier systems within the crude oil industry.

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No one walks alone and when one is walking on the journey of life just where you start to thank those that joined you, walked beside you, and helped you along the way. There are lots of people I would like to thank for a huge variety of reasons.

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Mohamed Alnifro

March 22nd, 2017

Dedication

To Mom and Dad, who always picked me up on time and encouraged me to go on every adventure, especially this one.

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CHAPTER 1: INTRODUCTION

1.1 Background

Several developed countries have recently invested in renewable energy sources based on their cleaner nature and declining cost of electricity production. These sources have been found to be economic, relatively clean, inexhaustible and have the potential to be used anywhere on the planet. Moreover, renewables produce significantly less amount of greenhouse gases (GHG) and pollutants that affect the climate as compared to fossil fuels. Yet, there is a high demand for energy, derived from fossil fuels, as shown in Figure 1 [1].

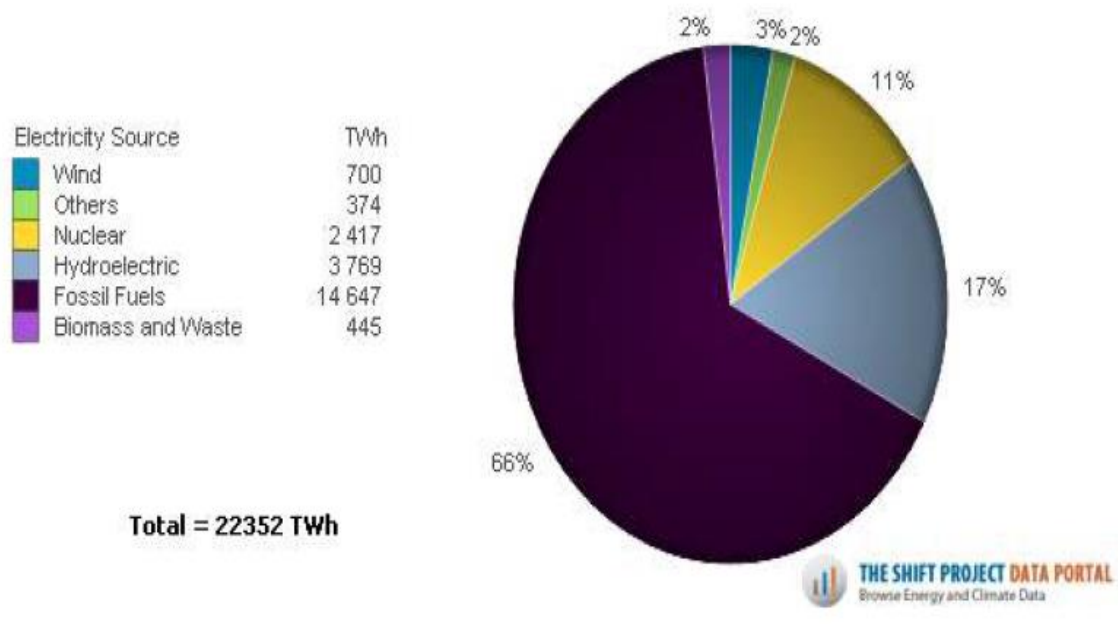

Figure 1. Global production of electricity from all energy sources in 2014[1].

Global warming has been a topic of particular concern and researchers have been studying renewable energy sources to help mitigate this problem. In a study, RETScreen software data was used to evaluate the wind and solar energy potential in the Middle East [2]. The European Academies Science Advisory Council (EASAC) has addressed the possibility area of energy supply and consumption by the end of 2050 and beyond, by focusing on solar photovoltaics, carbon based biofuels and nuclear. In addition, it is suggested that energy should not be contributed independently by means of heat, electricity and mechanical work, rather in a synergistic manner. In some countries, wind and solar have remarkable growth depending upon the climate and topography of the location [3] .

Renewable energy is defined as “the energy generated from natural resources that can be renewed naturally in the environment” by sustainable energy resources. These resources include hydropower, wind, biomass, geothermal, and solar. Many countries depend on these as their primary energy sources. In 2014, the primary production of renewable energy by EU-28 was about 25.4 % of the energy production from different sources. Figure 2 shows the available data for the renewable energies share in gross energy consumption and the required goels that have been set for 2020. The renewable shares in gross final energy consumption reached 16.0 % in the EU-28 in 2014 [4]

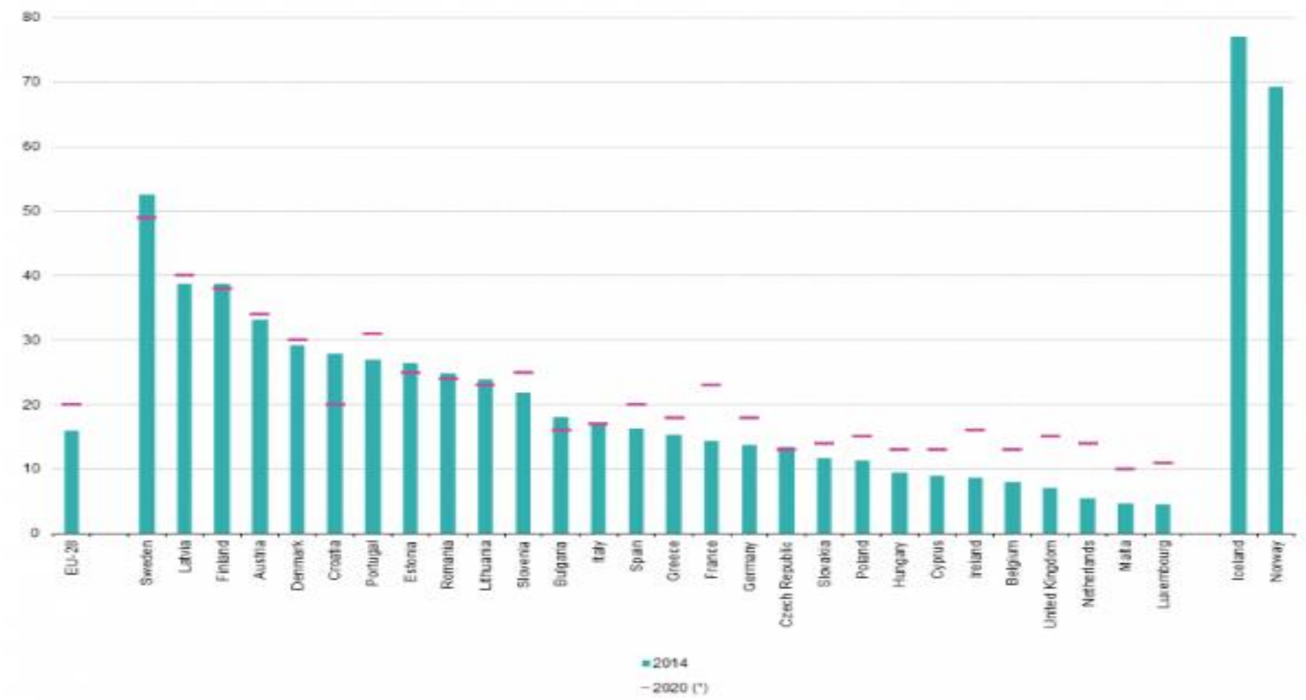

Figure 2. Share of renewables in gross final energy consumption, 2014 and 2020 [4]

Over the past few years, United Arab Emirates (UAE), has shown interest in economically producing renewable energy. Renewable energy sources ramping up to 10% of the total energy mix the country, and 25% of the total power generation, 1.9 billion USD could be saved yearly by 2030 through avoidance consuming of fossil-fuel and lower energy costs. With health and environmental benefits factored in, 1 billion USD to 3.7 billion USD could be saved by transition to renewable energy sources by 2030.

In the past couple of decades, demand of electricity has increased dramatically in the United Arab Emirates. Its production has increased from 39.9 TWh to 110 TWh, in the years 2000 to 2013, respectively. UAE ranked 10th in 2012 in the list of those countries with highest energy consumption per capita with a consumption of 10.13 MWh. Additionally, it ranked 25th in the highest CO_2 emitting countries. The increase in energy demand is due to its population and economic growth. However, UAE has a huge amount of available solar resources to further reduce greenhouse gas emissions and the fossil energy consumption [5]

The United Arab Emirates (UAE) has a plan to switch to solar and nuclear energy as compared to oil and gas. Nuclear plants, across many countries, are generating a significant amount of energy as compared to other energy resources. By combining nuclear and solar energies, a new model can be developed and installed in UAE by integrating hydrogen production system. Orhan et al. has conducted a study in which a thermodynamic analysis has been carried out on solar as well as on nuclear energy systems. By using an integrated system, results have shown that the overall energy efficiency achieved was up to 35% [6].In another study, a hybrid renewable energy system was designed in the western region of Abu Dhabi, the capital of UAE. The hybrid system that includes of wind turbines, photovoltaic (PV) array, diesel generators and batteries was designed to meet the primary load for 250, 500 and 2500 households. The Hybrid Optimization Model for Electric Renewable (HOMER) was used to model, optimize and simulate the proposed hybrid system. Results depicted a reduction in CO_2 emission by 37% as compared to the conventional diesel generator power system for the 500 kW optimal hybrid system [7].

In an analysis carried out by Sgouridis et al. [8], it was suggested to integrate renewable energy sources into existing industries that require enormous amounts of energy. In addition, it was stated that there is a need to overcome the integration of different types of renewable energy resources to the current energy system for refineries.

1.2 Aims and Objectives

Considering the different scenarios explained in the previous section, the goal of this research is to design a “green” refinery with the integration of renewable energy into the existing petroleum refining unit, which can ultimately reduce cost, improve energy efficiency and reduce air pollution. The study focuses on conducting a simulation for a refinery and estimating energy consumed during the refining process. A superstructure is designed to depict available energy sources that could meet energy demand of units within the refinery. Furthermore, a model will be developed to find the optimal distribution of energy to the different units within the refinery. Finally, economic feasibility studies and sensitivity analyses are conducted to determine viability of integrating the renewable energy sources.

1.3 Significance of Research

The outcome of this research is a developed model that will be utilized to determine the optimal production planning for this oil refinery while reducing GHG emissions. The model will incorporate the daily production, the supply and demand for energy, the supply and demand of each product as well as the CO_2 constraint.

CHAPTER 2: LITERATURE REVIEW

2.1 Petroleum Refining

Petroleum refining is one of the most complex processes in the oil and gas industry. It includes many unit processes and subsidiary facilities such as storage tanks and utility units. Generally, most refineries are different from each other and have a unique combination and arrangement of units. These depend on several factors such as the refinery location, the economic consideration and the desired products. The capacity of modern petroleum refineries usually range from 800,000 to 900,000 barrels of crude oil feed per day [9,10].

Since the mid of 20th century, petroleum products have become a dominant energy source, surpassing coal demand. By using petroleum refinery from crude oil, we can get useful products such as gasoline, diesel fuel, liquefied petroleum gas (LPG) and various other petroleum products. Modern refineries as shown in Figure 3 usually have several principal processes: distillation (atmosphere, vacuum), catalytic reforming, alkylation, hydrocracking, hydro-treating, residuum desulfurizing, and coking [9].

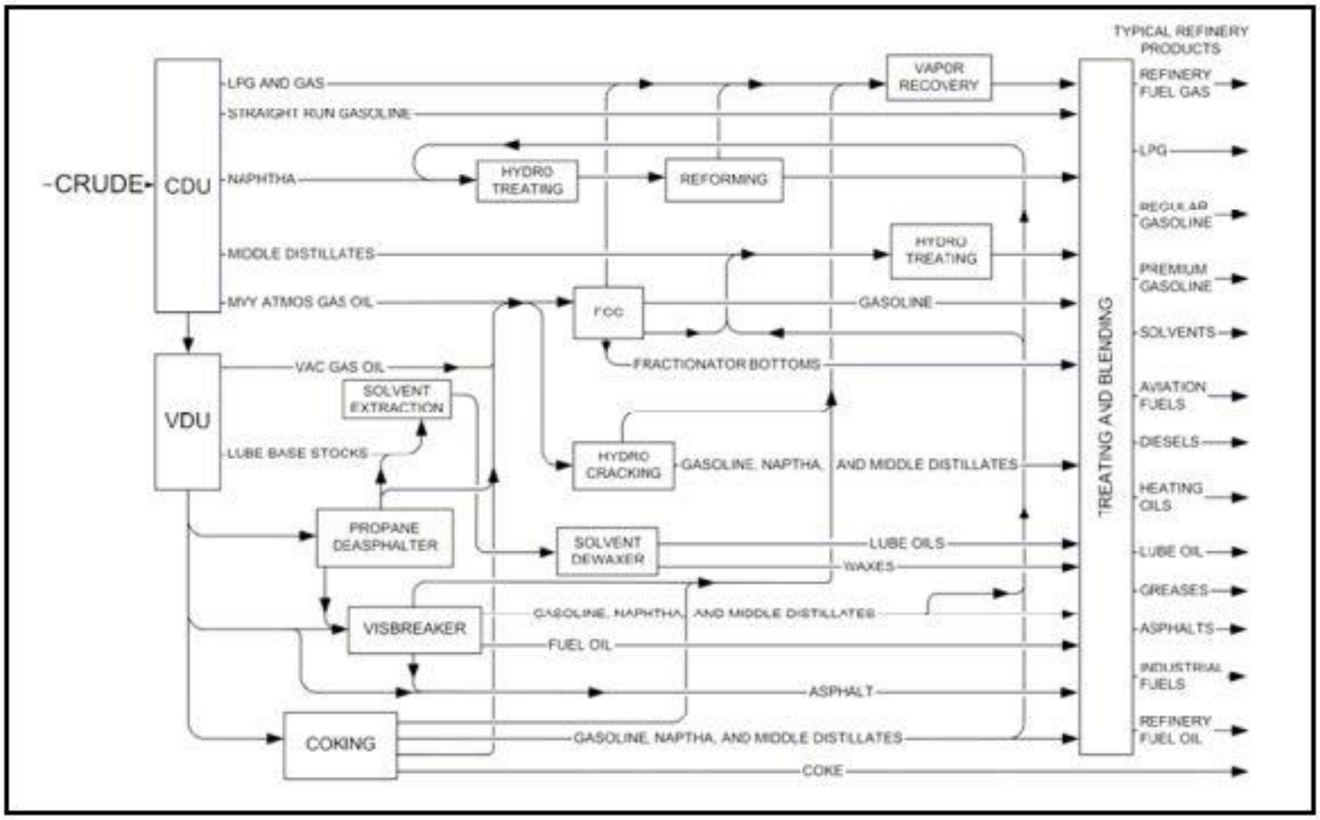

Figure 3. Typical Refinery Configuration [9]

2.2 Refinery Units

2.2.1 Distillation

Modern distillation (separation) as shown in figure 4 involves pumping crude oil through hot furnaces in pipes where it is separated into liquid (heavy hydrocarbons) and vapors (light hydrocarbons). Generally, these vapors and liquids are separated to fractions according to their boiling point and molecular weight. Light fractions exist towards the top of the tower and heavy fractions exist towards the bottom. Some fractions such as gasoline and liquefied petroleum gas, which are the lightest fractions, vaporize and rise to head of the tower where they are condensed to liquids [9]. Some medium weight fractions stay in the middle of the tower such as diesel distillates and kerosene. Heavier fractions (gas oils) flow down in the tower and the heaviest fractions settle down at the bottom of the distillation tower. Furthermore, most of the separation processes have more than one distillation columns working at different pressures, some of them work at near atmospheric pressure and others work at less than atmospheric pressure called (vacuum distillation) [10]. The energy used in refinery by a crude distillation unit (CDU) is about 35–45% [11].

