

Mathematical Modeling and Analysis of Distributed Energy Systems for a Refinery in Kuwait

Ibrahim H. Alhajri* and Syed Taqvi

Cite This: *ACS Omega* 2021, 6, 19778–19788

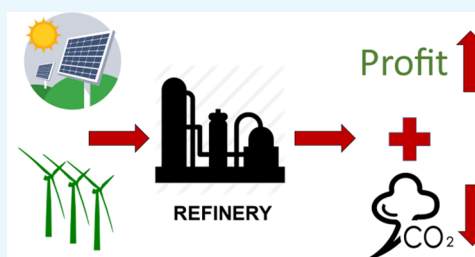
Read Online

ACCESS |

Metrics & More

Article Recommendations

ABSTRACT: In this study, a model is developed to optimally integrate various energy generation technologies within a refinery to help reduce economic costs as well as mitigate carbon emissions. The combined heat and power system was found to reduce 80 Mton of CO₂ emissions while saving \$2.61 billion dollars over 30 years as opposed to utilizing boilers and grid-connected electricity. Maximum carbon emissions can be prevented by installing wind turbines to reduce further 49 Mton of carbon emissions, saving at an added cost of \$53.4 million. Purchasing electricity completely from the grid was found to be the most expensive option, resulting in a monthly average of \$25 million. Changes in various factors such as the land available for installation of technology, electricity tariffs, and efficiency of modules and their impacts on the total project costs and emissions were studied. It was found that solar photovoltaic (PV) modules can be a more economical and environmentally friendly option than wind technology if they were equally efficient. Moreover, grid-connected electricity would only be the most economical option if it were purchased at \$0.03/kWh or lower. However, it is currently sold at close to \$0.10/kWh, making CHP the most economic option for refineries.



1. INTRODUCTION

Distributed generation systems, essentially, can be regarded as the primitive form of energy systems. Before the period of industrialization, almost every household was equipped with a local source of heating for domestic purposes. The first era of decentralization came to an end when the economy revolutionized through technological advancement and mass production.¹ On the other hand, prior to the discovery of fossil-based fuels, people would utilize renewable energy resources (RERs) to perform their day-to-day activities. Sails of various geometries would be used to harness wind energy for ships to travel far and wide within the oceans.² Wood was used extensively for cooking and heating. Now, infrastructures have been developed globally, strongly depending on these nonrenewable resources.³ In 2018, oil, gas, and coal industries contributed to more than 80% of the global energy supply, as shown in Figure 1.⁴ Moreover, oil and gas are expected to play a vital role in meeting the global energy demand until 2035.⁵ However, the interest of the economy is shifting back to renewable energy resources as well as distributed generation.

The persistent decline in the energy return on the energy invested in fossil-based fuels and the increase in carbon emissions have given rise to extensive research in the area of renewable energy and distributed generation.⁶ Due to promising technical findings and environmental awareness, many challenges have been successfully overcome to a certain degree in these recent years. The high capital cost of renewable energy resources was one of the major arguments used to neglect its mass adoption.⁷ In 2014, the leveled costs of

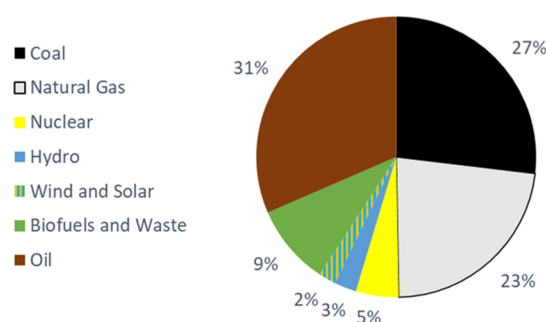


Figure 1. World electricity production from all energy sources in 2018.⁴

electricity of photovoltaic (PV) and natural gas systems were reported to be as low as \$0.056/kWh and \$0.049/kWh, respectively.⁸ Lack of financial incentives was another major barrier that held back investments in this area.⁷ Now, several countries have taken various initiatives, incorporated different strategies, and set targets to significantly increase their renewable energy share and decrease greenhouse gas

