

Optimal Renewable Energy Integration into Refinery with CO₂ Emissions Consideration: *An Economic Feasibility Study*

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Abstract. With increasing 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 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 CO₂ 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 CO₂ emissions, was solved using GAMS to determine optimal energy distribution from each energy source to units within the refinery. Additionally, an economic feasibility study was carried out to determine the viability of renewable energy technology project implementation to overcome energy requirement of the refinery. Electricity generation through all renewable energy sources considered (i.e. solar PV, solar CSP and wind) were found feasible based on 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

1. Introduction

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 [1]. 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 [2]. In addition, 28% of the world's primary energy is being consumed in transportation sector. Moreover, transportation fuel demand is predicted to increase up to 40 % by 2040 [3], [4]. However, the fact remains that fossil fuels are non-renewable scarce resources of energy [5].



Generally speaking, production of petroleum yields involve enormous amounts of energy. Petroleum refining is one of the most complex processes in the oil and gas industry. It includes many unit processes and subsidiary facilities. Most refineries are different from each other and have a unique combination and arrangement of units. They are highly energy intensive due to their large production capacity. The capacity of modern petroleum refineries usually range from 800,000 to 900,000 barrels of crude oil feed per day [6], [7]. Since the mid of 20th century, petroleum products have become a dominant energy source, surpassing coal demand.

Present scenario focuses on meeting future challenges to cope with the energy demand throughout the world in developed countries. Renewable energy resources have been utilized in pursuit of overcoming this problem, since the past several decades. They play an important role in producing ‘clean’ energy that reduces greenhouse gas (GHG) emissions, specifically CO₂, as compared to fossil fuels. The aim of this study is to determine the feasibility of optimal renewable energy integration into a refinery within the Middle East. Specifically, simulating a refinery to define energy demand by various units within the environment. Additionally, developing a model to find optimal distribution of energy. Lastly, investigating the economic feasibility of having such an integration.

2. Methodology

2.1 Superstructure

A superstructure was designed, outlining the available energy resources as well as the energy required by each unit, within the refinery, as seen in figure 1. These energy sources are limited due to their availability within the Middle East region. Moreover, electricity provided via the grid is assumed to be produced by natural gas.