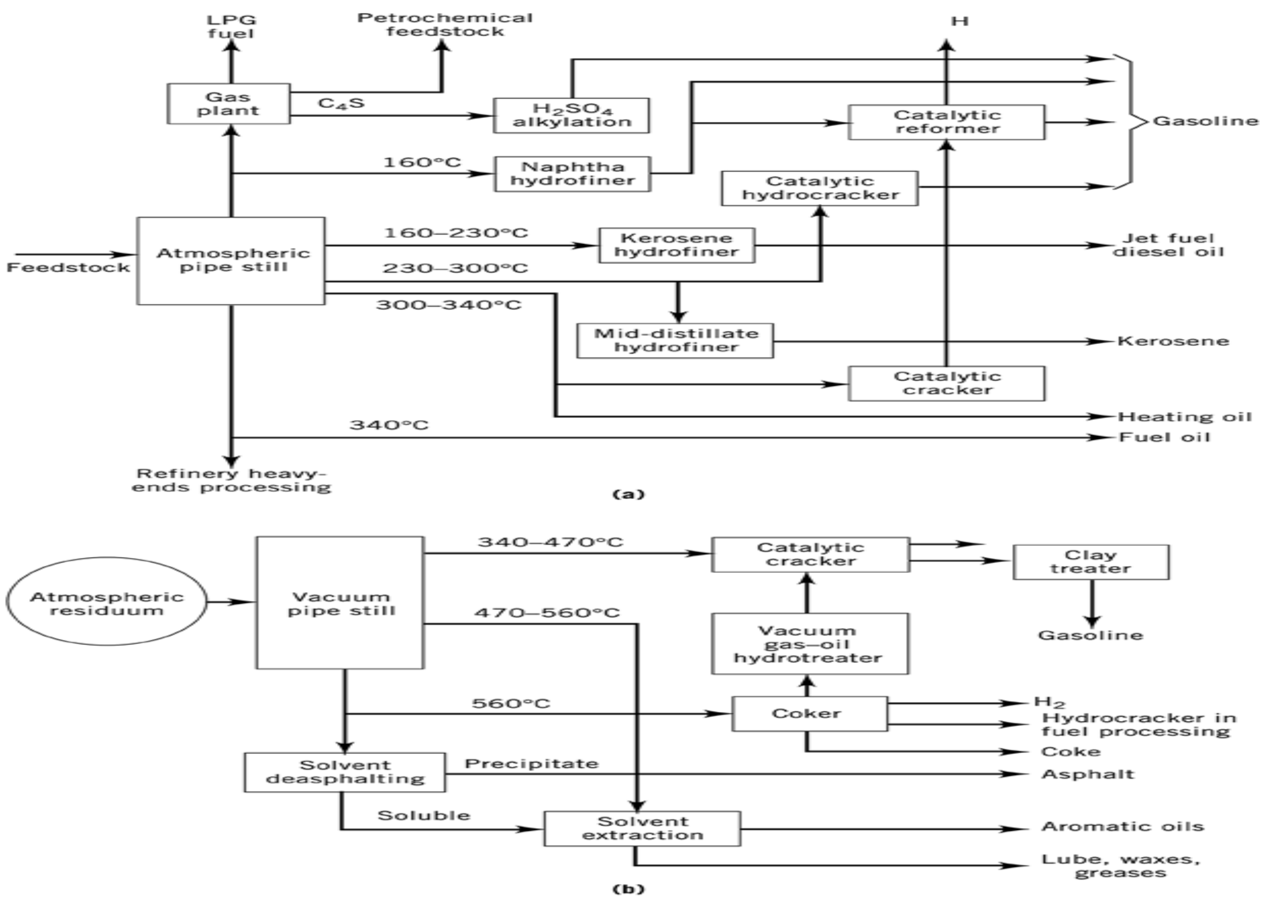

Figure 4. Typical Crude Oil Distillation Unite Flow Diagram [10]

2.2.2 Conversion (Cracking) Processes

After separation, there are many heavy, lower-value products that are cracked into two or more lighter, higher-value products such as gasoline. The stream, where these fractions from the separator are combined, move into pipelines (intermediate products) that become later finished products [12, 13]. This conversion process is carried out at 500°C in the presence of a catalyst to increase the speed of the chemical reaction. 75% of the heavy fractions are converted to gas, gasoline and diesel. Hydrogen is added to increase the yield of products through hydrocracking. It also provide flexibility for maintenance and permit the economic use of sour and heavy crude [14]. Conversion process is further divided into branches as follow:

Fluid Catalytic Cracking (FCC)

There are mainly two types of molecules present in the crude oil lighter products and heavier products. Lighter Products could be separated by direct distillation at different temperature ranges were include gasoline, LPG, naphtha, diesel fuels and kerosene. Heavier products include resids and vacuum gas at temperature > 650oC. Thermal and catalytic cracking processes are used to reduce the molecular weight of heavy products that produce more valuable lighter products such as gasoline, diesel fuels and LPG [15, 16].

FCC unit take part more than 40 % of total refinery output on large scale transportation fuels oriented refinery. Also, produces significant volumes of light gases including olefins and light olefins [14].

Hydrocracking

Hydrocracking is a process in which hydrogen is added to remove impurities in feedstock. Also, converts some heavier molecules into lower weight than feed under desirable boiling temperature range suitable for cracking. Hydrocracking feeds can range from coker gas oil and heavy vacuum gas oils as well as products range from light naphtha to heavy diesel [15, 16]. In addition, Hydrocracker could convert its feed into gasoline blendstocks with yields ≈ 100 vol%. Alternatively, a hydrocracker can produce diesel fuel and jet fuel combined ratios of 85% to 90 vol% along with small quantity of gasoline. Hydrocracking has many advantage over FCC unit such as reducing the sulphur quantity that effect the feed and by-products and converting the heavy molecules to its lower weight than feed and lower the aromatic content [14]..

Coking

Coking is a non-catalytic and thermal conversion process that cracks heaviest residual oil into lighter intermediates for further processing for crude distillation [14]. The coking products are light gases, low quality naphtha and distillate streams that must be further processed and larger volumes of and of petroleum coke and cocker gas oil. The coker gas oil has many uses depend upon the nature of crude oil like it used primarily for FCC as a feed, petroleum coke could sold in industry and for external plants. It is also not fit for FCC feed as it has high volume of sulphur [15, 16].

2.2.3 Upgrading Processes

Upgrading processes involved to produce high value streams, low sulphur gasoline and high octane by chemical reactions and restructuring molecules. The upgrading processes of primary interest all employ small hydrocarbon molecules, involve catalysts and gasoline production [14]. Main upgrading processes, catalytic reforming, alkylation, isomerization, polymerization, and etherification are explained as follow:

Catalytic Reforming

In this unit light petroleum fractions contact the platinum contains catalyst at pressure range (330 - 3350 kPa) and at elevated temperatures to increase the octane number for these streams. In addition, Light hydrocarbons are produced as side products. It is also a primary source to produce aromatic for petroleum industry [14].

Alkylation

In this unit low branched olefins converted into high branched iso paraffins (2,2,4 tri-methyl pentane) by acid catalyst called alkylation or valuable gasoline product. [14]. Light olefins or iso-butane came from FCC unit of refinery. US has world's leading country with FCC unit capacity means the most alkylation capacity. Sue to no sulphur and aromatic capacity it is fine gasoline product for industrial purpose [14].

Isomerization

In isomerization process higher-octane C5 and C6 iso-paraffins may produce from low-octane normal-paraffin molecules in light naphtha, thereby significantly increased the octane of the resulting naphtha stream to produce valuable gasoline feedstock. After isomerization a product form with no sulphur and no benzene output, but some refineries had maintain a protocol for benzene according to gasoline output therefore, it is most economic source for reducing benzene content in gasoline product. Further research is focused on the aspect by introducing new blends and stable catalyst in it [14].

Polymerization

During Polymerization processes light olefin with two or three molecules combines to produce olefinic gasoline blendstock with high octane, called poly gasoline. Although it is relatively low cost process it is not used widely because of poly gasoline is undesirable gasoline blendstock in many refineries due to its high olefinc contents[17].

Etherification

FCC plant produce C4 and C5 olefins that combined with alcohol to produce ether called etherification. It is an expensive process because alcohol could be purchased from market.

These are gasoline products with blending properties and high octane. IN most common process methanol and isobutene combine to produce methyl tertiary butyl ether (MTBE) [14].

2.2.3 Treating

Treating processes remove or reduce the corrosive pollutants, such as sulphur, from the crude oil. Several countries around the globe have set standards on emissions of such harmful pollutants [13]. For instance, the standards of sulfur emission, set by the European Union, are very strict. Sulfur content in diesel and gasoline in Europe market cannot be more than 10 milligrams per kilogram, 10 (ppm). These firm conditions are made to increase the quality of the air and optimize the quality of the catalysts that used to process exhaust gas. Desulfurization process of diesel works at (370°C and 60 bar) where the hydrogen is used to combine with sulfur producing hydrogen sulfide (H_2S) that is treated to remove sulfur.

2.3 Renewable Energy Resources

The depletion of fossil fuel reserves has caused an increase in demand and price of petroleum compounds. Fossil fuel accounts for 88% of total primary energy consumption share with oil 35%, coal 29% and natural gas 24% as the major fuels[18]. 28% of the world's primary energy is being consumed in transportation sector. Transportation fuel consists of gasoline, diesel and kerosene. Total world consumption of diesel was about 1460 trillion litters, as documented in 2011. Transportation fuel demand is predicted to increase up to 40 % by 2040 [19, 20]. However, the fact remains that fossil fuels are non-renewable scarce resources of energy [21].

In recent years, intensity of heat waves has affected the human life through a range of pathways. For example, it has led to an increase in vector borne diseases, malnutrition, increased flood and droughts [22]. The potential threat to global climate change due to enhanced Green House Gas (GHG) emissions has become a top priority environmental concern, which is subsequently worsening global warming. Burning of fossil fuels is believed to be a major contributor of GHGs[23]. Increasing concentration of CO_2, CH_4, CFCs, halons, N_2O and peroxyacetylnitrate in atmosphere continuously raising the temperature of the earth[22]. Since the industrial revolution, industries have been contributing directly and indirectly in increased concentration of atmospheric CO_2 [24]. Hence, global interest moved towards the development of sustainable energy sources. These energy sources include geothermal, solar, wind, nuclear, hydroelectric, and biofuels.

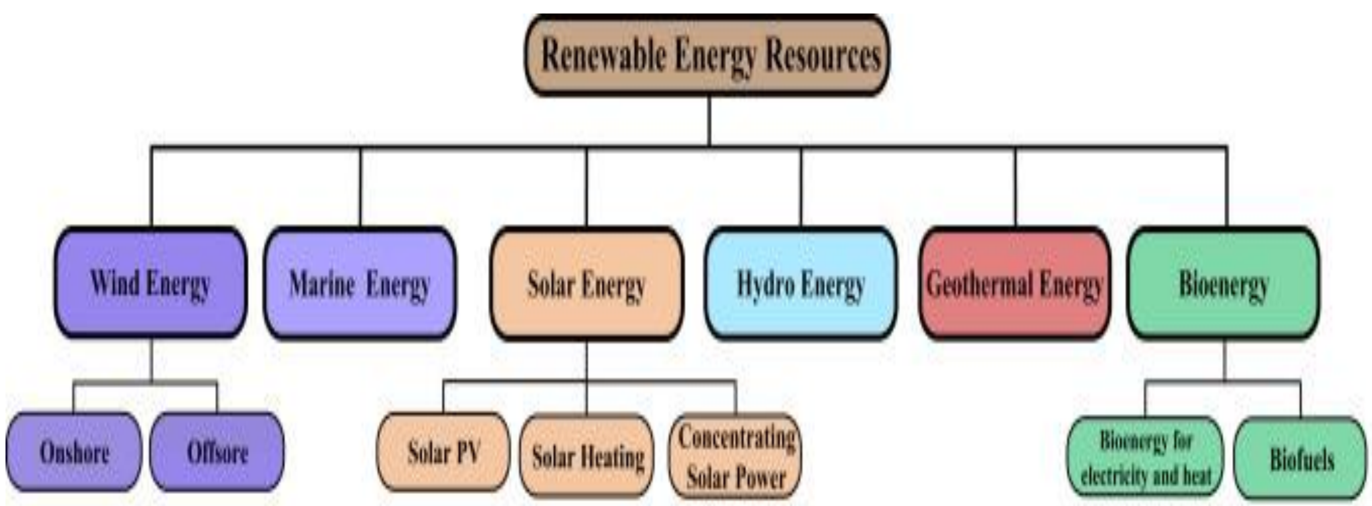

Figure 5. Overview of renewable energy sources [25].

2.3.1 Geothermal Energy

An efficient way to extract energy through natural process by considering parameters including cost and environment friendliness is through geothermal energy. It could be used on a large scale as well as on small, where heat is provided to a residential unit by using and geothermal power plant and geothermal heat pump, respectively [26].

There are many resources including thermal energy that come from the interior of the earth in the form of steam. Geothermal energy resources are present throughout the world under different temperature ranges [25, 27]. Electric power cam be generated through these resources by using heat to generate power in cogeneration applications [25].

2.3.2 Hydropower

Hydropower is a type of energy produced from moving water that can be captured by using turbine systems. Across the globe, dams are used for this purpose to generate electricity from hydropower. Nowadays, tidal power and harnessing waves are also used to produce electricity on small as well large scale. Hydrological cycles, driven by solar energy that move water in a cycle from an elevated surface to the ground through the force of gravity and water flow in rivers also have the potential to produce power. The world's largest plants with a capacity of 80 and 100 TWh/year are the Gorges and Itaipu, in China and Brazil, respectively. [28]. USA, Canada, China, Russia and Brazil contributed to half of the world's energy generation through hydroplants [25]. Hydroplants are categorized according to their type of water flow and operation. Firstly, Run-of-River (RoR) varies from large to small scale applications, depending upon the topography and hydrology of the watershed. A RoR produces energy for the electricity production mainly through available river flow. This type of hydropower plant includes short term storage capacity of water, but the local river flow conditions may also cause fluctuations in the profile of electricity generation. Thus, generation depends on runoff and precipitation and may have substantial variations on a daily, monthly or seasonal basis.

Secondly, the storage hydropower plants store water according to domestic needs through a reservoir system. The power generating stations for these hydroplants are located at the downstream, connected to the reservoir through pipelines. These types of hydropower plants are subjected to less variability of inflow [29]. Lastly, pumped storage hydropower plants do not act as an energy source but are able to transfer water from a lower level to an upper level reservoir, during off-peak hours. The plant is able to provide large-scale energy storage system benefits in future. [30].

Hydropower is an extremely flexible type of power technology with the best conversion efficiencies across all energy sources (90%, water to wire) due to its direct transformation of hydraulic energy to electricity [30].

2.3.3 Solar Energy

Solar energy can be used to heat water and generate electricity through turbines, via concentrating solar power (CSP) and photovoltaic (PV) systems. Over the past few decades, many countries have focused on these solar energy systems. In addition, studies have been conducted to reduce cost of electricity generated through PV and CSP systems [31].

Photovoltaic (PV) technology

Electricity can be produced from solar energy by direct conversion through photovoltaic systems. A PV cell plays an important role in energy conversion, with the help of a semiconductor. A PV module can be formed by interconnecting PV cells with each other, from 50W to 200 W. PV system consists of additional components such as batteries, mounting systems and other electrical components. In PV systems, modules can be used to generate power from few watts to tons of megawatts. Commonly, modules used in PV systems are made of silicon but some countries use non-silicon materials that had been first introduced in 1997 [32]. However, these thin layer PVs produce less energy as compared to silicon modules. Another type of PV technology, known as concentrating PVs, exists in which light is focused on a small area. It has been found to be 40% more efficient than any other PV technology [33].

Solar PV has two advantages: (i) module manufacturing whilst achieving economies of scale can be done in large-scale plants and (ii) it uses direct sunlight as well as diffuse component of sunlight when sky is not clear, as opposed to CSP technology [34].

PV systems can be classified into two branches: off grid and connected-grid applications. For developing countries, off-grid systems play an important role as they are economically feasible. These systems can be used in remote areas and can eliminate the need for diesel generators [35]. Tied grid PV systems convert alternative current to direct current through inverters that supply electricity to electric grid through generators. It used as a buffer as there is no electricity storage but it is cheaper than off-grid technology.

Concentrated Solar Power Technology

Concentrating Solar Power (CSP) systems use solar beam irradiation, focused on a small area to heat a particular solid, liquid or gas for electricity generation. CSP applications produce electricity from small distribution units to hundreds of megawatts (MW) of electricity generation. The CSP plant in California generates about 354 MW electricity. In 2009, more than 700 MW connected grid CSP were installed throughout the world that increased to 2550 MW in 2012 and is continuously growing [36].

2.3.4 Wind Energy

Wind energy is converted using wind turbines into useful power, (i.e. electricity, wind pumps for pumping water or drainage and wind mills for mechanical power). In the beginning of the 20th century, the first wind turbine was used to generate electricity. The application of this technology grew and by the end of 1990, it was reborn as a new renewable energy resource for all over the world [37].

In the era between 1970 to 1980, both models of turbines were used (i.e. vertical and horizontal models) but horizontal model was found to be more advantageous over the vertical model. Offshore wind power pants were found to generate electricity, ranging from 5 MW to 300 MW

Furthermore, Offshore wind technology was not matured until the end of 2000 due to its limitations such as wind blow, wind usually not blow and sometimes very low amount in regions that far from sea and it used to be expensive to apply, but now a day's scientist had worked on this aspect also that in offshore area hills may include where wind blow rapidly but there is a problem of maintenance and cost in the production in that areas [38]. In 2012 United States and China accounted about (60%) of the global market, followed distantly by Germany, India, and the United Kingdom. Others in the top 10 for capacity added were Italy, Spain, Brazil, Canada and Romania [39, 40]

2.3.5 Biomass

Biofuels have proven to be renewable, more efficient and an environmental friendly alternative of the traditional fossil based fuels [41]. Yet, their cost of production is still a concern. Biofuel is obtained from carbon-rich biomass mainly either plants, animals or unicellular microorganisms. Main sources for biofuel production include agricultural, municipal, agro-industry and food-industry waste [42]. Biofuels are classified into two groups: primary and secondary biofuels.

Primary biofuels are in an unprocessed form and are used for electricity generation, cooking and heating while processed secondary biofuels are used for transportation purposes. Biofuels are also classified into solid (such as fuelwood, charcoal), liquid fuels (such as bioalcohals, biodiesel and pyrolysis oil) and gaseous fuels (biomethane and biohydrogen [43]. Solid biofuel like biochar is an organic material which is produced by pyrolysis (i.e. heating of biomass at higher temperature ~250 °C under anaerobic conditions). It is a rich source of carbon, phosphorous, magnesium, calcium and sometimes nitrogen. The biochar production methods also release heat, oil and gas use for power generation [44]. Liquid biofuel, such as bioalcohols, are derived exclusively from the fermentation of biomass and are of great interest to be used as fuels in Brazil, USA and Europe. Higher octane rating, increased fuel efficiency and lower energy density are some valuable advantages associated with alcohol fuels [45]. Gaseous biofuels are one clean, valuable and renewable alternative energy source especially for rural areas [46]. Out of these, biodiesel has gained much attention as it is nontoxic, biodegradable and is the best candidate to replace the petro-diesel[47] because it burns in a similar way to conventional diesel and has better efficiency than gasoline[48].

Biodiesel is recognized as an attractive alternative fuel and its use as a motor fuel has grown dramatically in recent years [49]. It is equivalent to petroleum-based diesel in terms of performance but better than the later in terms of environmental safety. It can easily be mixed with petro-diesel in any proportion to make a stable biodiesel blend, which greatly improves the performance of engine. Moreover, it has lower ignition point and higher flash point[50]. Four ways are reported to produce biodiesel including, direct use and blending, micro emulsions, pyrolysis, and transesterification. But the most common way to produce biodiesel is to trans-esterify the lipids into Fatty Acids Methyl Esters (FAME) or Fatty Acids Ethyl Esters (FAEE), which is biodiesel and glycerine (by product)[51]. Glycerol has its industrial importance too, minimizes the overall production cost. In this process TAG reacted with alcohol to produce fatty acid alkyl esters in the presence of catalyst[52]. It is reported alkali catalyst is faster than the acid and enzyme[53].This technique has been used for a number of years in biodiesel production history[54]. In pyrolysis method, thermal decomposition of biomass occurs in the absence of oxygen result in production of bio oils, bio gas and biochar. Nowadays, this technology is extensively used for biodiesel production. Fast pyrolysis technology has been proved to produce high quality bio oils with high fuel to feed ratio. Many research studies have been published on the development of pyrolysis technology for bio diesel production[55, 56].