Received: May 10, 2021

Accepted: July 12, 2021

Published: July 21, 2021



emissions. Moreover, they are providing various incentives on the federal as well as the provincial level to encourage investments. Perera et al. conducted a detailed study, analyzing various scenarios based on the clean energy incentives that Canada offers.⁹ Intermittency was another issue with certain RERs that has been mitigated to a great extent with the help of energy storage technologies.¹⁰ In addition, Pepermans et al. identified several benefits of distributed generation and outlined two main driving forces for a transition toward it: electricity market liberalization and environmental concerns.¹¹

Despite these benefits, an overnight shift by abandoning all fossil-based applications may not be feasible at this stage. It is unanimously agreed that renewable energy is going to be a vital source for power generation in the future. Theoretically, it does have the ability to meet the global energy demand sustainably and protect the environment.¹² Nevertheless, energy crisis researchers have regarded the strategy of systematic coupling of different energy sources as more effective as opposed to the direct substitution of fossil-based energy or the conventional approach of incremental alterations in technology, especially in energy-intensive sectors.¹³ Additionally, they have identified the need to integrate a methodological framework to represent the reality of supply chains and generate alternative solutions to improve the performance of sustainable and renewable energy supply chains.¹⁴ Such a systematic framework would enable the optimal integration of RERs to energy-intensive sectors and significantly reduce greenhouse gas emissions. In 2006, Szklo and Schaeffer introduced the concept of alternative energy systems where oil was proposed to be integrated with other energy sources to pave way for new systems.¹⁵ The term “virtues of oil” was coined to signify the economies of scale that the oil industry experiences and its economical advantage of vertical integration that is crucial for driving energy services of the modern society.¹⁵

Petroleum refining is a highly energy-intensive complex process within the oil industry and is one of the largest carbon dioxide emitters.^{15–17} In 2013, Absi-Halabi, Al-Qattan, and Al-Otaibi surveyed the oil industry and found that almost 10% of the produced oil was consumed in the production and refining stages, split almost evenly.⁵ Forsberg regarded refineries as the largest industrial facilities and recorded their consumption to be over 7% of the total energy demand in the US.¹³ In a study, more than 200 projects were examined and it was concluded that up to 64% of the energy demand of refineries can be fed with solar energy alone.¹⁸ Another study considered 75 crude oil refineries and found the solar PV and thermal potential to be 21–95 GW_{thermal} and 17–91 GW_{electricity}, respectively.¹⁹ Significant research has been carried out where rigorous process models have been developed to increase the overall profitability for refineries.²⁰ Researchers have formulated mixed-integer programs to integrate hydrogen within refineries to mitigate carbon dioxide emissions.²¹ Several papers have been published focusing on process control planning as well as scheduling using mixed-integer and nonlinear programming.^{22,23} Yet, with the potential RERs hold, significant work pertaining to the integration of these vectors has not been carried out.

On the other hand, Kuwait is one the most densely populated petroleum exporting country with a recorded population of around 4.4 million in 2019.²⁴ It is oil-dependent and hosts one of the world's largest refineries, processing around 1 million barrels of crude oil per day.²⁵ According to a study, the emission rates of operating refineries were estimated

between 2.88 and 3.78 million tons per year.²⁵ The energy outlook report showed that Kuwait produced 21.1 tons of CO₂ per capita in 2015 and was forecasted to be around 20 tons of CO₂ per capita in 2035.²⁶ This is 4 times the world average emissions per capita forecasted in 2035. Another study revealed that the current installed capacity of electricity can barely meet the increasing demand.²⁷ To tackle these problems, Kuwait has set renewable energy targets for 2030 and has announced a number of projects to attain those targets. One such project is Al-Shagaya Renewable Energy Park (SREP), which utilizes solar photovoltaic (PV), concentrated solar power (CSP), and wind power technologies.²⁸ In 2015, Kuwait recorded renewable energy to contribute to 0.003% of the energy supply.²⁹ This increased to 0.021% in 2018 and is expected to further increase significantly as Kuwait has announced the construction of the Al-Dibdibah Solar Project, one of the largest solar projects in the world.²⁸ Yet, these are renewable energy projects that will remotely provide energy and experience similar problems as centralized systems. Hence, there is a need for the systematic integration of renewables through distributed energy systems for energy-intensive industries such as refineries.