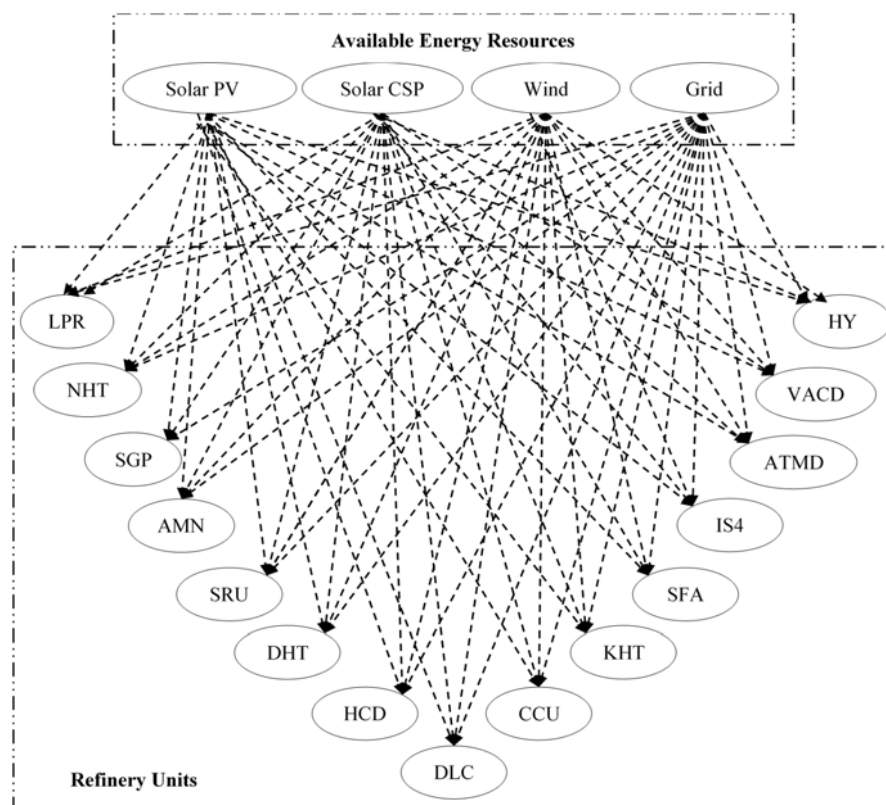


Figure 1. Superstructure diagram for the crude oil refinery units connected with all available energy resources.

2.2 Data collection

Each refinery unit was simulated in Aspen HYSYS and the amount of energy required by each unit was determined. Moreover, literature was surveyed in order to find the carbon emissions produced from each unit. Table 1 shows the energy demand and CO₂ emissions data, obtained from these two sources.

Table 1. Energy required by each unit and CO₂ emissions for each unit in the refinery.

Refinery unit	Abbreviation	MJ/year	g CO ₂ / MJ
Hydrogen plant	HYD	3.38 x10 ⁷	0.362
Sulfur Recovery Unit	SRU	2.42 x10 ⁸	0.056
Amine plant	AMN	2.53 x10 ⁷	0.056
Saturated Gas Plant	SGP	1.00 x10 ⁸	0.168
Naphtha Hydrotreater	NHT	1.63 x10 ⁷	0.187
Reformer	LPR	1.34 x10 ⁸	0.998
Kerosene Hydrotreater	KHT	7.07 x10 ⁶	0.187
Diesel Hydrotreater	DHT	8.50 x10 ⁶	0.187
Hydrocracker	HCD	1.80 x10 ⁸	0.561
Delayed Coker	DLC	3.31 x10 ⁷	0.312
Catalytic Cracking	CCU	3.29 x10 ⁸	0.686
Sulfur Acid Alkylation	SFA	2.35 x10 ⁸	0.000
C4 Isomerization	IS4	2.20 x10 ⁷	0.062
Unsaturated Gas Plant	UGP	1.11 x10 ⁸	0.168
Atmospheric Distillation	ATMD	2.06 x10 ⁵	1.684
Vacuum Distillation	VACD	4.01 x10 ⁶	0.561

Table 2 shows the available and/or potential energy sources in the region with CO₂ emissions due to electricity generation and the levelized cost of electricity (LCOE) [8-10]. It is observed that the highest amount of CO₂ emissions was produced from the grid energy source (i.e. natural gas) in comparison to other renewable energy sources.

Table 2. Potential energy sources in Abu Dhabi with CO₂ emissions due to electricity generation and the levelized cost of electricity [11].

Source	gCO ₂ /MJ	LCOE \$/kWh	Capacity (MJ/year)
Solar CSP	9.2	0.18	7.6 x10 ⁸
Solar PV	36.8	0.27	6.3 x10 ⁷
Wind	2.2	0.07-0.13	7.2 x10 ⁶
Grid	119	0.05-0.07	3.7x10 ¹¹

2.3 Assumptions

The following assumptions were made whilst developing the model:

- Crude oil feed of 100,000 barrels of crude oil per day
- Cost of electricity generated from each source is independent of the unit it is consumed within.
- Intermittent energy is stored and thus, available to be used throughout the year

2.4 Mathematical model

The ε (epsilon) constraint method was used where the cost of energy was defined as the objective function and the amount of CO₂ emissions was posed as a constraint. Thus, mathematical expression of this problem statement consists of minimizing cost (objective function) while observing inequality constraints and equality denoting the limitations for demand and supply of energy, and amount of emissions, respectively. It is written in a general form as the following Linear Programming (LP) problem:

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

subject to

$$(1-\alpha) 7.92 \times 10^7 \leq g \leq \alpha(5.44 \times 10^8) \quad \alpha \in [0,1] \quad (2)$$

$$\sum_{p=1}^6 x_{p,d} - b(d) \geq 0 \quad (3)$$

$$\sum_{d=1}^{16} x_{p,d} - a(p) \leq 0 \quad (4)$$

$$g = \sum_{p=1}^6 \sum_{d=1}^{16} gh_{p,d} x_{p,d} \quad (5)$$

where: z total cost of producing electricity
 $x(p,d)$ energy from energy supplier to energy demand
 p energy supplier (i.e. solar CSP, solar PV, grid, and wind)
 d energy demand (i.e. 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 by each energy supplier (CO₂ g / MJ)
 $lcoe(p,d)$ cost of energy production (USD / MJ)
 α weight varying between 0 and 1

3. Results and discussion

Results obtained from the simulated refinery unit as well as the optimization of the developed model are presented. The carbon dioxide emission was posed as a constraint with an assigned weight, α , that ranges between 0 and 1. A value of $\alpha=0$ signifies a focus on minimizing carbon dioxide emissions with no regard to cost. Conversely, a value of $\alpha=1$ signifies a focus on minimizing cost with no consideration of carbon dioxide emissions. Figure 2 shows the changes in the cost and carbon dioxide emissions as

α varies between 0 and 1. The cost is found to be minimum when emissions are maximum, and vice versa.

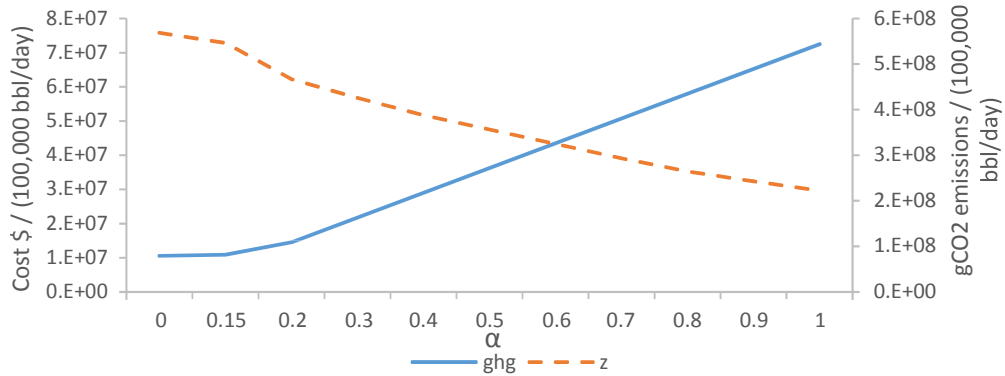


Figure 2. Cost and CO₂ emissions with respect to α

Furthermore, a Pareto front was constructed, based on the results obtained from the developed model, as seen in Figure 3. This Pareto curve shows the optimal cost corresponding to the carbon dioxide emissions emitted by the refinery when renewable energy is integrated optimally.

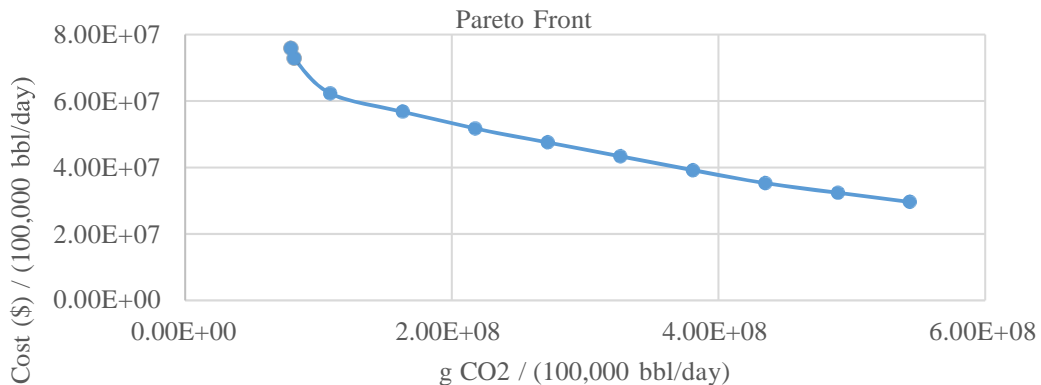


Figure 3. Cost and CO₂ emissions optimum points.