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter discusses the methodology followed in order to conduct the study of optimal renewable integration into a refinery. It states the sources of data, modeling techniques used in the thesis work and the selected software used to achieve these objectives. Aspen HYSYS, an industrial process simulation software, is used to simulate a crude oil refinery and estimate the energy consumption by each unit in this refinery. Additionally, General Algebraic Modelling System (GAMS) software is used to solve the LP problem of finding optimal energy distribution, whilst minimizing cost and CO_2 emissions.

3.2 Superstructure

A superstructure of alternatives was developed on the basis of energy demand by the crude oil refinery units and available energy resources. All units in the refinery are connected with different energy sources that provide the energy depending on the CO_2 emissions and the cost of the energy. Each energy source gives energy to a specific refinery unit, as seen in Figure 6, where all the refinery units are shown in different symbols as explained in Table 1.

Table 1. Refinery Units Symbols

Hydrogen plant	HYD
Sulfur Recovery Unit	SRU
Amine plant	AMN
Saturate Gas Plant	SGP
Naphtha Hydrotreater	NHT
Reformer	LPR
Kerosene Hydrotreater	KHT
Diesel Hydrotreater	DHT
Hydrocracker	HCD
Delayed Coker	DLC
Catalytic Cracking (CCU)	CCU
Sulfur Acid Alkylation	SFA
C4 Isomerization	IS4
Unsaturate Gas Plant	UGP
Atmospheric Distillation	ATMD
Vacuum Distillation	VACD

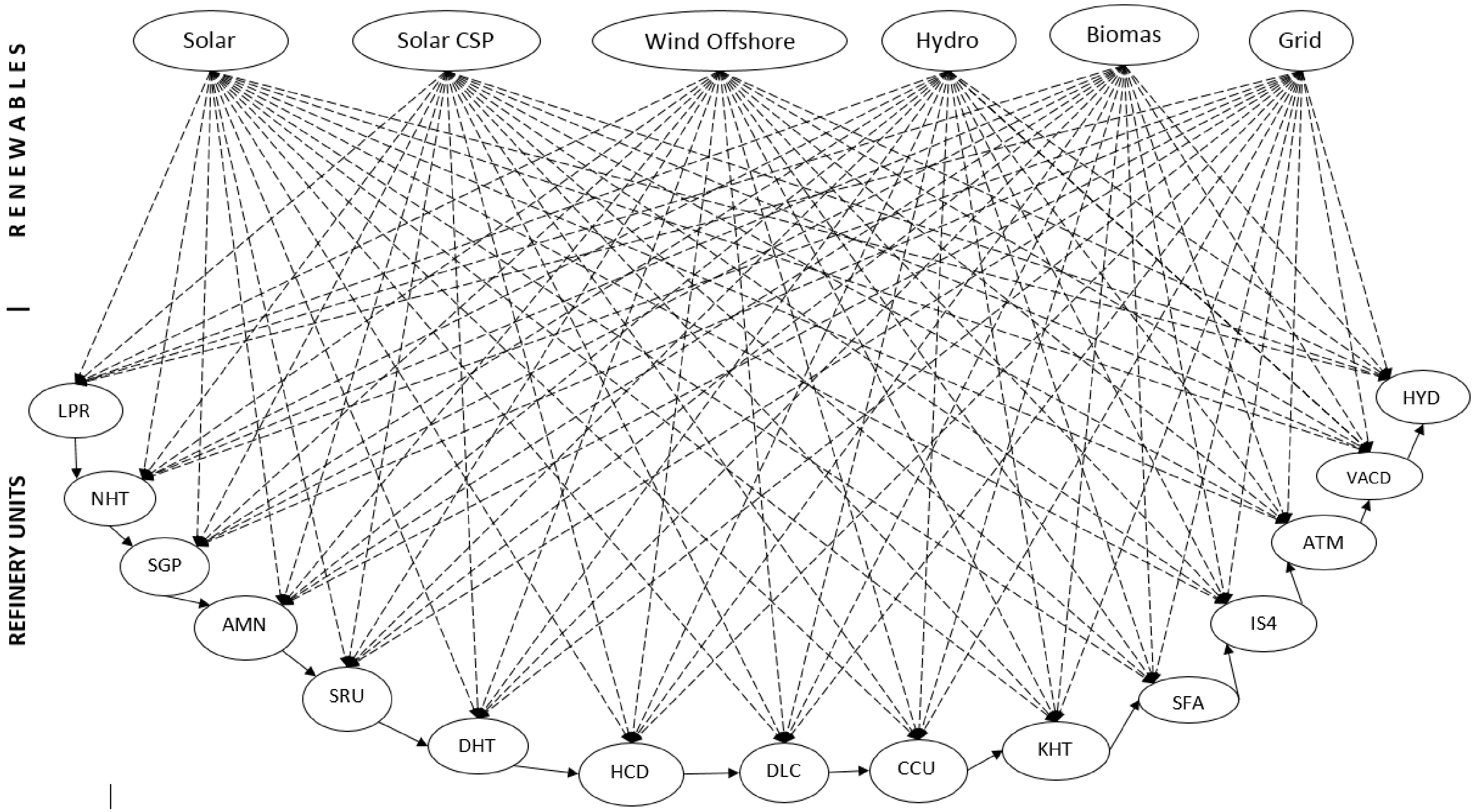

Figure 6. Superstructure diagram for the crude oil refinery units connected with all available energy resources.

3.3 Refinery Simulation

Petroleum refineries are a set of large continuous flow manufacturing processes. Figure 7 is a simplified flow chart for a modern refinery, simulated using Aspen HYSYS in this work. It is assumed that 100,000 bbl of crude oil blend is refined per day. The refining process starts with the desalting and separation process. The mixture of sweet and sour crude oil enter the refinery at a temperature of 21 °C and a pressure of 1480 KPa. The stream enters the separation unit which includes the atmospheric and vacuum distillation units. The 12 main crude fractions (cuts) streams leaving the separation are listed below along with their conditions:

- Naphtha fraction on stream (Win1) at 21 °C and 790.8 KPa goes to Naphtha Splitter (NSP)
- Kerosene fraction stream (KE1) at 236 °C and 101.3 KPa goes to the Kerosene Hydrotreater unit (KHT)
- Vacuum residual (VR1) at 652 °C and 790.8 KPa goes to Coker Unit (DLC)
- Vacuum residual (VR2) at 625 °C and 790.8 KPa goes to Coker Unit (DLC)
- Light Vacuum Gas oil (LV1) LVGO at 353 °C and 790.8 KPa to Catalytic Hydrocracker Unit FCC
- Light Vacuum Gas oil (LV1) at 353 °C and 790.8 KPa goes to Hydrocracker unit (HCD)
- Light Vacuum Gas oil LV2 at 352 °C and 790.8 KPa goes to Hydrocracker unit (HCD)
- Light Vacuum Gas oil (LV2) at 352 °C and 790.8 KPa goes to Catalytic Hydrocracker unit FCC
- Aromatics Atmospheric residual (AR2) at 450 °C and 101.3 KPa goes to Catalytic Hydrocracker unit FCC

- Heavy Vacuum Gas Oil VGO stream (HV1& HV2) at 425 °C and 790.8 KPa goes to Catalytic Hydrocracker unit FCC
- Diesel (DS1) at 311 °C and 101.3 KPa goes to Diesel Hydrotreater unit (DHT)

These streams go through different refining processes for further processing and end with final valuable products, Liquefied petroleum Gas, Petrol (Gasoline), Kerosene, Diesel, Sulfur, and Coke.

3.3.1 Liquefied petroleum Gas

LPG is produced from crude oil in this refinery at 71 °C and 101.3 KPa after several processes. However, full range Naphthas generated from CDU from stream (WN1) is separated by Naphtha splitter into Light Naphtha (LN1), Medium Naphtha (MN1), and Heavy Naphtha (OVHD) fraction. Heavy Naphtha fraction through stream NAP at 35 °C and 101.3 KPa enters to the Saturate Gas Plant (SGP) and is processed with Iso-Butane iC4 and separate other refinery gas components including Methane C1, which goes through stream C1 at 21 °C and 100 KPa into the Hydrogen Plant (HYD). Beside of Methane C1, Propane C3 is produced from Saturate Gas Plant (SGP) and leaves at 21 °C and 790.8 KPa through stream C3 towards Mixing unit (MIX-100) to produce Liquefied Petroleum Gas fuel (LPG) at 71 °C and 101.3 KPa

3.3.2 Petrol (Gasoline)

Gasoline, one of the valuable products from this refinery, is produced by the Gasoline Blending unit that is fed with several products from different units on the following manner:

- Catalytic Cracked Distillates (gasoline or naphtha) HCN is produced from the Catalytic Cracker Unit (CCU) with high olefin content, a moderate octane rating, and moderate aromatics content at 100 °C and 101.3 KPa. Catalytic Cracker Unit is fed with Coker gas oil (DCG) at 100 °C and 790.8 Kpa produced by the Coker DLC and other fractions from the Crude Distillation Unit (CDU).

- Light Naphtha from stream (LN1) at 50 °C and 101.3 KPa from NSP unit

- Hydrocracker Light Naphtha stream (HCL) at 100 °C and 101.3KPa comes from the Hydrocracker unit (HCD). However, Hydrocracker unit is fed by Coker Diesel (DCD), Light Cracked Oil (FCC LCO), and Coker Gas Oil (DCG) produced by the Coker (DLC) respectively at 100 °C and 790.8 KPa, 100 °C and 790.8 KPa, 100 °C and 101.3 KPa. Also, it is fed by light vacuum distillates LV1 and LV2 from the Crude Distillation Unit (CDU).

- Reformates fractions RFT at 100 °C and 101.3 KPa from the Reformer (LPR), this unit is fed by Treated Sour Naphtha (TSN) and Treated Coker Naphtha (TCN) from the Naphtha Hydrotreater Unit (NHT) at 100 °C and 101.3 KPa , and Heavy Naphtha (HCH) at 100 °C and 101.3 KPa produced from Hydrocracker unit (HCD).

- Alkylate (ALK) at 100 °C and 101.3 KPa produced by the Sulfuric Acid Alkylation Unit (SAF).This unit is fed by low molecular weight alkenes (primarily propene C3m and butene C4m) at 21 °C and 101.3 KPa made by the Unsaturated Gas Plant (UGP) and Iso-butane IS4 at 100 C °C and 790.8 KPa which produced from the Isomerization process for the recycled and purchased normal butane nC4 at 21 °C and 790.8 KPa.

- Light Naphtha (LCN FCC) at 100 °C and 101.3 KPa which comes from a Catalytic Cracker Unit (CCU)

<u>3.3.3 Kerosene and Diesel</u>

These fractions come from the Distillate Blending Unit at 203 °C and 101.3 KPa. However, this unit is fed with four streams at 100 °C and 101.3 KPa; Hydrotreated Kerosene (HTK) produced from the Crude Distillation Unit (CDU) and treated by the Kerosene Hydrotreater Unit (KHT) and Diesel comes from:

- Diesel Hydrotreater unit (DHT)
- Hydrocracker Unit (HCD)
- Catalytic Cracker Unit (FCC)

3.3.4 Fuel Oil

The Fuel oil is produced from three units at 100 °C and 101.3 KPa before it enters the blending unit and produce the final product at 154 °C and 101.3 KPa. These units are:

- Diesel Hydrotreater Unit (DHT)
- Hydrocracker Unit (HCD)
- Catalytic Cracker Unit (FCC)

3.3.5 Coke

Coke is produced at 100 °C and 790.8 KPa from the Delay Coker Unit (DLC)

3.3.6 Sulfur (H2S)

Sulfur is produced in this refinery by Amine Unit (AMN) that comes from these units:

- Catalytic Hydrocracker unit (FCC)
- Diesel Hydrotreater unit (DHT)
- Coker Unit (DLC)
- Hydrocracker unit (HCD)

- Naphtha Hydrotreater (NHT)
- Kerosene Hydrotreater (KHT)

It is then processed by the Sulfur Recovery unit (SRU) and Sulfur is produced at 35 °C and 101.3 KPa.

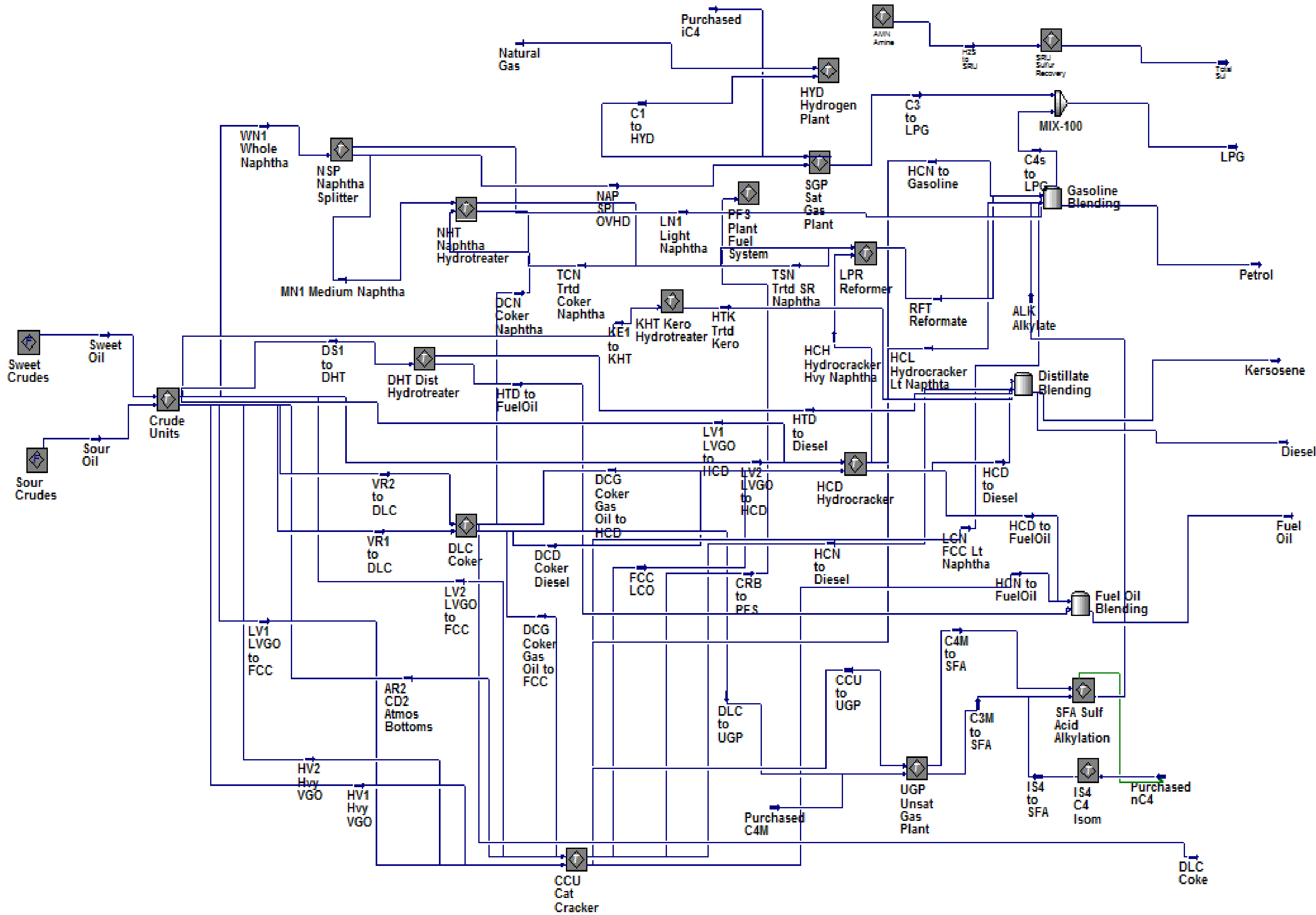

Figure 7. Process flow diagram (PFD) of the modern refinery simulated using Aspen HYSYS

3.4 Simulation Results

The refinery was simulated in Aspen HYSYS and the amount of energy required by each unit was determined. Table 2 depicts the energy required by each unit and the associated emissions [57].

Table 2. Energy required by each unit and CO2 emissions for each unit in the refinery [57]

Plant	MJ/year	g CO2/ MJ
Hydrogen Unit	3.38×10^{7}	0.362
Sulfur Recovery	2.42×10^{8}	0.056
Amine	2.53×10^{7}	0.056
Saturate Gas Plant	1.00×10^{8}	0.168
Naphtha Hydrotreater	1.63×10^{7}	0.187
LPR Reformer	1.34×10^{8}	0.998
Kerosene Hydrotreater	7.07×10^{6}	0.187
Diesel Hydrotreater	8.50×10^{6}	0.187
Hydrocracker	1.80×10^{8}	0.561
Delayed Coker	3.31×10^{7}	0.312
Catalytic Cracking	3.29×10^{8}	0.686
Sulfur Acid Alkylation	2.35×10^{8}	0.000
C4 Isomerization	2.20×10^{7}	0.062
Unsaturated Gas Plant	1.11×10^{8}	0.168
Atmospheric Distillation	2.06×10^{75}	1.684
Vacuum Distillation	4.01E+06	0.561

It is seen that the catalytic cracking unit (CCU) requires 3.78 x10^7 MJ/hr (i.e 3.29 x10^8 MJ/year) while the atmosphere distillation unit requires 2.35 x10^4 kJ/hr of energy. In the case of CO_2 emissions, the atmosphere distillation unit emits the highest amount of CO_2, 1.684 gCO_2/MJ. On the other hand, the sulfur recovery and amine units, each emit 0.056 gCO_2/MJ, the lowest among the fifteen units. However, the Sulfur Acid Alkylation unit emits negligible amount of CO_2 as compared to other units [57, 58].