This research work aims to model a distributed energy system for a Kuwait refinery, which incorporates renewable and nonrenewable energy vectors in economic and environmentally friendly scenarios. Since RERs are considered, a multiperiod mathematical model is formulated to tackle the issue of seasonal imbalances. Data pertaining to the potential energy available within the region as well as the refinery are collected. Processes that take place within the refinery and the associated CO₂ emissions are identified. Constraints are formed based on product supply and demand, energy supply and demand, and possible CO₂ regulatory limits as well as technological restrictions. Based on these conditions, the model will provide the mechanism of energy production to meet electricity, heat, and steam demand. Furthermore, it will provide areas of integration of renewable energy within the refinery for different processes. Using the findings of this study, decisions/policymakers will be able to assess the economic and environmental impact of integrating renewable energy into their complex refinery structure and make informed decisions accordingly to meet set targets.

2. COMPUTATIONAL METHODS

Several techniques exist that can model distributed energy systems effectively. The most common modeling methodologies include virtual power plants (VPPs), integrated energy systems (IESs), microgrids, energy hubs (EHs), intelligent power grids, and various others. Mancarella carried out a comprehensive survey of these methodologies and regarded the energy hub approach as “the most elegant way to describe energy flows in a synthetic way”.³⁰ Maroufmashat et al. reviewed more than 200 articles on energy hubs and found its numerous applications in the field of distributed energy resources, plug-in hybrid electric vehicles, storage systems, and others.³¹ It was found to be more reliable, flexible, and offered a wider range for optimization above other techniques.^{32,33} Based on these benefits, the energy hub approach is used, in this study, to model the distributed energy system for the refinery. Energy hubs are multiple energy carriers designed for the optimal flow of energy.³⁴ In this modeling approach, the energy hub can host multiple energy conversion and storage technologies with multiple types of

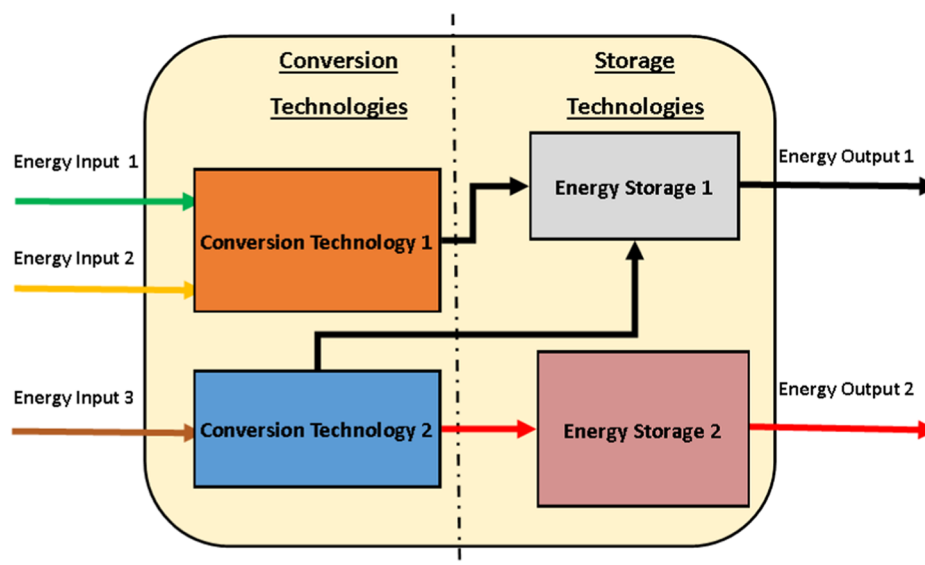


Figure 2. Example of an energy hub with multiple energy conversion and storage technologies.

energy vectors, as depicted in Figure 2. In this approach, a network of energy hubs is studied, where each node (i.e., energy hub) allows the exchange of energy between other nodes (i.e., energy hubs). In the case of refineries, each processing unit is regarded as an energy hub to which the energy production and/or consumption will be attributed to.