Furthermore, figures 4 and 5 show the energy distribution between energy sources and the refinery units at α equal to 0 and 1, respectively:

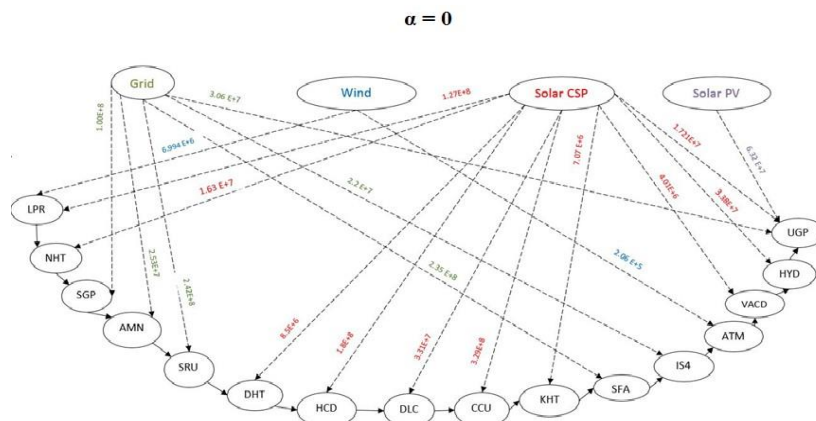


Figure 4. Optimal energy distribution to refinery units at $\alpha=0$.

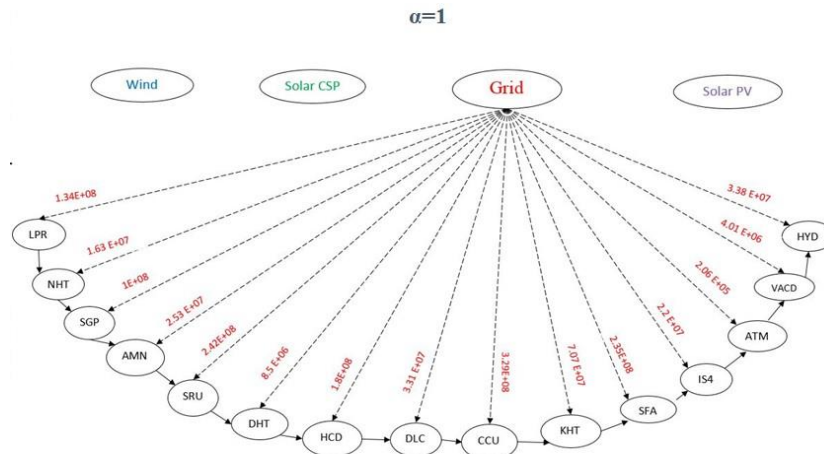


Figure 5. Optimal energy distribution to refinery units at $\alpha=1$.

4. Economic Analysis

The economic feasibility for integrating renewable energy sources to a refinery in Abu Dhabi was examined. 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 [11]:

$$CRF = \frac{D(1+D)^N}{(1+D)^N - 1} \quad (6)$$

$$LCOE = \frac{\text{Capital Cost} \times CRF \times (1 - TD_{PV})}{8760 \times \text{Capacity Factor} \times (1 - T)} + \frac{\text{fixed O\&M}}{8760 \times \text{Capacity Factor}} + \frac{\text{Variable O\&M}}{1,000 \frac{KW}{MW}} \quad (7)$$

where

<i>Capital cost</i>	cost of plant
<i>CRF</i>	capital recovery factor
<i>T</i>	tax rate paid
<i>DPV</i>	present value of depreciation
8760	number of hours in a year
<i>Capacity factor</i>	yearly average percentage of power as a fraction of capacity
<i>Fixed O&M</i>	fixed operating and maintenance cost
<i>Variable O&M</i>	variable operating and maintenance cost

Table 3. Calculated economic and environmental parameters for available renewable energy resources at different *LCOE*.