3.5 Energy suppliers

Table 3 shows the available and/or potential energy sources in the region of Abu Dhabi where the refinery is assumed to exist with CO_2 emissions due to electricity generation and the levelized cost of electricity. It is observed that the highest amount of CO_2 emissions are produced from the grid energy source (i.e. natural gas) in comparison with other renewable sources. Although, it generates electricity at the least cost while wind and hydro appear to be the cheapest sources of energy, among all the renewable energy resources. Table 2 shows the CO2 emissions and the cost of energy per MJ for different potential energy sources in Abu Dhabi [59-61].

Table 3. Potential energy sources in Abu Dhabi with CO_2 emissions due to electricity generation and the levelized cost of electricity [62]

Source	gCO2/MJ	LCOE $/kWh	Capacity (MJ/year)
Solar CSP	9.166667	0.18	7.56 x10^8
Solar PV	36.80556	0.27	6.32 x10^7
Wind	2.222222	0.07-0.13	7.2 x10^6
Hydro	2.5	0.07-0.10	0
Biomass	6.111111	0.09	0
Grid	119.4444	0.05-0.07	3.6972 x10^{11}

3.6 Model Development

A model was developed, in order to utilize the viable alternatives and technologies available in the region to meet the demand of electricity with the lowest cost while reducing CO_2 emissions. This is a multi-objective optimization problem where the two objectives are total cost and carbon dioxide emissions. The ε constraint method is used where the objective function is the cost of energy that is minimized and the CO_2 emissions are posed as a constraint. Thus, the mathematical expression of this problem statement consists of minimizing cost (objective function) while observing inequality and equality constraints and equality. It is written in a general form as the following Linear Programming (LP) problem:

$$\min z = \sum_{p=1}^{6} \sum_{d=1}^{16} lcoe_{p,d} x_{p,d} \tag{1}$$

subject to

$$(1-\propto)7.92 \times 10^7 \leq g \leq \propto (5.44 \times 10^8); \propto \in [0,1]$$

$$\sum_{p=1}^{6} x_{p,d} - b(d) \geq 0 \tag{2}$$

$$\sum_{d=1}^{16} x_{p,d} - a(p) \leq 0 \tag{3}$$

$$g = \sum_{p=1}^{6} \sum_{d=1}^{16} ghg_{p,d} x_{p,d} \tag{4}$$

Where:

z: The total project cost

x(p,d): Energy from energy supplier to energy demand

p: Energy suppliers solar CSP, solar PV, grid, hydro, wind, and biomass

d: Energy demand by the refinery units

a(p): Production capacity of energy supplier (MJ / year)

b(d): Energy demand by each unit in the refinery (MJ)

ghg(p,d): Carbon dioxide emission from each energy supplier (CO2 g / MJ)

lcoe(p,d): Cost of energy production (USD / MJ)

α: constant weight varying between 0 and 1

As stated above, the carbon dioxide emissions (g) is posed as a constraint and it is bounded between the maximum and minimum emissions the refinery emits. A weight, α, is multiplied to the upper bound while the lower bound is multiplied by (1- α). By varying the value of the weight between 0 and 1, the optimal values of cost and carbon dioxide emissions can be obtained and a Pareto front is constructed.

In this work the considered constraints are as follows:

- Emission Constraint: The total CO_2 emissions must be within the upper and lower bounds, subjected to a weight, α.
- Demand constraints: Total generated electricity must be greater or equal to the nominal electricity demand, $b(d)$.

- Capacity factor: The total electricity required for all units must be equal or less than the electricity generated from all the sources, $a(p)$.

CHAPTER 4. RESULTS AND DISCUSSION

In this chapter, the results obtained from the simulated refinery unit as well as the optimization of the developed model are presented as previously mentioned, the carbon dioxide emission was posed as a constraint with an assigned weight, α, that ranges between 0 and 1. A value of α=0 signifies a focus on minimizing carbon dioxide emissions with no regard to cost. Conversely, a value of α=1 signifies a focus on minimizing cost with no consideration of carbon dioxide emissions. Figure 8 shows the changes in the cost and carbon dioxide emissions as alpha varies between 0 and 1. The cost is found to be minimum when emissions are maximum, and vice versa.

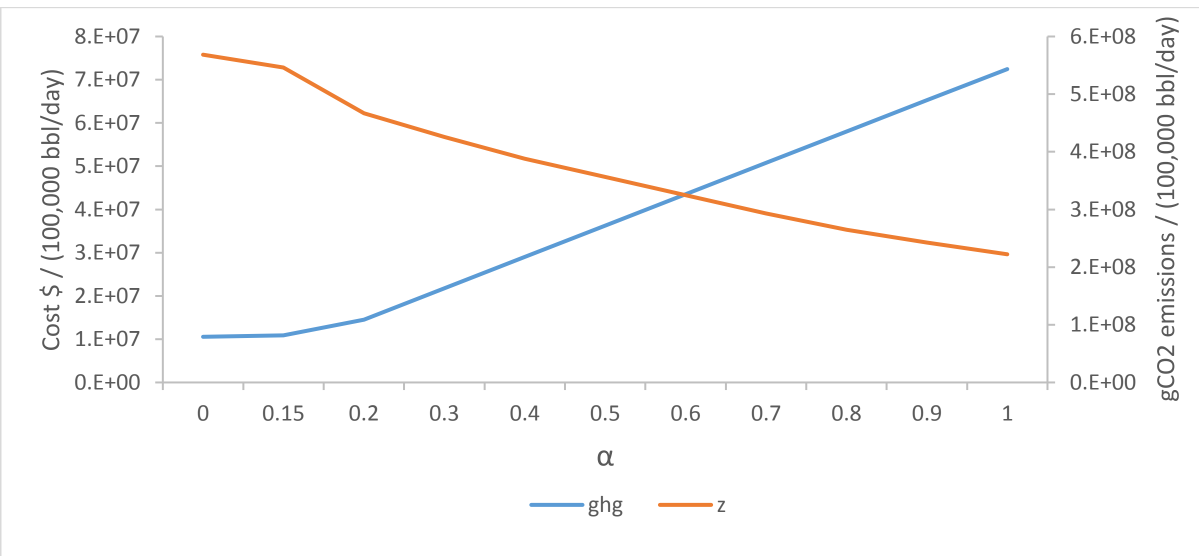

Figure 8. Cost and CO2 emissions with respect to α

The results showed in Figure 8 can further be used to calculate the increase in cost as a decrease in CO_2 emissions. For example, by increasing cost from \$81 m to \$108 m (i.e. a 33% increase), the emissions can be reduced from 7.9×10^7 gCO_2 to 6.22×10^7 gCO_2 (i.e. a 15% decrease) when alpha ranges between 0.2 - 0.3. A similar set of analysis have been shown in Table 3.

Table 4. Cost and CO_2 emissions with different values for **α**

α	Cost % Increased	CO2 % Decreased
0.1-0.2	3.08%	-4%
0.2-0.3	33.33%	-15%
0.3-0.4	50.00%	-9%
0.4-0.5	33.33%	-9%
0.5-0.6	25.00%	-8%
0.6-0.7	20.00%	-9%
0.7-0.8	16.67%	-10%
0.8-0.9	14.29%	-10%
0.9-1.0	12.50%	-8%

Furthermore, a Pareto front was constructed, based on the results obtained from the developed model, as seen in Figure 9. This Pareto curve shows the optimal cost corresponding to the carbon dioxide emissions emitted by the refinery when renewable energy is integrated optimally.

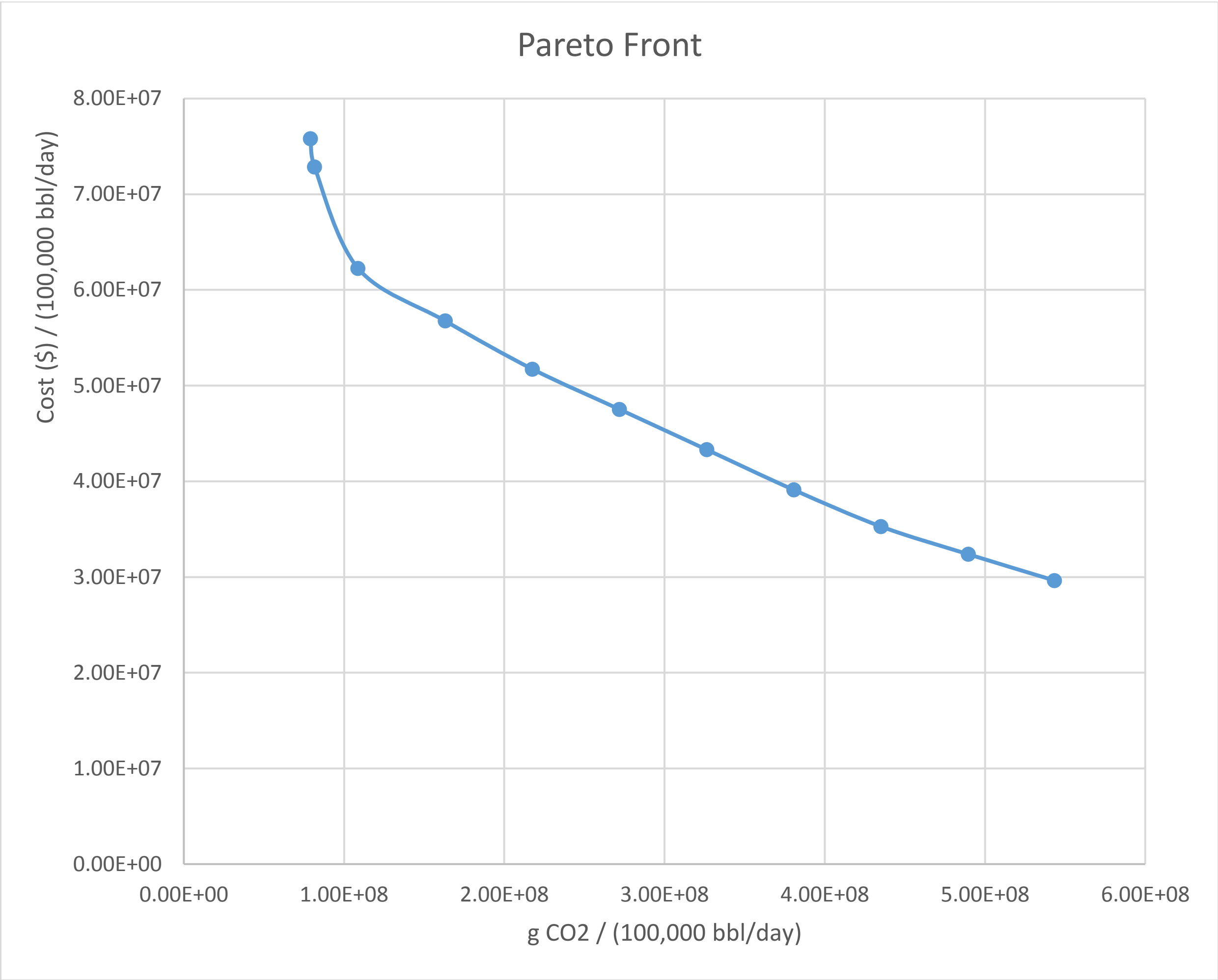

Figure 9. Cost and CO2 emissions optimum points

From the Pareto curve for the energy cost and CO_2 emissions shown in Figures 8 and 9 for different Alpha ranges, the distribution of energy resources with different units is shown in Figures 10, 11, and 12. As shown it different α values lead to the four resources solar CSP, Grid, wind and Solar PV.

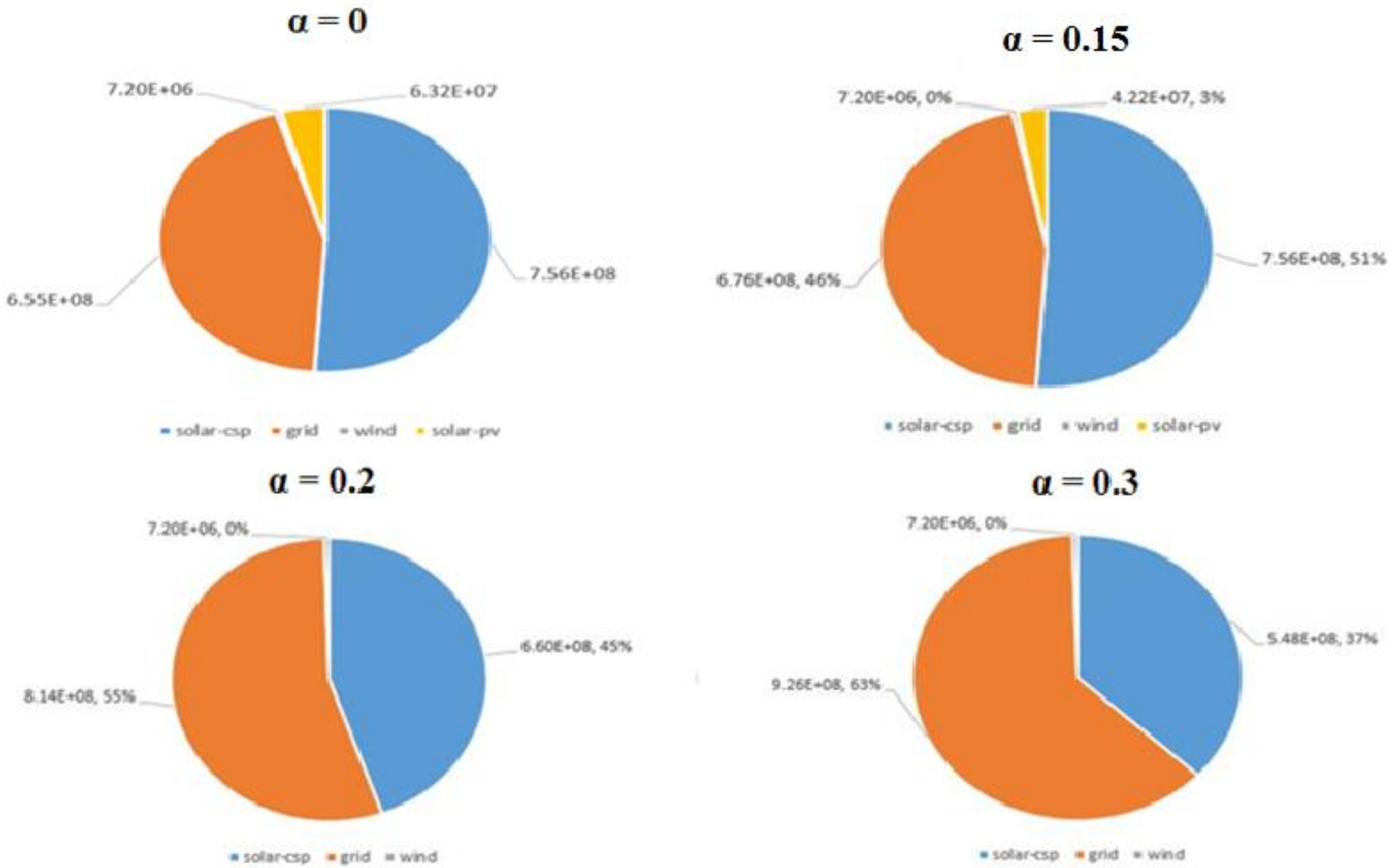

Figure 10. Renewable Energy Resources Distribution at α values of 0, 0.15, 0.2, and 0.3

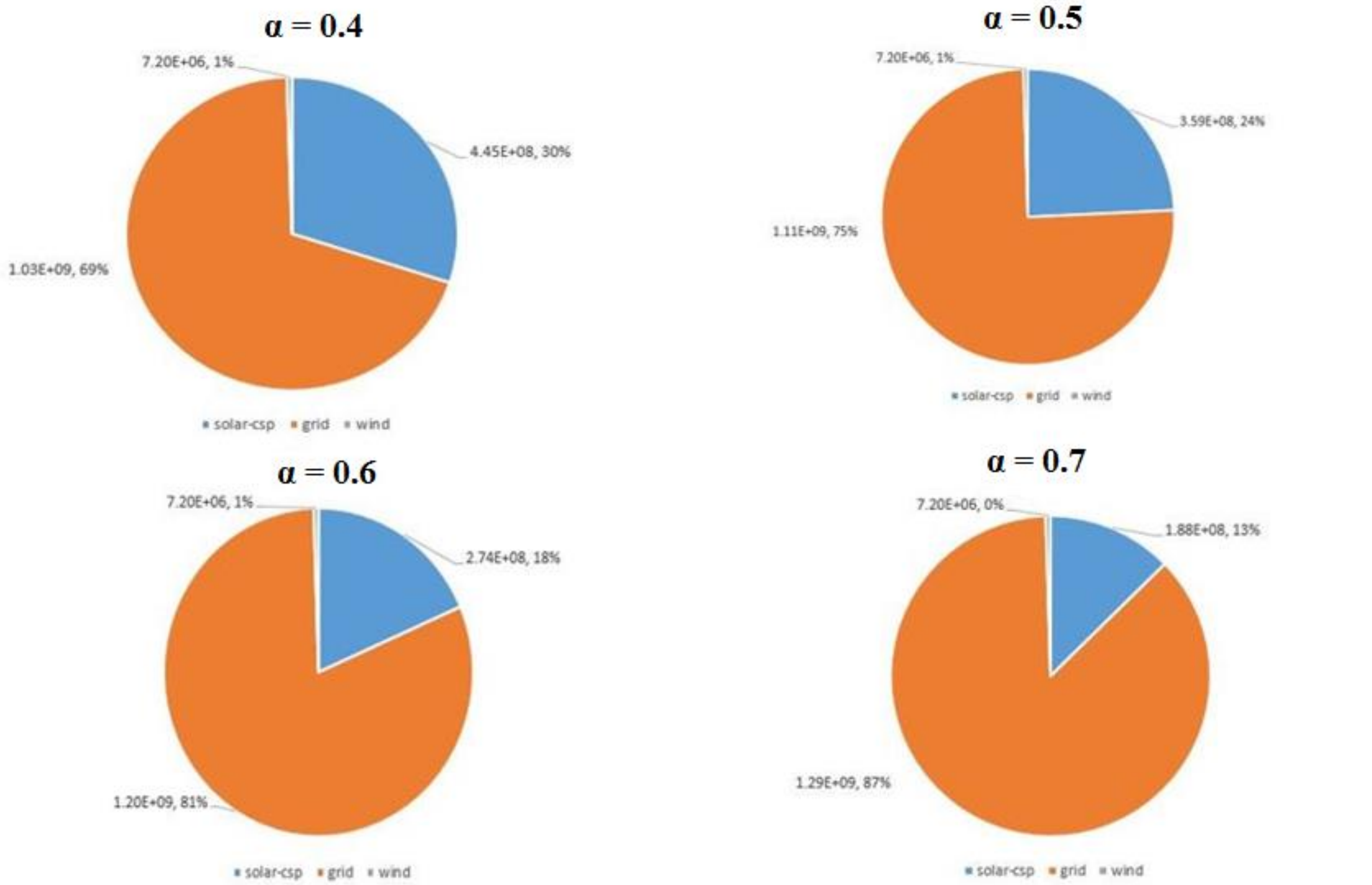

Figure 11. Renewable Energy Resources Distribution at α values of 0.4, 0.5, 0.6, and 0.7