2.1. Objective Functions. As the aim of this study is to mitigate carbon emissions while yielding economic benefits, a multiobjective function (z) is developed with varying weights, ω , assigned to each, as in eq 1. The total economic and environmental costs (i.e., CO₂ emissions) incurred throughout the lifetime of the project (i.e., 30 years) are the objective functions, represented by z_1 and z_2 , respectively. If $\omega = 0$, the z is minimized, thereby minimizing project carbon dioxide emissions. Conversely, if $\omega = 1$, the model is solved to minimize the project cost.

$$\min z = \omega \frac{z_1}{z_{1,\min}} + (1 - \omega) \frac{z_2}{z_{2,\min}}; \omega \in [0, 1] \quad (1)$$

In certain cases, the epsilon constraint method is utilized to counter the convexity problem of the weighted sum technique. For this particular study, the economic objective function will be minimized when constraining the emission function by the maximum emissions multiplied by a varying weight, ω , shown in eq 2.

$$\min z_1 \text{ s. t. } z_2 \leq \omega z_{2,\max} \quad (2)$$

$$\begin{aligned} z_1 &= \text{cost}_{\text{energy}}^T = \text{capital}_{\text{energy}}^T + \text{O\&M}_{\text{energy}}^T \\ &= \sum_t \sum_s \sum_j P_{s,j,t} \times \text{LEC}_j \end{aligned} \quad (3)$$

$$z_2 = \sum_t \sum_s \left(\sum_j P_{s,j,t} \text{CO}_{2,s,j} + \sum_i D_{s,i,t} \text{CO}_{2,s,i} \right) \quad (4)$$

The economic objective function (z_1) is mainly the cost of energy technologies utilized by the refinery. z_1 can be expanded to incorporate further elements such as the cost of storage technologies employed, the cost of carbon capture and storage techniques applied, and the cost of carbon cap and

trade. The environmental objective function (z_2) accounts for all CO₂ and/or CO₂-eq emissions generated from these energy technologies as well as the refinery process units as a result of production.

2.2. Equations. $\text{Cost}_{\text{energy}}^T$ as in eq 3, is described by the capital cost as well as the operational costs of energy production technologies. Wherever applicable, this cost may be calculated by multiplying the amount of energy utilized and its associated levelized cost (LEC). This levelized cost of energy is the ratio of the total lifetime cost of the respective energy technology to its expected power output, as in eq 5. Moreover, it primarily comprises the capital, operating, and fuel costs. In addition, it incorporates factors like capital recovery, interest, depreciation, tax rate, and various others. Extensive studies have been carried out to develop such a formulation for aiding in planning research.^{35,36} Moreover, such formulations are being used by researchers in their respective work, especially for renewable energy technologies.^{37,38}

$$\begin{aligned} \text{LEC}_j &= \frac{C_j^{\text{cap}} \times \text{CRF}_j \times (1 - D_{\text{PV}})}{8760 \times \text{CF}_j \times (1 - T)} + \frac{C_j^{\text{fixed O\&M}}}{8760 \times \text{CF}_j} \\ &+ C_j^{\text{var O\&M}} + C_{j,t}^{\text{fuel}} \end{aligned} \quad (5)$$

The energy demand of each refinery unit ($D_{s,i,t}$) is dictated by the volume of production, prod_t , and the energy requirement per product, $E_{s,i,t}$, as in eq 6.

$$D_{s,i,t} = E_{s,i,t} \times \text{prod}_t \quad (6)$$

The required input energy vector for respective energy hubs ($P_{s,j,t}$) is multiplied by the coupling matrix that contains the conversion efficiencies, as defined by Geidl and Andersson, as in eq 7.³⁴

$$L_{s,i,t} = C_{i,j} \times P_{s,j,t} \quad (7)$$

To form the network of energy hubs and allow energy exchange, the output load ($L_{s,i,t}$) is tied in with the energy demand of the refinery units ($D_{s,i,t}$) as well as the energy transferred from an energy hub s to b ($Tr_{s,b,i,t}$) if a connection,