Source	Solar PV (low <i>LCOE</i>)	Solar PV (high <i>LCOE</i>)	Solar CSP (low <i>LCOE</i>)	Solar CSP (high <i>LCOE</i>)	Wind (low <i>LCOE</i>)	Wind (high <i>LCOE</i>)
<i>LCOE</i>	0.05	0.56	0.04	0.23	0.04	0.12
Carbon credit value w/renewable (\$/ton of CO ₂)	8.68	8.68	8.68	8.68	8.68	8.68
CO ₂ emissions w/grid (tons)	543.42	543.42	543.42	543.42	543.42	543.42
CO ₂ w/source (tons)	167.45	167.45	41.704	41.704	10.11	10.11
Total capital cost (\$MM)	70.5	392	86.0	517	56.4	187

Daily capacity (MWh)	47.0	47.0	47.0	47.0	47.0	47.0
Total fixed cost (\$MM)	0.355	5.2	2.33	5.40	0.482	2.82
Fixed cost per year (\$M)	11.8	172.2	77.5	180	16.1	94.0
Price per kWh in Abu Dhabi Industrial (\$)	0.04	0.04	0.04	0.04	0.04	0.04
Annual Cost of 17564 MWh Grid Electricity (\$MM)	16.5	16.5	16.5	16.5	16.5	16.5
Total Amortized Payments (\$MM)	170	948	207	1,249	136	454
Total savings per year	16.5	16.3	16.4	16.3	16.4	16.4
Payback period (years)	7	83	10	77	6	40
Project lifetime (years)	30	30	30	30	30	30

As seen from Table 3, all sources of renewable energy are economically feasible at low *LCOE* with wind being most viable and solar CSP the least.

5. Sensitivity Analysis

A sensitivity analysis was conducted, on Solar CSP, to determine how critical parameters impact the payback period and *LCOE* with changes in capital cost and capacity. Other renewable technologies yielded similar results; hence, not presented in this paper.

Table 4. Sensitivity analysis for capital cost and capacity factor on *LCOE* and payback period.

Capital Cost	<i>LCOE</i>	Payback Period Years	Capacity Factor	<i>LCOE</i>
1830	0.04	10	25.3	0.29
2000	0.08	11	30	0.24
3000	0.1	29	40	0.18
4000	0.13	40	50	0.15
5000	0.15	50	60	0.12
6000	0.18	59	70	0.11
7000	0.21	69	80	0.09
8000	0.23	79		
9000	0.26	89		
10000	0.29	99		
11000	0.31	108		

As evident from the table above, as capital cost increases, the *LCOE* and payback period increases. In addition, since the assumed lifetime of each project is 30 years, the feasible capital cost is 3000. On the other hand, as capacity factor increases, the *LCOE* decreases significantly. Thus, indicating that technical improvements can help reduce *LCOE* substantially.

6. Conclusion

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 CO₂ 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 CO₂ 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 CO₂ 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.

Based on this study, it is feasible for integrating renewable energy into the refinery. However, for future work, the following areas need to be incorporated within the scope:

- Energy hubs; only electricity through the grid and renewable sources were considered. A multi-energy hub network may be developed that involves additional energy input such as natural gas for on-site generators, heat streams, etc.
- Intermittent nature of renewable energy; an average annual potential of renewable energy sources such as solar and wind were 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 in integrating renewable energy systems with current energy systems.

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