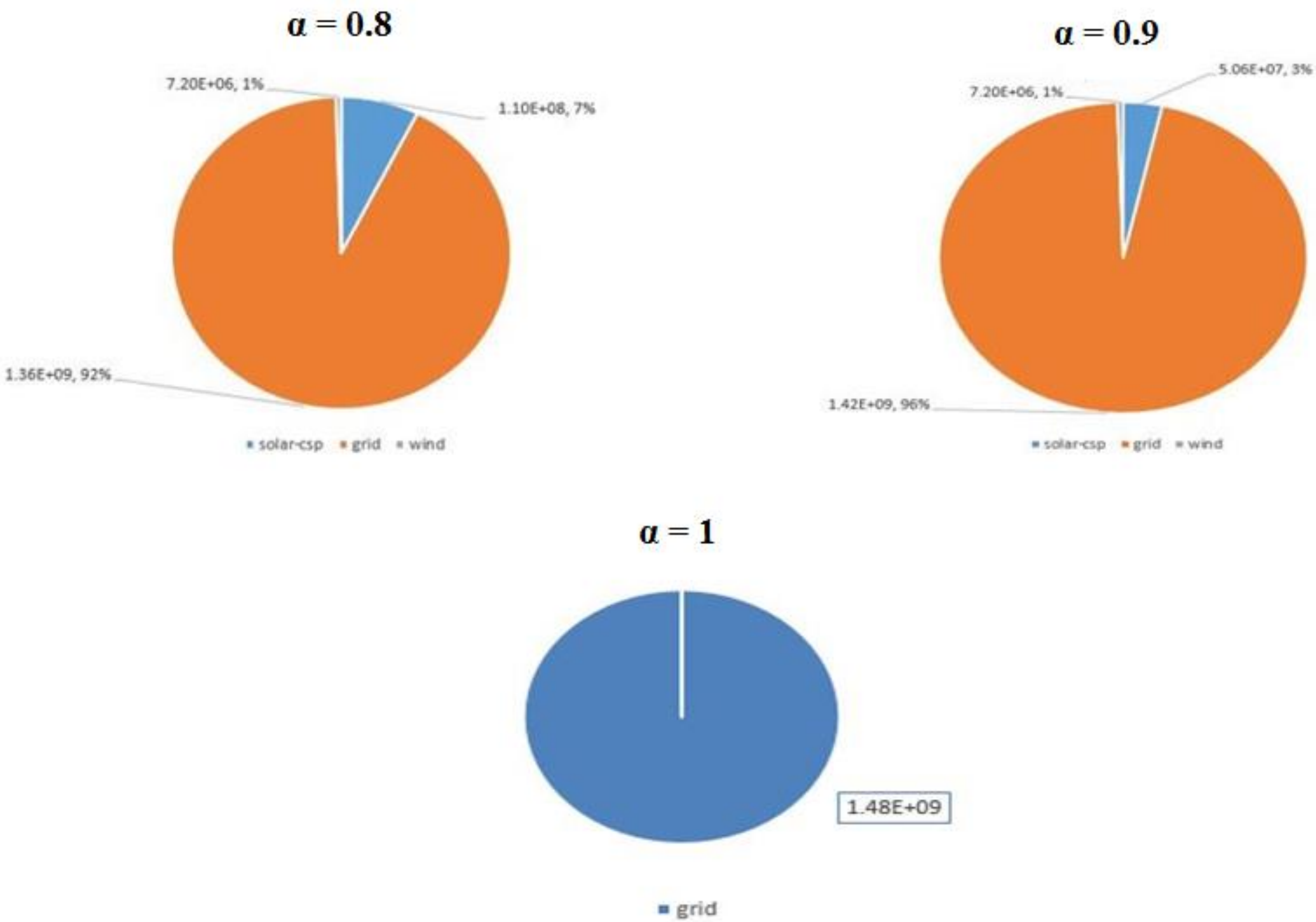

Figure 12. Renewable Energy Resources Distribution at α values of 0.8, 0.9, and 1.

Furthermore, Figures 12, 13, and 14 show the superstructure for the energy distribution between energy sources and the refinery units at α equal to 0, 0.5, and 1.0 respectively:

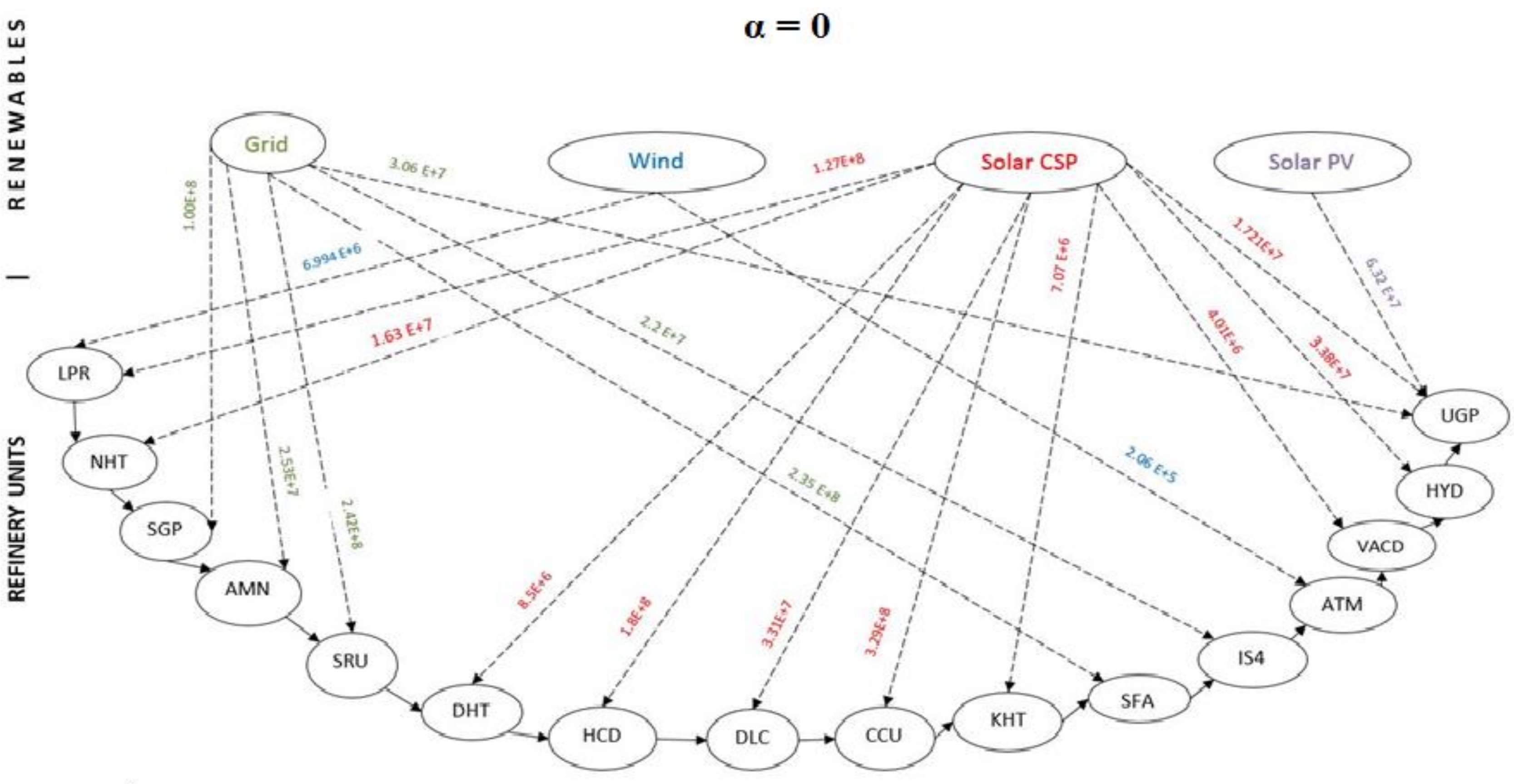

Figure 13. Superstructure for Energy Resources Distribution and Refinery Units at an α value of zero.

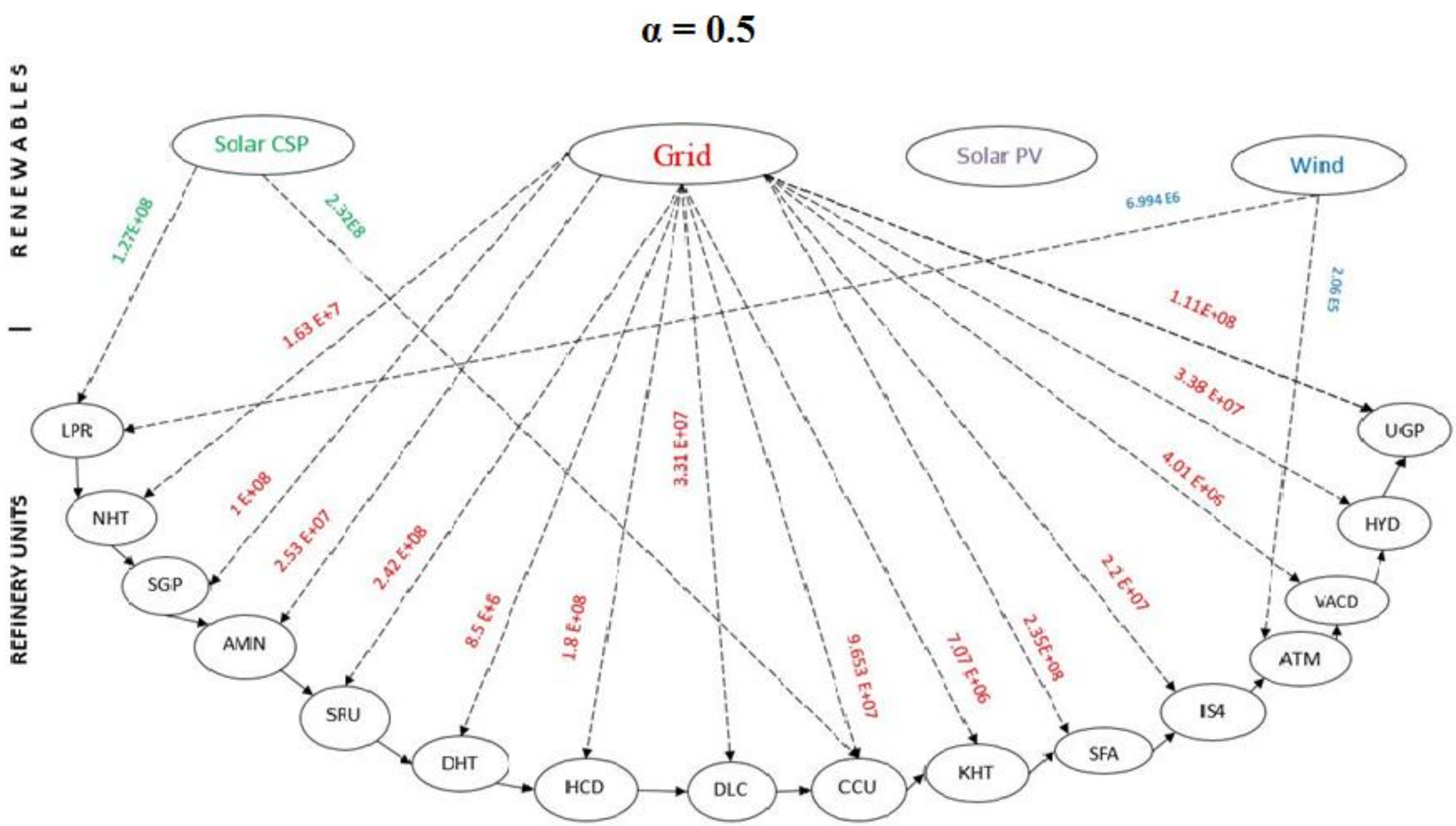

Figure 14. Superstructure for Energy Resources Distribution and Refinery Units at an α value of 0.5

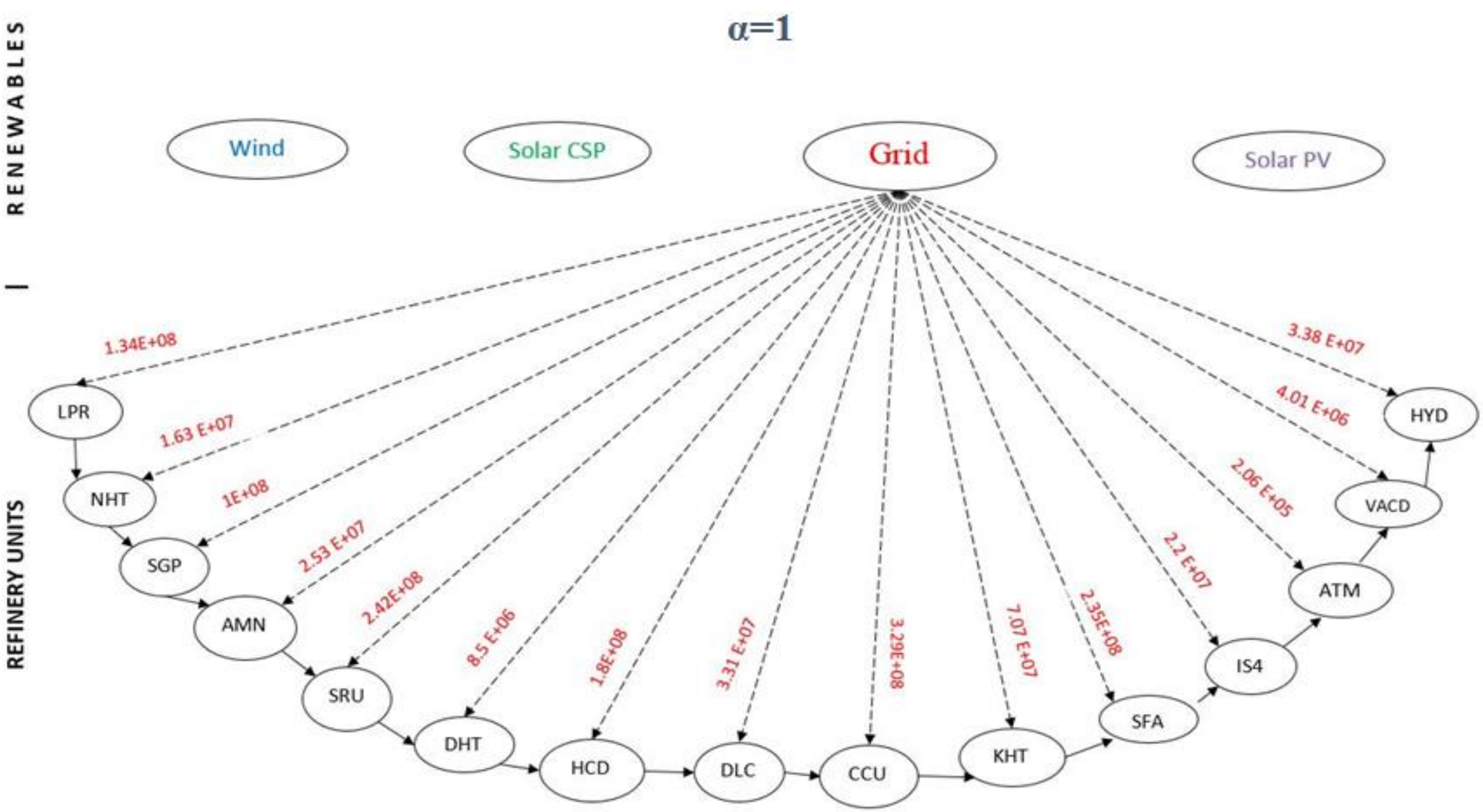

Figure 15. Superstructure for Energy Resources Distribution and Refinery Units at an α value of One

CHAPTER 5- ECONOMIC ANALYSIS

This chapter examines the economic feasibility of applying alternative renewable energy sources for localized use in Abu Dhabi. Solar PV, solar CSP, and wind energy sources are studied for high and low values of calculated Levelized Costs of Electricity (LCOE). However, these LCOEs are dynamically estimated for energy generation using the following mathematical formulae [63] :

$$CRF = \frac{D\ (1 + D)^N}{(1 + D)^N - 1}$$

$$LCOE = \frac{Capital\ Cost\ \times CRF\ \times\ (1 - TD_{PV})}{8760\ \times Capacity\ Factor\ \times (1 - T)} + \frac{fixed\ O\&M}{8760 \times Capacity\ Factor} + \frac{variable\ O\&M}{1{,}000\ \frac{kWh}{MWh}}$$

Where:

Capital cost: Cost of plant

CRF: Capital recovery factor

T: Tax rate paid

DPV: Present value of depreciation

8760: Number of hours in a year

Capacity factor: Yearly average percentage of power as a fraction of capacity

Fixed O&M: Fixed operating and maintenance cost

Variable O&M: Variable operating and maintenance cost

5.1 Solar PV

5.1.1 Solar PV- Low LCOE

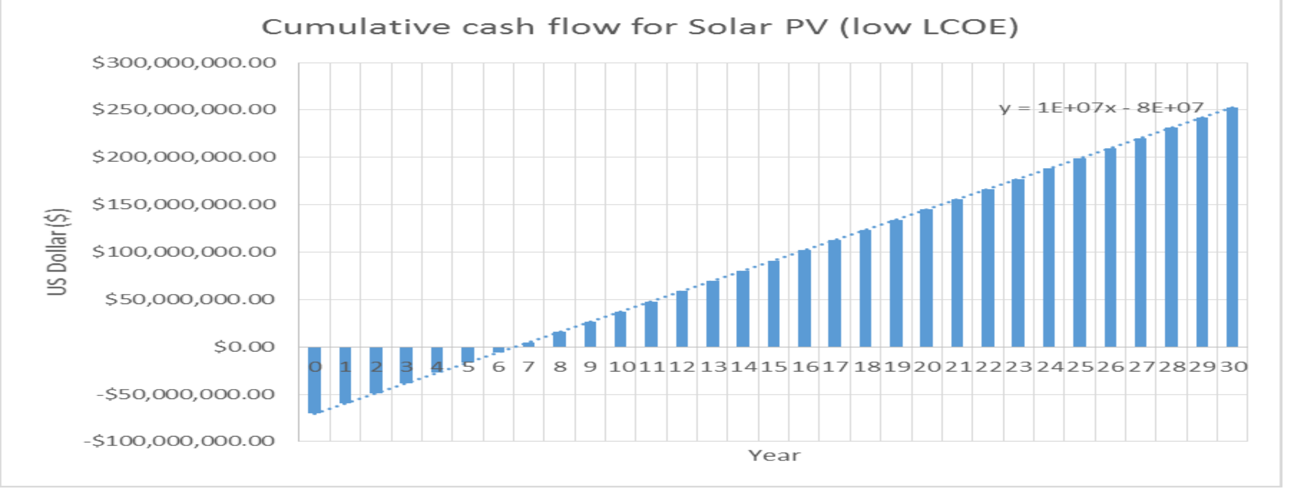

Figure 16. Cumulative cash flow for solar PV (low LCOE)

Table 5. Cumulative cash flow for solar PV (low LCOE) results

Carbon credit value (Renewable) h	8.68	$/tonnes of CO2
CO2 emissions with only grid	543.42	tonnes of CO2
CO2 with only PV	167.45	tonnes of CO2
Total Capital Cost	$70,457,572.30	
Daily capacity	46.97171487	MWh/hour
Total fixed cost	$355,106.16	
Fixed cost per year	$11,836.87	
Price per kWh in Abu Dhabi (Industrial)	$0.04	
Annual Cost of 17564 MWh Grid Electricity	$16,458,888.89	
Total Ammortized Payments	$170,337,670.55	
Total savings per year	$16,450,315.44	
Pay-off period	**7**	years
Lifetime of project	**30**	years

As shown in Figure 16 and Table 5, the pay-off period for the solar PV project, with the above settings, is 7 years. Assuming a lifetime of the project of 30 years, the project appears to be economically feasible.

5.1.2 Solar PV- High LCOE

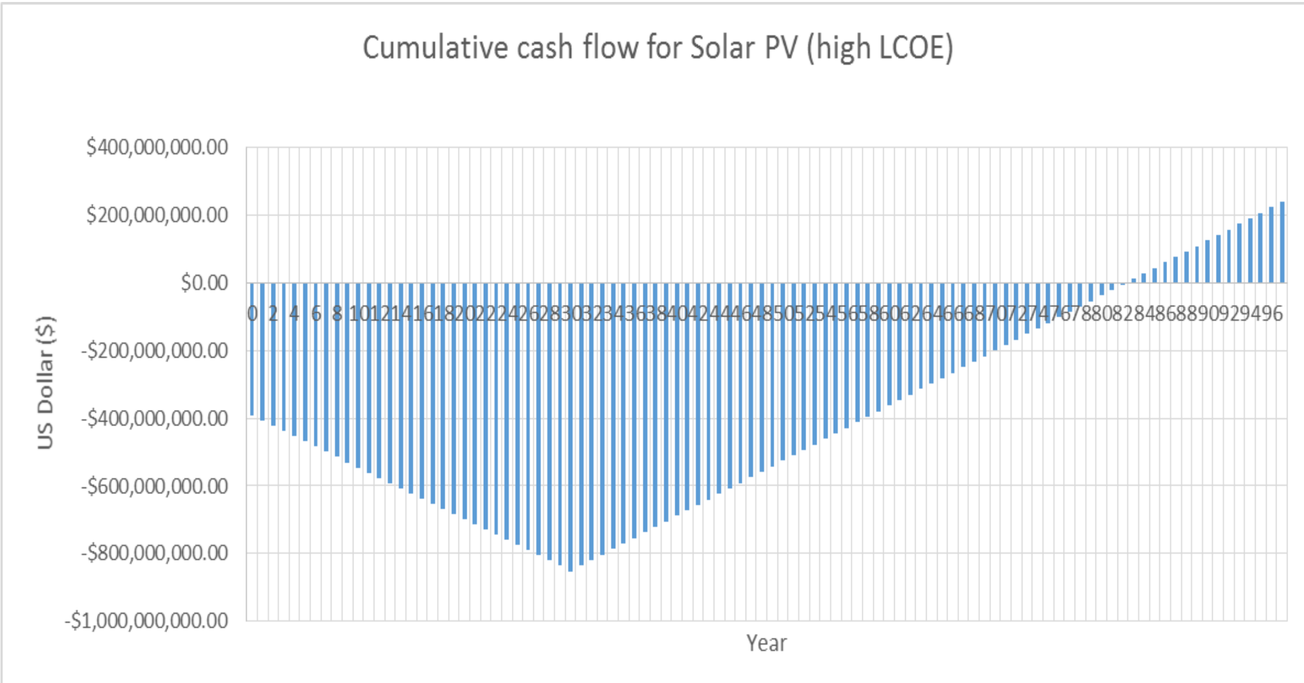

Figure 17. Cumulative cash flow for solar PV (High LCOE).

Table 6. Cumulative cash flow for solar PV (High LCOE) calculation data.

Carbon credit value (Renewable)	8.68	$/tonnes of CO2
CO2 emissions with only grid	543.42	tonnes of CO2
CO2 with only PV	167.45	tonnes of CO2
Total Capital Cost	$392,213,819.13	
Daily capacity	46.97171487	MWh/hour
Total fixed cost	$5,166,888.64	
Fixed cost per year	$172,229.62	
Price per kWh in Abu Dhabi (Industrial)	$0.04	
Annual Cost of 17564 MWh Grid Electricity	$16,458,888.89	
Total Ammortized Payments	$948,213,032.72	
Total savings per year	$16,289,922.69	
Pay-off period	**83**	Years
Lifetime of project	**30**	Years

As shown in Figure 17 and Table 6, the pay-off period for the solar PV project, with the above settings, is 83 years. Assuming a lifetime of the project of 30 years, the project is economically infeasible.

5.2 Solar CSP

5.2.1 Solar CSP- Low LCOE

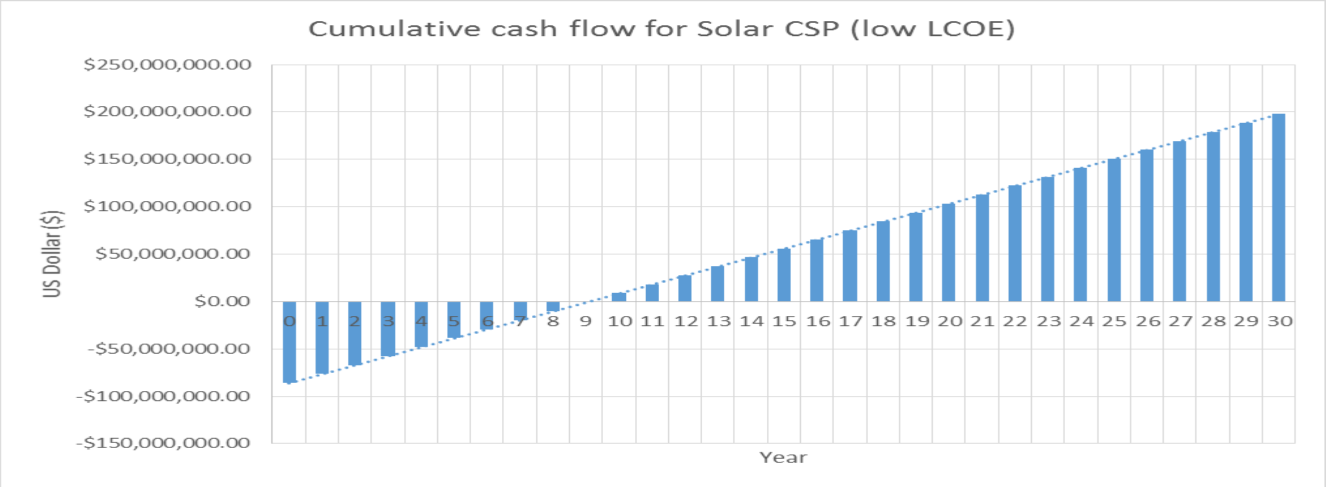

Figure 18. Cumulative cash flow for solar CSP (Low LCOE).

Table 7. Cumulative cash flow for solar CSP (Low LCOE) calculation data.

Carbon credit value (Renewable)	8.68	$/tonnes of CO2
CO2 emissions with only grid	543.42	tonnes of CO2
CO2 with only PV	41.704	tonnes of CO2
Total Capital Cost	$85,958,238.20	
Daily capacity	46.97171487	MWh/hour
Total fixed cost	$2,325,099.89	
Fixed cost per year	$77,503.33	
Total variable cost	$33.35	
Variable cost per year	$1.11	
Price per kWh in Abu Dhabi (Industrial)	$0.04	
Annual Cost of 17564 MWh Grid Electricity	$16,458,888.89	
Total Ammortized Payments	$207,811,958.07	
Total savings per year	$16,385,740.45	
Pay-off period	**10**	years
Lifetime of Project	**30**	years

As shown in Figure 18 and Table 7, the pay-off period for the solar CSP project, with the above settings, is 10 years. Assuming a lifetime of 30 years, the project appears to be economically feasible.

5.2.2 Solar CSP- High LCOE

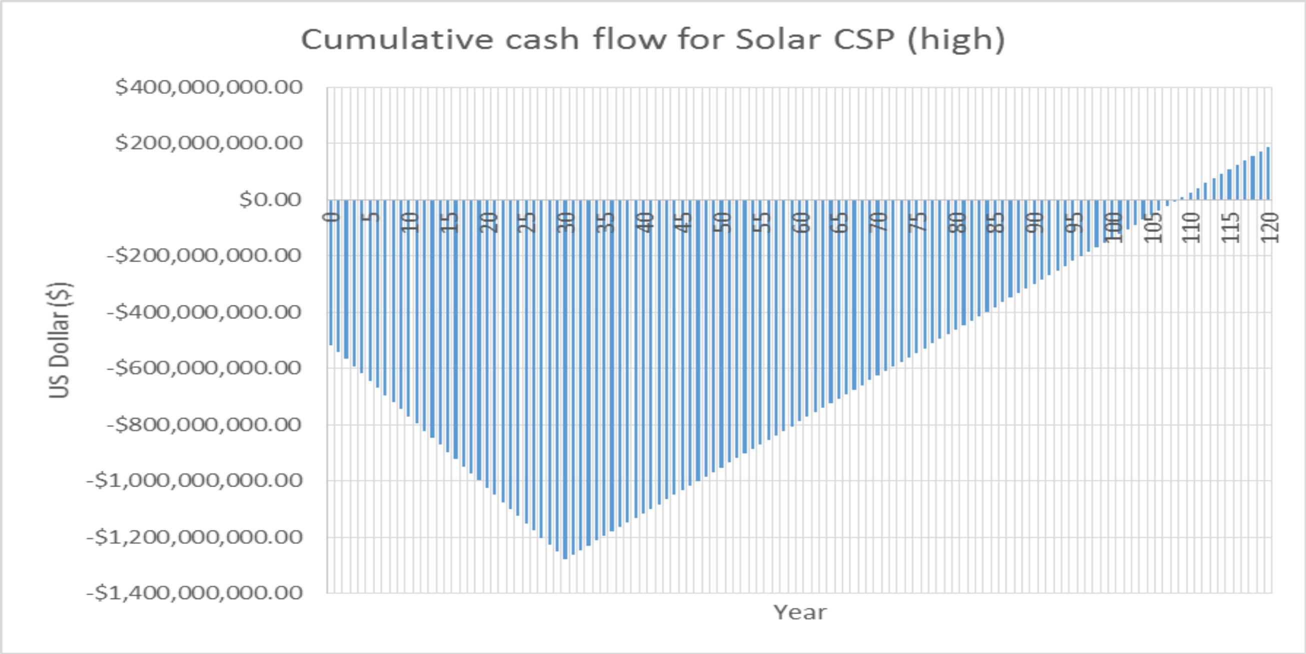

Figure 19. Cumulative cash flow for solar CSP (High LCOE).

Table 8. Cumulative cash flow for solar CSP (High LCOE) calculation data.

Carbon credit value (Renewable)	8.68	$/tonnes of CO2
CO2 emissions with only grid	543.42	tonnes of CO2
CO2 with only PV	41.704	tonnes of CO2
Total Capital Cost	$516,688,863.52	
Daily capacity	46.97171487	MWh/hour
Total fixed cost	$5,401,747.21	
Fixed cost per year	$180,058.24	
Price per kWh in Abu Dhabi (Industrial)	$0.04	
Annual Cost of 17564 MWh Grid Electricity	$16,458,888.89	
Total Ammortized Payments	$1,249,142,917.36	
Total savings per year	$16,283,185.54	
Pay-off period	**77**	years
Lifetime of Project	**30**	years

As shown in Figure 19 and Table 8, the pay-off period for the solar CSP project, with the above settings, is 77 years. Assuming a lifetime of the project of 30 years, the project appears to be economically infeasible.

5.3 Wind Energy

5.3.1 Wind Energy - Low LCOE

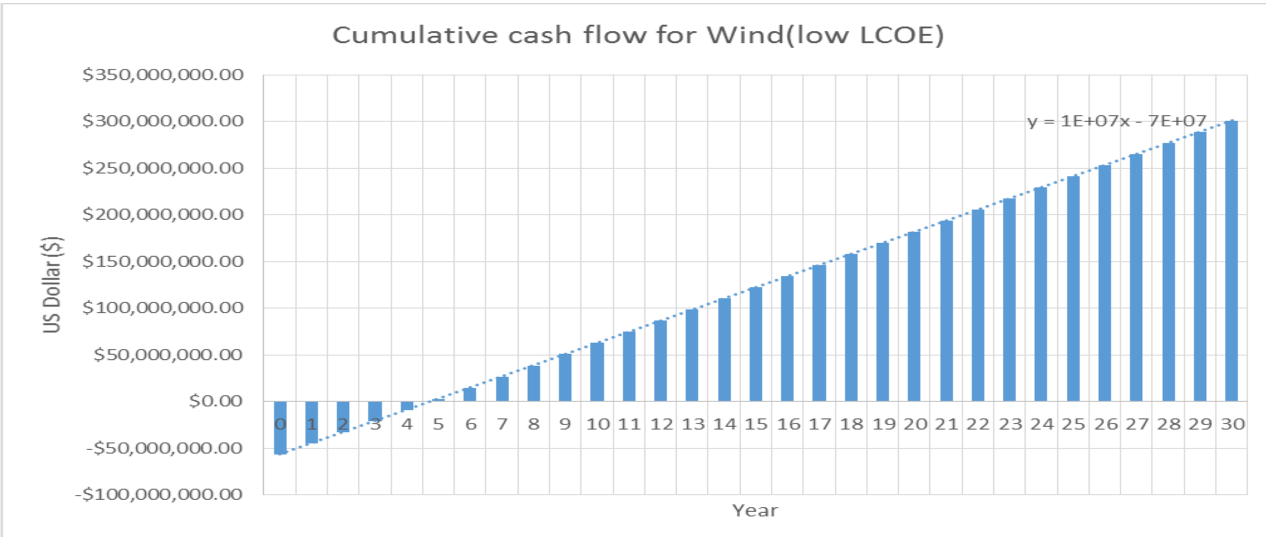

Figure 20. Cumulative cash flow for Wind Energy (Low LCOE).

Table 9. Cumulative cash flow for Wind Energy (Low LCOE) calculation data.

Carbon credit value (Renewable)	8.68	$/tonnes of CO2
CO2 emissions with only grid	543.42	tonnes of CO2
CO2 with only PV	10.11	tonnes of CO2
Total Capital Cost	$56,366,057.84	
Daily capacity	46.97171487	MWh/hour
Total fixed cost	$482,869.23	
Fixed cost per year	$16,095.64	
Total variable cost	$226.40	
Variable cost per year	$7.55	
Price per kWh in Abu Dhabi (Industrial)	$0.04	
Annual Cost of 17564 MWh Grid Electricity	$16,458,888.89	
Total Ammortized Payments	$136,270,136.44	
Total savings per year	$16,447,422.38	
Pay-off period	**6**	years
Lifetime of Project	**30**	years

As shown in Figure 20 and Table 9, the pay-off period for the wind energy project, with the above settings, is 6 years. Assuming a lifetime of the project of 30 years, the project appears to be economically feasible.