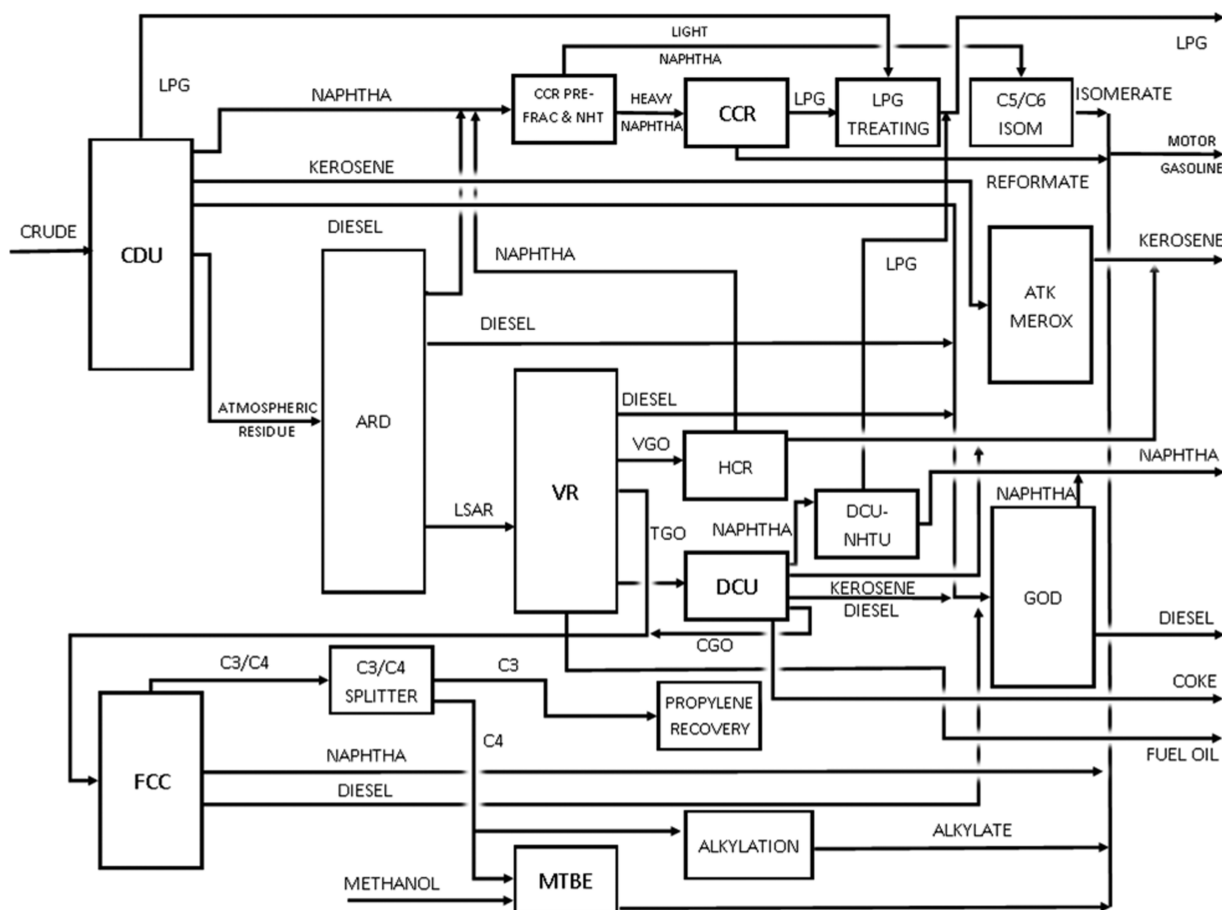


Figure 3. Schematic diagram of the refinery process units considered in this study.

$\beta_{s,b}$ exists between them. If a connection exists between energy hubs s and b , $\beta_{s,b}$ would be 1. Otherwise, it would be zero.

$$L_{s,i,t} = D_{s,i,t} + \sum_{b \in S-s} T_{r,b,i,t} \times \beta_{s,b} \quad (8)$$

2.3. Constraints. Based on the energy outlook report of Kuwait, the technologies considered for this particular study are based on solar, wind, natural gas, oil, and grid.²⁶ The grid-connected electrical power generation of Kuwait heavily depends on natural gas.²⁷ Therefore, the carbon emissions and conversion efficiencies of the grid are considered. Electricity purchased from the grid is subjected to a constraint as there are other domestic applications for it. Moreover, similar constraints exist for other energy technologies.

$$\gamma_{s,grid,t} P_{s,j,t}^{\min} \leq P_{s,grid,t} \leq \gamma_{s,grid,t} P_{s,grid,t}^{\max} \quad (9)$$

For this distributed energy system, two solar technologies, solar concentrated power (CSP) and photovoltaic (PV), are considered. The constraints defining their potential to produce respective energies are illustrated in the equations below. Their efficiency to be used for electricity, heat, or steam is defined in the coupling matrix, C_{ij} . The total area of PV modules is multiplied by a factor of 1.7 to calculate the land area occupied by an onshore solar PV farm, based on completed projects, as in eq 12. Similarly, the total aperture area is multiplied by 4 to calculate the required land area for the installation of CSP solar collector assemblies, as in eq 15.

