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

M Alnifro\textsuperscript{1}, S T Taqvi\textsuperscript{1}, M S Ahmad\textsuperscript{1}, K Bensaida\textsuperscript{1,2}, and A Elkamel\textsuperscript{1,3}

1 Department of Chemical Engineering, University of Waterloo, 200 University Avenue W, Waterloo, ON
2 Department of Mechanical Engineering, National Engineering School of Sfax, Tunisa
3 Department of Chemical Engineering, The Petroleum Institute, Khalifa University, UAE
E-mail: jacky.mucklow@iop.org

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 CO\textsubscript{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\textsubscript{2} 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 seem 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.

![Superstructure diagram for the crude oil refinery units connected with all available energy resources.](image-url)
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 CO2/ 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                | gCO2/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 $\varepsilon$ (epsilon) constraint method was used where the cost of energy was defined as the objective function and the amount of CO$_2$ 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:

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

subject to

$$(1-\alpha) \times 10^7 \leq g \leq \alpha \times 10^8 \hspace{1cm} \alpha \in [0,1]$$  \hspace{1cm} (2)

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

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

$$g = \sum_{p=1}^{6} \sum_{d=1}^{16} ghg_{p,d} x_{p,d}$$  \hspace{1cm} (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)
- $\alpha$ 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, $\alpha$, 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
alpha 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 $\alpha$

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 $\alpha$ equal to 0 and 1, respectively:

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

\[ \alpha = 0 \]
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]:

\[ CRF = \frac{D(1+D)^N}{(1+D)^N-1} \]  
\[ LCOE = \frac{\text{Capital cost} \times CRF \times (1-T)D_{PV}}{8760 \times \text{Capacity Factor} \times (1-T)} + \frac{\text{fixed O&M}}{8760 \times \text{Capacity Factor}} + \frac{\text{Variable O&M}}{1,000 \times \text{MW}} \]  

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

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

| Source | Solar PV (low LCOE) | Solar PV (high LCOE) | Solar CSP (low LCOE) | Solar CSP (high LCOE) | Wind (low LCOE) | Wind (high LCOE) |
|--------|---------------------|----------------------|---------------------|----------------------|----------------|----------------|
| LCOE   | 0.05                | 0.56                 | 0.04                | 0.23                 | 0.04           | 0.12           |
| Carbon credit value w/renewable ($/ton of CO2) | 8.68                | 8.68                 | 8.68                | 8.68                 | 8.68           | 8.68           |
| CO2 emissions w/grid (tons) | 543.42              | 543.42               | 543.42              | 543.42               | 543.42         | 543.42         |
| CO2 w/source (tons) | 167.45              | 167.45               | 41.704              | 41.704               | 10.11          | 10.11          |
| Total capital cost ($MM) | 70.5                | 392                  | 86.0                | 517                  | 56.4           | 187            |
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 | LCOE | Payback Period Years | Capacity Factor | LCOE |
|--------------|------|----------------------|----------------|------|
| 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.

7. References

[1] N. Kholod, M. Evans, and V. Roshchanka, "Energy Efficiency as a Resource: Energy Efficiency’s Role in Meeting Ukraine’s Energy Needs," 2015.

[2] L. Brennan and P. Owende, "Biofuels from microalgae: a review of technologies for production, processing, and extractions of biofuels and co-products," Renewable and Sustainable Energy Reviews, vol. 14, pp. 557-577, 2011.

[3] G. B. Leite, A. E. Abdelaziz, and P. C. Hallenbeck, "Algal biofuels: challenges and opportunities," Bioresource Technology, vol. 145, pp. 134-141, 2013.

[4] H. Khatib, "IEA World Energy Outlook 2011—A comment," Energy policy, vol. 48, pp. 737-743, 2012.

[5] M. K. Lam and K. T. Lee, "Microalgae biofuels: a critical review of issues, problems and the way forward," Biotechnology advances, vol. 30, pp. 673-690, 2012.

[6] A. Groysman, "Physico-Chemical Properties and Corrosiveness of Crude Oils and Petroleum Products," in Corrosion in Systems for Storage and Transportation of Petroleum Products and Biofuels, ed: Springer, 2014, pp. 1-21.

[7] X.-M. Li, B. Zhao, Z. Wang, M. Xie, J. Song, L. D. Nghiem, et al., "Water reclamation from shale gas drilling flow-back fluid using a novel forward osmosis–vacuum membrane distillation hybrid system," Water Science and Technology, vol. 69, pp. 1036-1044, 2014.

[8] E. watch, "Economy Watchhttp://www.economywatch.com/economic-statistics/United-Arab-Emirates/Electricity_Production/.

[9] "Shams Power Company Saudi Arabia, http://www.shamspower.ae/en/the-project/factsheets/overview/.

[10] M. C. Energy, "Masdar clean energy, http://www.masdar.ae/en/energy/detail/masdar-city-solar-pv-plant.

[11] U. E. Information. http://en.openei.org/apps/TCDB/. Available:http://en.openei.org/apps/TCDB/, 2017