5.3.2 Wind Energy – High LCOE

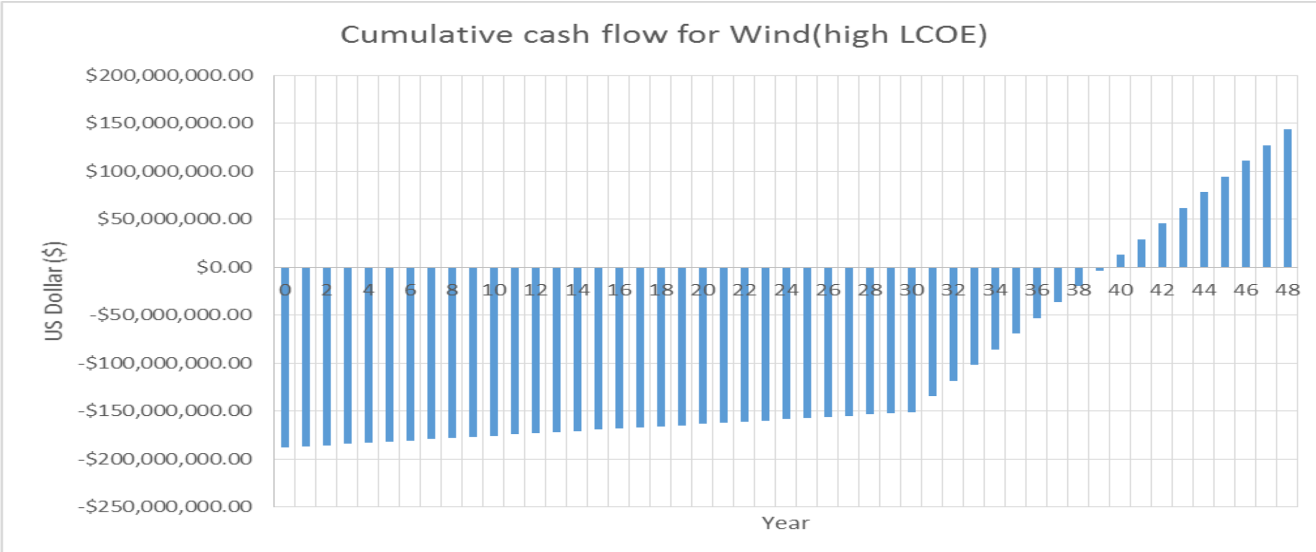

Figure 21. Cumulative cash flow for Wind Energy (High LCOE).

Table 10. Cumulative cash flow for Wind Energy (High LCOE) calculation data.

Carbon credit value (Renewable)	8.68	$/tonnes of CO2
CO2 emissions with only grid	543.42	tonnes of CO2
CO2 with only PV	10.11	tonnes of CO2
Total Capital Cost	$187,886,859.46	
Daily capacity	46.97171487	MWh/hour
Total fixed cost	$2,818,302.89	
Fixed cost per year	$93,943.43	
Total variable cost	$1,080.35	
Variable cost per year	$36.01	
Price per kWh in Abu Dhabi (Industrial)	$0.04	
Annual Cost of 17564 MWh Grid Electricity	$16,458,888.89	
Total Ammortized Payments	$454,233,788.13	
Total savings per year	$16,369,574.59	
Pay-off period	**40**	years
Lifetime of Project	**30**	years

As shown in Figure 21 and Table 10, the pay-off period for the wind energy project, with the above settings, is 40 years. Assuming a lifetime of the project of 30 years, the project appears to be economically infeasible.

CHAPTER 6- SENSITIVITY ANALYSIS

As seen in the previous chapter, feasibility studies for each renewable energy source at high and low LCOE were conducted. In this chapter, a sensitivity analysis was conducted to determine how critical parameters impact the payoff period and Levelized Costs of Electricity (LCOE) under a set of assumptions. Specifically altering critical parameters, such as capital cost, capacity factor, fixed costs, and variable costs and keeping other parameters constant at the average value, economic results are analyzed for different tested scenarios. During the analyses, the following mathematical formulae are used to calculate LCOEs [63]:

$$CRF = \frac{D\ (1 + D)^N}{(1 + D)^N - 1}$$

$$LCOE = \frac{Capital\ Cost\ \times CRF\ \times\ (1 - TD_{PV})}{8760\ \times Capacity\ Factor\ \times (1 - T)} + \frac{fixed\ O\&M}{8760 \times Capacity\ Factor} + \frac{variable\ O\&M}{1{,}000\ \frac{kWh}{MWh}}$$

Where:

Capital cost: Cost of plant

CRF: Capital recovery factor

T: Tax rate paid

DPV: Present value of depreciation

8760: Number of hours in a year

Capacity factor: Yearly average percentage of power as a fraction of capacity

Fixed O&M: Fixed operating and maintenance cost

Variable O&M: Variable operating and maintenance cost

6.1 Solar CSP

6.1.1 Capital Cost

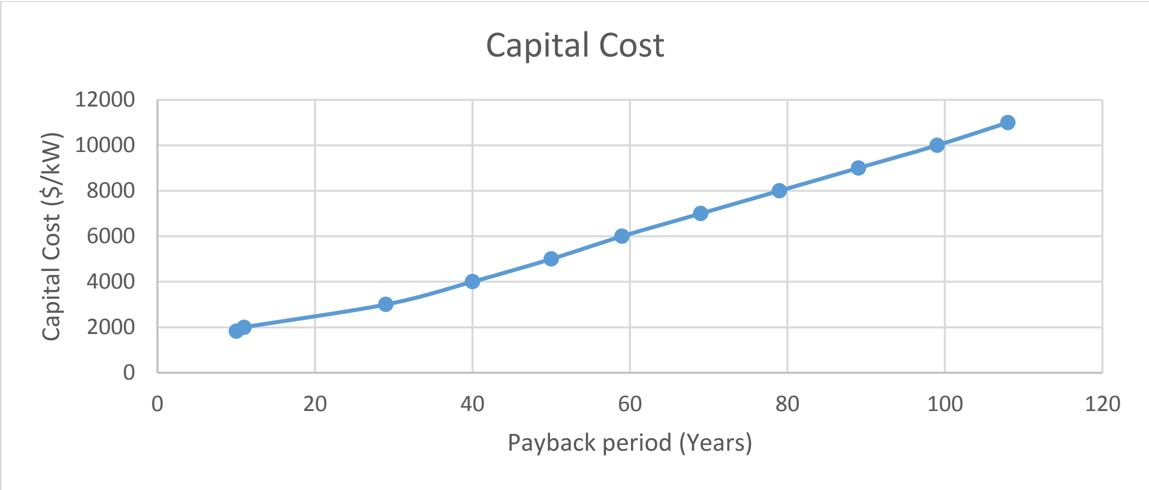

Figure 22. Payback period for Solar CSP with different capital cost values

Table 11. Payback period and LCOE calculation data with different capital cost values for Solar CSP

Capital Cost	LCOE	Payback Period Years
1830	0.04	10
2000	0.08	11
3000	0.1	29
4000	0.13	40
5000	0.15	50
6000	0.18	59
7000	0.21	69
8000	0.23	79
9000	0.26	89
10000	0.29	99
11000	0.31	108

As shown in Figure 22 and Table 11, the pay-off period for the solar CSP, with the capital cost above 3000, is more than 40 years. Assuming a lifetime of 30 years, the project appears to be economically feasible with capital cost less than or equal to 3000.

6.1.2 Capacity Factor

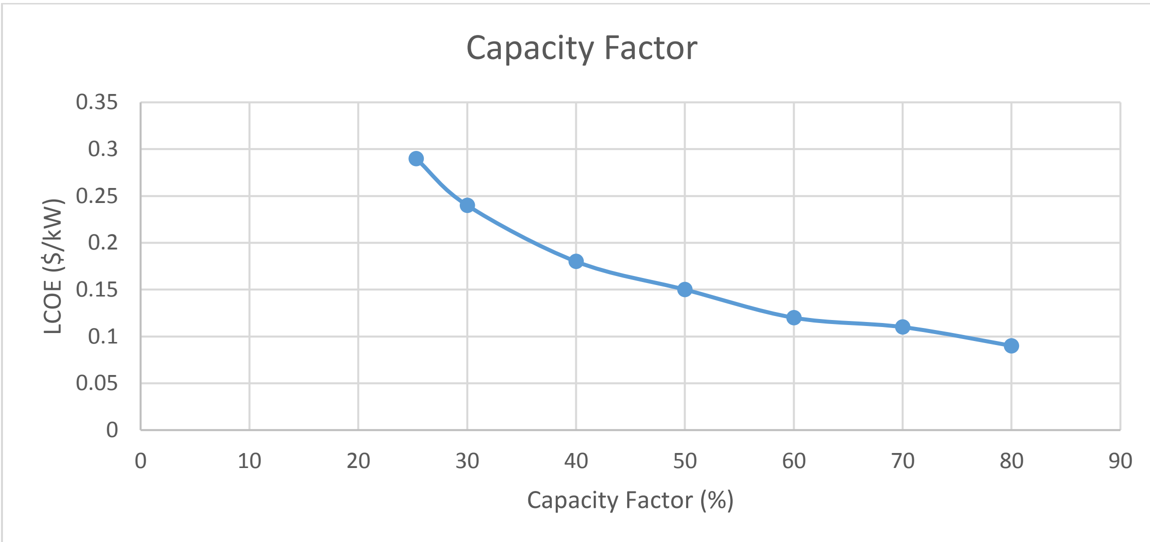

Figure 23. LCOE for Solar CSP with different capacity factor values

Table 12. Payback period and LCOE calculation data with different values of the capacity factor for Solar CSP

Capacity factor	LCOE
25.3	0.29
30	0.24
40	0.18
50	0.15
60	0.12
70	0.11
80	0.09

As seen in Figure 23 and Table 12, the LCOE is observed to decrease with increasing capacity. At lower capacity factor, a higher decrease is observed relative to at higher capacity factor. For example, increase capacity factor from 30% to 40% decreases the LCOE by $0.06/kW. On the other hand, an increase from 60% to 70% decreases the LCOE by $0.01/kW. It is found that the same results were conducted for Solar PV and wind energy as shown in next sections.

6.1.3 Fixed costs

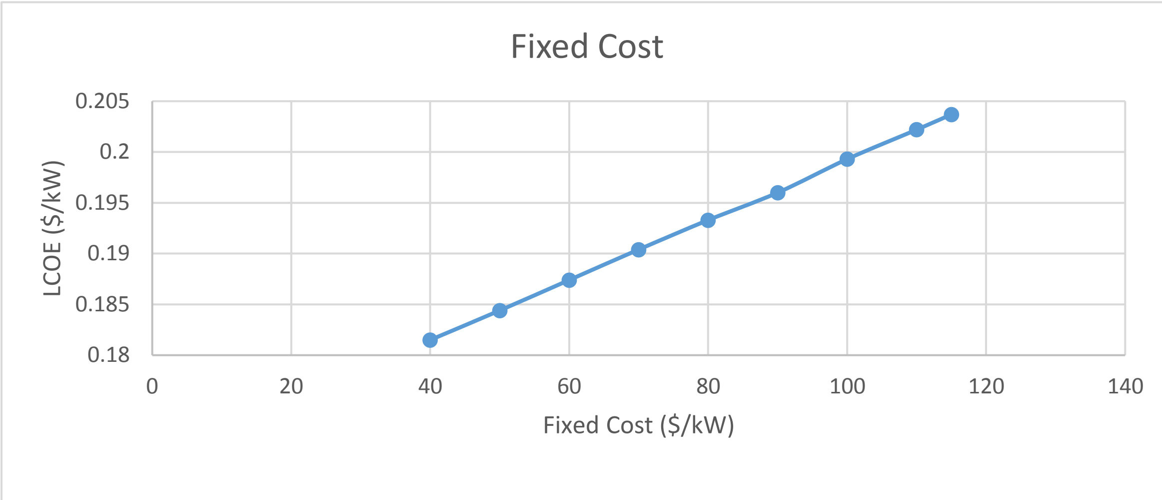

Figure 24. LCOE for Solar CSP with different values of fixed cost

Table 13. Payback period and LCOE calculation data with different values of the Fixed cost for Solar CSP

Fixed Cost	LCOE
40	0.1815
50	0.1844
60	0.1874
70	0.1904
80	0.1933
90	0.196
100	0.1993
110	0.2022
115	0.2037

As shown in Figure 24 and Table 13, the LCOE is observed to increase with increasing fixed cost. At lower fixed cost, a lower increase is observed relative to at higher fixed cost. For example, increase fixed cost from 40% to 50% increases the LCOE by $0.0029/kW. Furthermore, an increase from 60% to 70% increases the LCOE by $0.003/kW. It is found that the same results were conducted for Solar PV and wind energy as shown in next sections.

6.1.4 Variable Costs

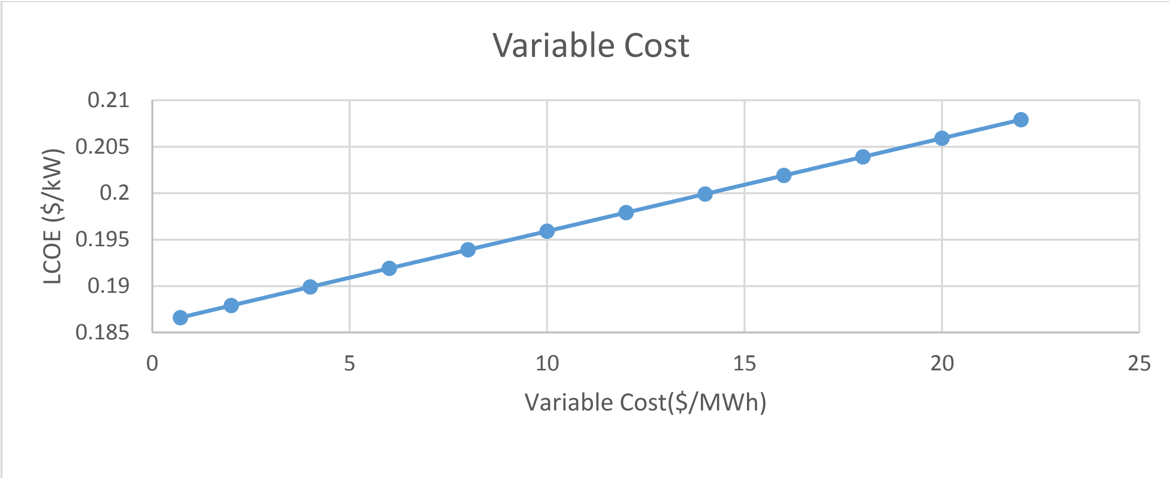

Figure 25. LCOE for Solar CSP with different values of Variable Costs

Table 14. Payback period and LCOE calculation data with different values of the Variable cost for Solar CSP

Variable Cost	LCOE
0.71	0.1866
2	0.1879
4	0.1899
6	0.1919
8	0.1939
10	0.1959
12	0.1979
14	0.1999
16	0.2019
18	0.2039
20	0.2059
22	0.2079

As shown in Figure 25 and Table 14, the LCOE is observed to increase with increasing variable cost. At lower variable cost, a lower increase is observed relative to at higher variable cost. For instance, by increasing variable cost from 2% to 4% increases the LCOE by $0.002/kW. Also, an increase from 16% to 18% increases the LCOE by $0.002/kW. It is found that the same results were conducted for Solar PV and wind energy as shown in next sections.

6.2 Solar PV

6.2.1 Capital Cost

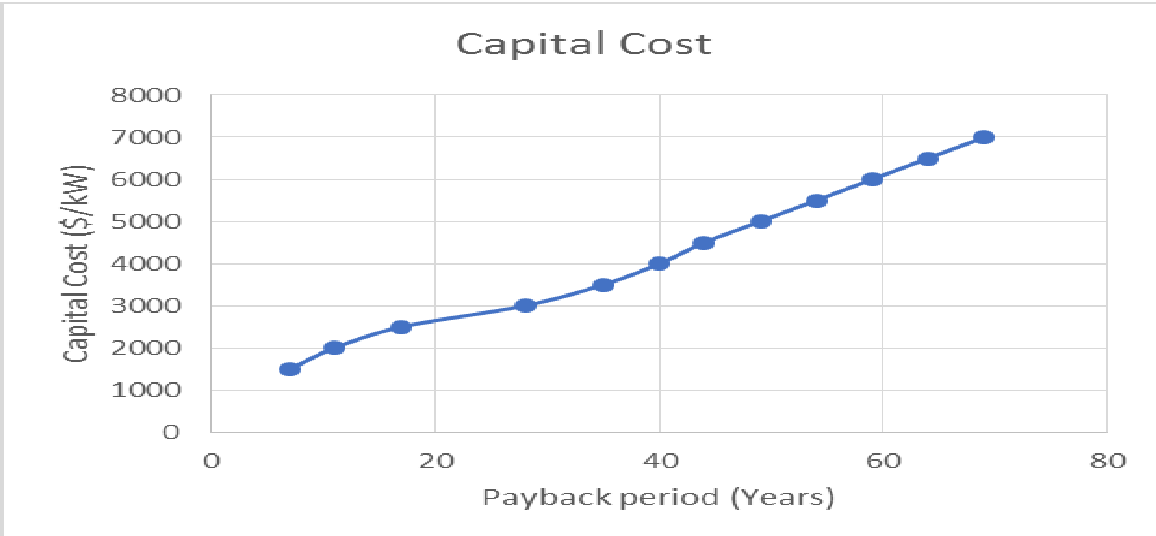

Figure 26. Payback period for Solar PV with different capital cost values

Table 15. Payback period and LCOE calculation data with different capital cost values for Solar PV

Capital Cost	LCOE	Payback Period Years
1500	0.07	7
2000	0.09	11
2500	0.11	17
3000	0.13	28
3500	0.15	35
4000	0.18	40
4500	0.2	44
5000	0.22	49
5500	0.24	54
6000	0.26	59
6500	0.28	64
7000	0.3	69

As shown in Figure 26 and Table 15, the pay-off period for the solar PV, with the capital cost above 3000, is more than 35 years. Assuming a lifetime of the project of 30 years, the project appears to be economically feasible with capital cost less than or equal to 3000.