$$P_{s,pv,t} \leq \text{land}_{s,pv} \times \text{GHI}_t \times \text{PR}_{pv} \quad (10)$$

$$\sum_t P_{s,pv,t} = N_{s,pv} \times \text{CF}_{pv} \times \text{power}_{pv} \times \text{PR}_{pv} \times h_{pv} \quad (11)$$

$$\text{land}_{s,pv} = 1.7 \times \text{area}_{pv} \times N_{s,pv} \quad (12)$$

$$P_{s,csp,t} \leq \text{land}_{s,csp} \times \text{DNI}_t \times \text{PR}_{csp} \quad (13)$$

$$\sum_t P_{s,csp,t} = N_{s,csp} \times \text{CF}_{csp} \times \text{power}_{csp} \times \text{PR}_{csp} \times h_{csp} \quad (14)$$

$$\text{land}_{s,csp} = 4 \times \text{aperture}_{sca} \times \text{length}_{sca} \times N_{s,csp} \quad (15)$$

Energy harnessed from an onshore wind farm is represented by eqs 16–18 and have been utilized in various publications.^{39,40} The rotor diameter, in eq 18, is multiplied by a factor of 5 to avoid the wake effect between adjacent installed wind turbines.

$$P_{s,wt,t} \leq \text{land}_{s,wt} \times 0.5 \rho_{\text{air}} A_{\text{swept}} w_{s,t}^3 h \quad (16)$$

$$\sum_t P_{s,csp,t} = N_{s,wt} \times \text{CF}_{wt} \times \text{power}_{wt} \times h_{wt} \quad (17)$$

$$\text{land}_{s,wt} = 5 \times \text{rotor}_{wt}^2 \quad (18)$$

The available space for RER installation is crucial and is limited using the following constraint.

$$\sum_s \text{land}_{s,pv} + \text{land}_{s,csp} + \text{land}_{s,wt} \leq \text{area}_s^{\max} \quad (19)$$

The heating value of natural gas is used to calculate the energy extracted from it, using eq 20.

$$P_{s,j,t} = V_{s,j,t}^{\text{fuel}} \text{LHV}_j \quad \forall j = \text{natural gas, oil} \quad (20)$$

2.4. Process Units. As refining is a complex process, the configuration of each refinery is somewhat unique. Yet, the most common processes include crude oil and vacuum distillation, hydrotreating, catalytic cracking, isomerization, and sulfur recovery. Specifications of each refinery may differ based on the crude oil feed as well as the requirements of the market it caters to. The process units considered in this refinery and the list of acronyms are shown in Figure 3 and Table 1. Each of these process units have a direct electricity and/or heat demand.

Table 1. List of Acronyms in Figure 3 and Their Description

acronym	description
ARD	atmospheric residue desulfurization
ATK	aviation turbine kerosene
CCR	continuous catalytic reforming
CDU	crude distillation unit
CGO	coker gas oil
DCU	delayed coker unit
FCC	fluid catalytic cracking
GOD	gas oil desulfurization
HCR	hydrocracking
LPG	liquefied petroleum gas
LSAR	low sulfur atmospheric residue
MEROX	mercaptan oxidation
MTBE	methyl <i>tert</i> -butyl ether
NHT(U)	naphtha hydrotreating unit
TGO	hydrotreated vacuum gas oil
VGO	vacuum gas oil
VR	vacuum rerun

Data are collected pertaining to the energy requirements of each process unit based on the production profile of the refinery. The energy produced from the available resources will be used to meet the energy demand of each process unit. In addition, renewable energy data such as wind speed and solar irradiation are readily available in the public domain.⁴¹ For the initial case, a 6 km² land area is assumed to be available on-site that can be utilized toward RER technology installations.

3. RESULTS AND DISCUSSION

In the sections below, the results of energy generation via different technologies are presented and their impact on project costs and emissions is discussed. General Algebraic Modeling System (GAMS) v.24.5.6 was used to solve the model, utilizing the CPLEX 12.6.2.0 solver. The base model, for the case study considered in a monthly scenario, comprised of 17 718 single variables and 15 477 single equations. Moreover, for each of the assumed factors, a sensitivity analysis is carried out to observe the effect on the total project cost and emissions.

3.1. Total Project Cost and Emissions. As evident from Figure 4, the least carbon emissions are observed when wind turbines are utilized to meet the energy demand alongside the combined heat and power system. The total project cost (i.e., capital, operating and maintenance, installation, labor, etc.) and emissions realized over the lifetime (i.e., 30 years) for this

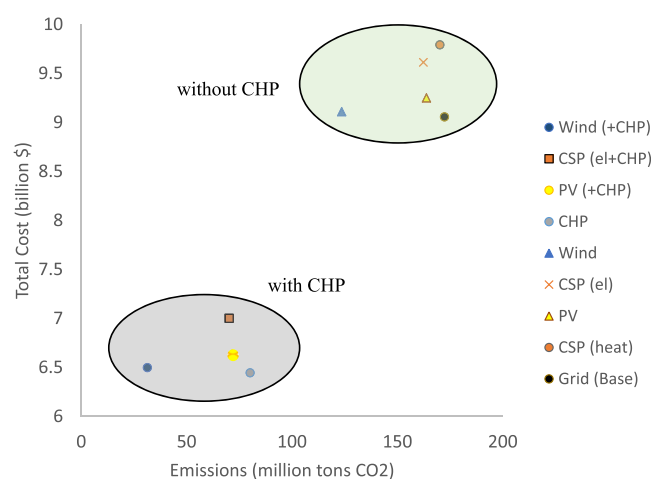


Figure 4. Total project costs versus carbon dioxide emissions for different energy generation technologies.

particular configuration are \$6.50 billion and 31.4 Mton CO₂, respectively. In Kuwait, grid electricity is completely produced from natural gas. Assuming the base case of using grid and natural gas boilers to meet the overall energy requirement, 140 Mton of emissions are mitigated over a period of 30 years while saving \$2.56 billion. Due to the low wind speed in the region, small wind turbines that have a cut-in wind speed of 0.2 m/s were utilized. Hence, the number of these turbines exceeds 4 million, as shown in Table 2.

The next best configuration with respect to emission reduction is that of CSP with CHP. In this particular configuration, about 70 Mton less carbon emissions are observed at a cost of \$2.19 billion. Concentrated solar power is used to complement combined heat and power in electricity production. The amount of natural gas consumed to provide the required energy is 22.4 bcf and its cost is included in this total cost. Solar photovoltaic technology complementing CHP in electricity production reduces 2 Mton less than the former case (i.e., CSP with CHP). Yet, it is \$363 million cheaper than CSP with CHP. As observed, all renewable energy technologies are significantly economical when complementing with the CHP technology. Without the CHP technology, all renewables exceed the base case (i.e., grid) in terms of cost of up to \$7.35 billion. CHP utilized alone leads to a savings of \$2.61 billion but emits 80 Mton of CO₂. Installing wind turbines can further reduce the emissions by 49 Mton at an added cost of \$53 million. Also, without CHP, renewable energy technologies result in increased emissions as the shortfall in energy supply is met with electricity and boiler.

3.2. Operating Costs. The operating cost of each month was calculated for different energy generation technologies, as shown in Figure 5. The operating cost comprises fixed and variable operating and maintenance costs. The lowest operating cost was observed for the wind and CHP configuration having a monthly average of around \$12 million. The next lowest operating cost was observed for CSP with CHP and PV with CHP, both had a similar monthly average of around \$17 million. In this study, CHP was not allowed to produce excess electricity. Therefore, in the CHP configuration, electricity was purchased from the grid, causing its operating cost to be higher compared with the former cases. In the cases where no CHP technology was utilized, the monthly costs were significantly higher. The difference between the