6.2.2 Capacity Factor

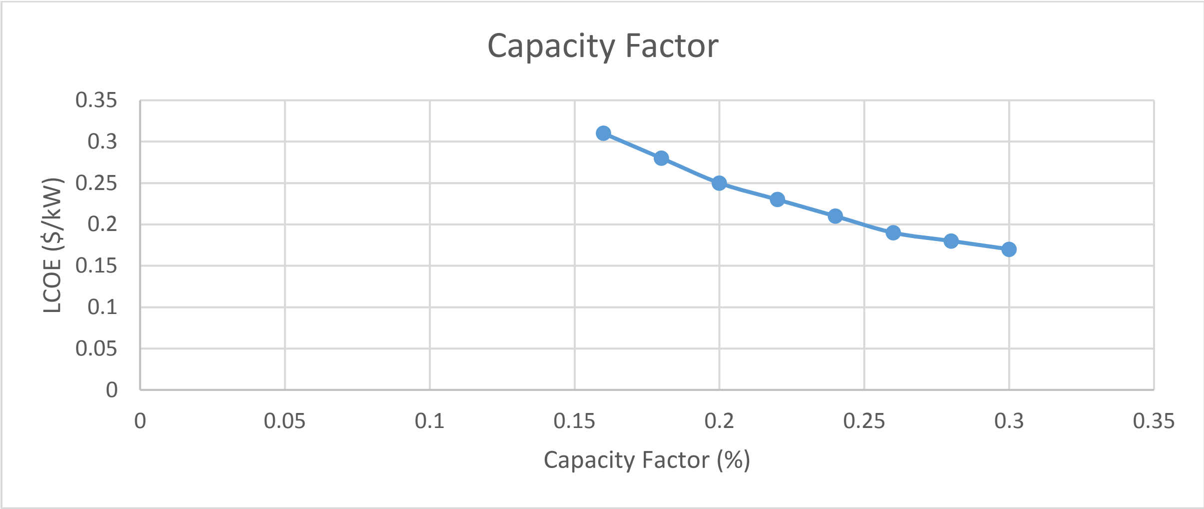

Figure 27. LCOE for Solar PV with different capacity factor values

Table 16. Payback period and LCOE calculation data with different values of the capacity factor for Solar PV

Capacity factor	LCOE
0.16	0.31
0.18	0.28
0.2	0.25
0.22	0.23
0.24	0.21
0.26	0.19
0.28	0.18
0.3	0.17

As shown in Figure 27 and Table 16, the LCOE is observed to decrease with increasing capacity. At lower capacity factor, a higher decrease is observed relative to at higher capacity factor. For instance, increase capacity factor from 0.16% to 0.18% decreases the LCOE by $0.03/kW. On the other hand, an increase from 0.26% to 0.28% decreases the LCOE by $0.01/kW.

6.2.3 Fixed Costs

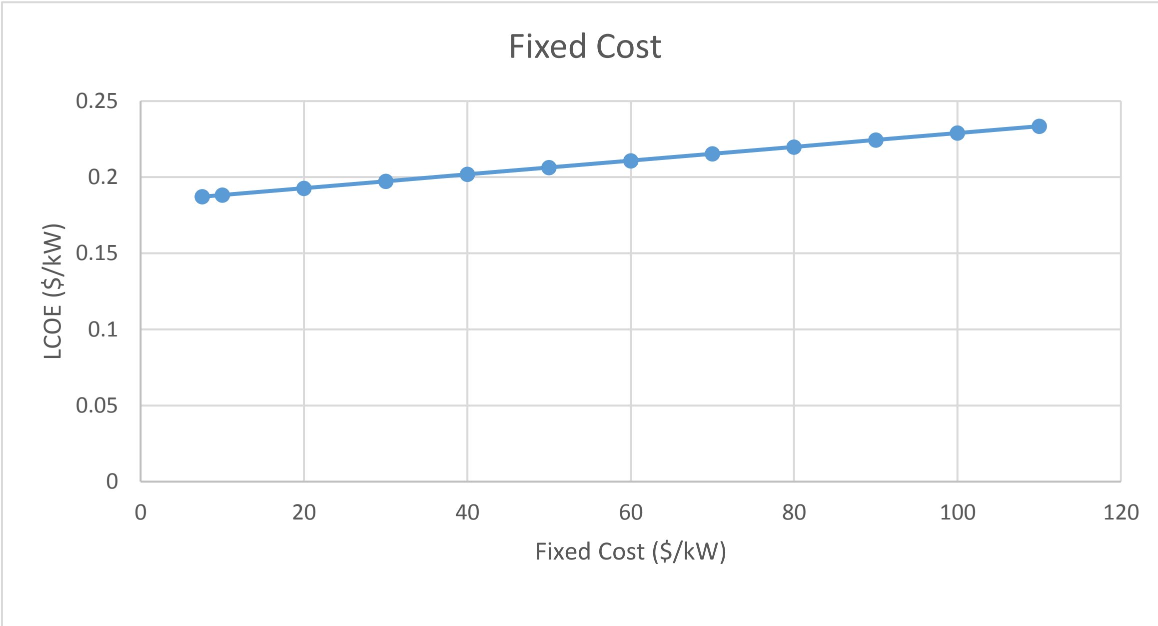

Figure 28. LCOE for Solar PV with different values of fixed cost

Table 17. Payback period and LCOE calculation data with different values of the Fixed cost for Solar PV

Fixed Cost	**LCOE**
7.56	0.1872
10	0.1883
20	0.1928
30	0.1973
40	0.2019
50	0.2064
60	0.2109
70	0.2154
80	0.2199
90	0.2245
100	0.229
110	0.2335

6.3 Wind

6.3.1 Capital Cost

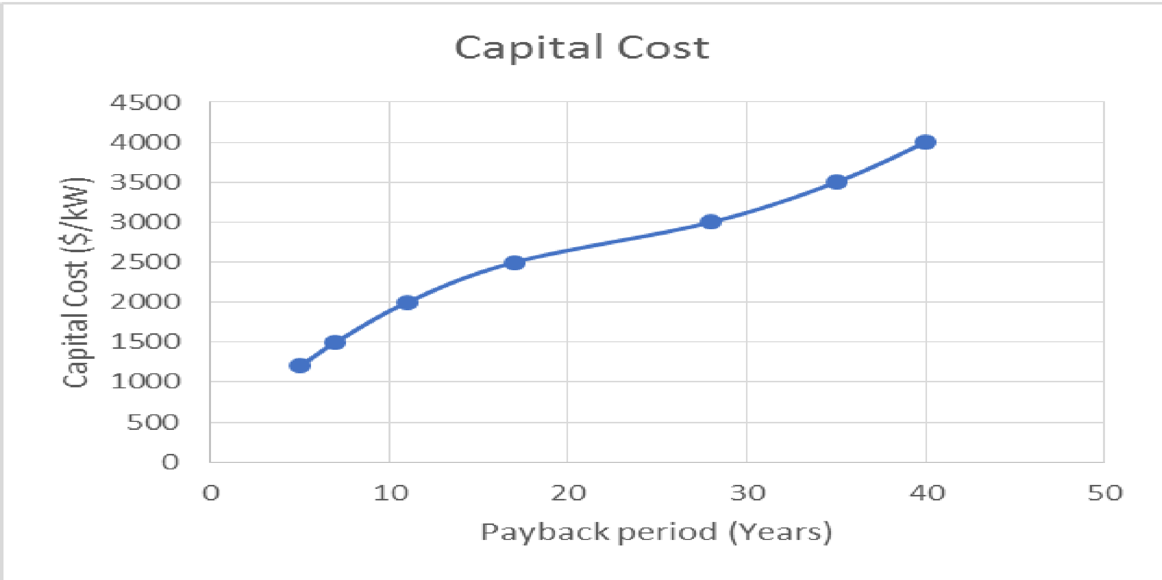

Figure 29. Payback period for Wind energy with different capital cost values

Table 18. Payback period and LCOE calculation data with different capital cost values for Wind energy

Capital Cost	LCOE	Payback Period Years
1200	0.05	5
1500	0.06	7
2000	0.07	11
2500	0.08	17
3000	0.1	28
3500	0.11	35
4000	0.12	40

As shown in Figure 29 and Table 18, the pay-off period for Wind energy, with the capital cost above 3000, is 35 years. Assuming a lifetime of 30 years, the project appears to be economically feasible with capital cost less than or equal to 3000.

6.3.2 Capacity Factor

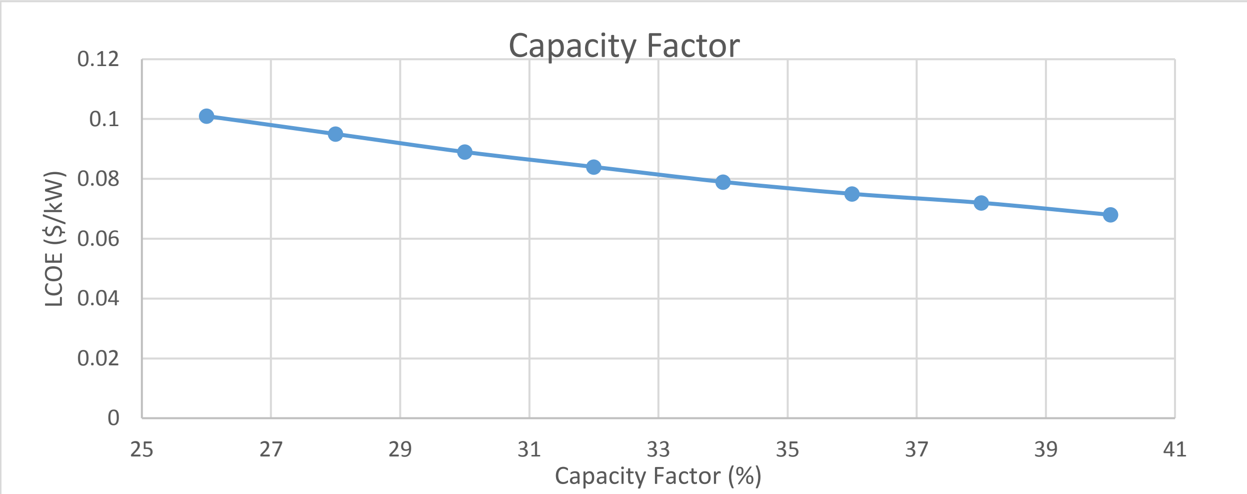

Figure 30. LCOE for Wind energy with different values of capacity factor

Table 19. Payback period and LCOE calculation data with different values of the capacity factor for Wind energy

Capacity factor	LCOE
26	0.101
28	0.095
30	0.089
32	0.084
34	0.079
36	0.075
38	0.072
40	0.068
42	0.066
44	0.063
46	0.061
48	0.058
50	0.056
52	0.054

As shown in Figure 30 and Table 19, the LCOE is observed to decrease with increasing capacity. At lower capacity factor, a higher decrease is observed relative to at higher capacity factor. For instance, increase capacity factor from 26% to 28% decreases the LCOE by $0.006/kW. On the other hand, an increase from 46% to 48% decreases the LCOE by $0.03/kW.

6.3.3 Fixed Costs

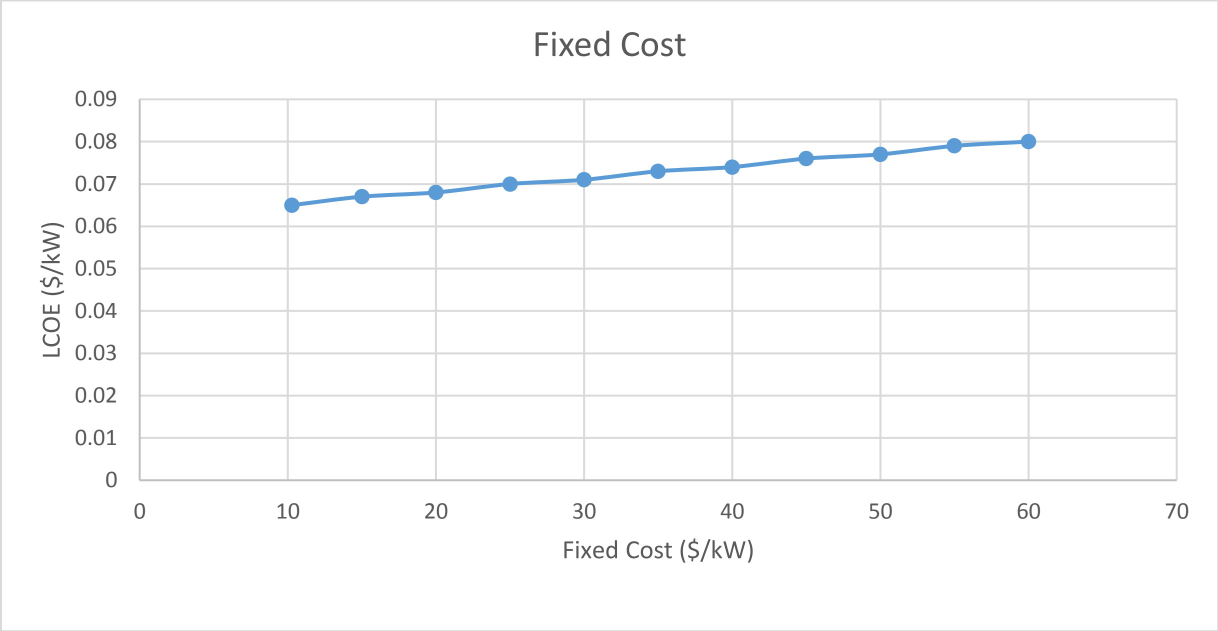

Figure 31. LCOE for Wind energy at different values of fixed cost

Table 20. Payback period and LCOE calculation data with different values of the Fixed cost for Wind energy

Fixed Cost	LCOE
10.28	0.065
15	0.067
20	0.068
25	0.07
30	0.071
35	0.073
40	0.074
45	0.076
50	0.077
55	0.079
60	0.08

6.3.4 Variable Costs

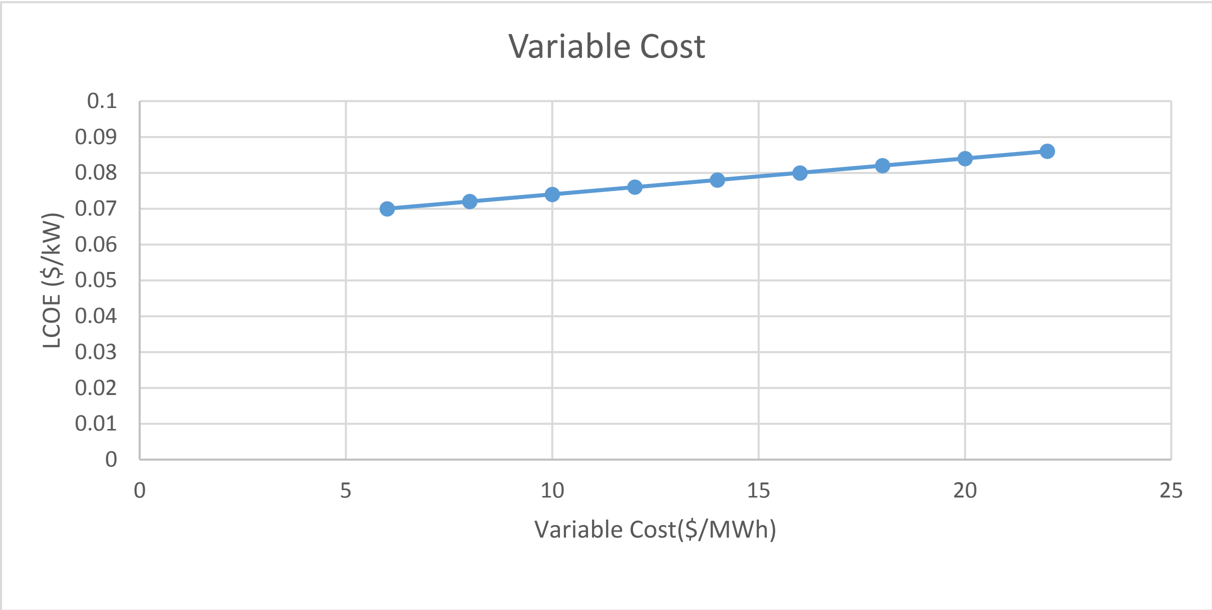

Figure 32. LCOE for Wind energy at different values of variable cost

Table 21. Payback period and LCOE calculation data with different values of the Variable cost for Wind energy

Variable Cost	LCOE
6	0.07
8	0.072
10	0.074
12	0.076
14	0.078
16	0.08
18	0.082
20	0.084
22	0.086

CHAPTER 7 – CONCLUSION AND RECOMMENDATION

In this study, a model was developed to determine the optimal production planning for an oil refinery while reducing GHG emissions. The model incorporates the daily production, the supply and demand for energy, the supply and demand of each product as well as the CO_2 constraint. A petroleum refinery with a set of different process units was simulated using Aspen HYSYS with a capacity of refining 100,000 bbl of crude oil blend is refined per day. From this refinery, the energy consumption by each unit was estimated. Also, a superstructure was designed to show the units within the refinery connected to available energy sources that could meet their energy demand.

Furthermore, the CO_2 emissions for each units within the refinery were estimated and the cost of the available energy sources. In addition, the developed model was used to determine the optimal distribution of energy to the different units within the refinery using GAMs which were later expressed by a Pareto curve. This curve shows the optimal cost for the energy supplier versus CO_2 emissions from different sources.

Finally, economic feasibility studies and sensitivity analyses were conducted in this work for the integrated renewable energy sources in Abu Dhabi, based on different factors. This study examined the economic feasibility for each renewable source based on the pay-off period from each source and the lifetime of the project. In addition, the sensitivity study was run by focusing on four parameters: Capital cost, Capacity factor, fixed costs, and variable costs, while the other parameters kept constant at their average values.

For future study, it is recommended to carry out renewable energy integration study on the two major energy consumers (i.e. industry and transport). However, three phases can be studied in this research:

- Only electricity through the grid and renewable sources was considered. An energy hub may be developed that involves additional energy input such as natural gas for on-site generators, heat streams, etc.
- Intermittent sources of energy such as solar, wind were considered but an average annual potential was considered. A more detailed study can be carried out that considers daily, monthly or seasonal changes in these sources of energy and determine the optimum conditions to operate at.
- Storage systems can be considered in future work that enhances reliability to renewable energy systems.

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