Table 2. Energy Distribution for the Different Energy Technologies Shown in Figure 4

configuration	TWh							bcf				
	PV	CSP	wind	CHP El.	CHP heat	grid	boiler	PV mod	SCA	WT	natural gas	
grid (base)	0.00	0.00	0.00	0.00	0.00	1.95	1.71	0	0	0	17.0	
CHP	0.00	0.00	0.00	1.20	1.71	0.75	0.00	0	0	0	22.4	
CSP (electricity)	0.00	0.13	0.00	0.00	0.00	1.82	1.71	0	19 992	0	17.0	
CSP (electricity), CHP	0.00	0.13	0.00	1.20	1.71	0.62	0.00	0	19 992	0	22.4	
grid with CSP (heat)	0.00	0.14	0.00	0.00	0.00	1.95	1.57	0	19 992	0	15.6	
PV	0.12	0.00	0.00	0.00	0.00	1.83	1.71	24 742 260	0	0	17.0	
PV, CHP	0.12	0.00	0.00	1.20	1.71	0.64	0.00	24 742 260	0	0	22.4	
wind	0.00	0.00	0.66	0.00	0.00	1.29	1.71	0	0	4 444 440	17.0	
wind, CHP	0.00	0.00	0.66	1.20	1.71	0.10	0.00	0	0	4 444 440	22.4	

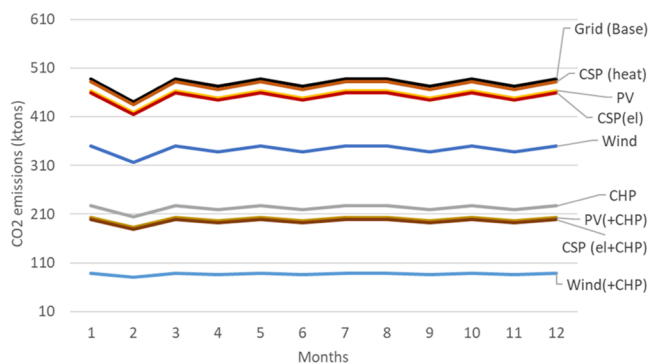


Figure 5. Monthly operating costs of different energy generation technologies.

monthly average of wind and that of CHP is around \$20 million. Comparing the CHP with that of the grid, the difference in the average monthly operating costs was found to be \$7.2 million. The slight dip in month 2 (i.e., February) is due to the smaller number of days, resulting in lower costs compared with other months.

3.3. Available Land. As stated earlier, a 6 km² land area was assumed to be available on-site for renewable energy installations. However, this factor was varied to observe its impact on the overall costs and emissions as shown in Figures 6 and 7, respectively.

The overall trend observed is a decrease in carbon emissions and an increase in costs as the available land increases. The most significant decrease in emissions was observed for the

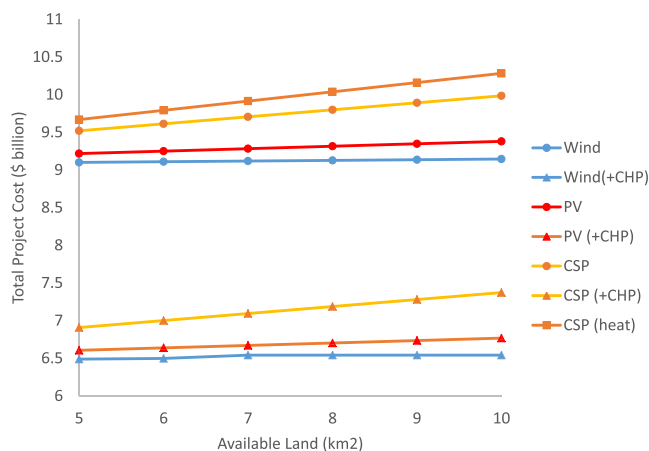


Figure 6. Sensitivity analysis on available land against total project costs.

wind(+CHP) emissions configuration. As the available land increased to 7 km², the emissions decreased to 24.2 Mton with a project cost of around \$6.54 billion. Compared to the previous analysis (i.e., wind(+CHP) for 6 km²), an additional investment of \$40 million can lead to a further 7.25 Mton carbon emissions mitigation. Beyond the 7 km² available land, no further reduction in carbon emissions is observed. Since excess electricity production is restricted, CHP contributes to electricity production in addition to heat. The shortfall in electricity production is met by wind and grid-purchased electricity, as evident from Table 2. As the available land increases, more wind turbines can be installed, contributing to this shortfall until it makes up for the electricity purchased by the grid. The PV(+CHP) and CSP(+CHP) configurations depicted a gradual decrease in carbon emissions with an increase in available land. For the CSP(+CHP) configuration, however, a more significant increase in cost was observed as compared to PV(+CHP). An increase of \$32.3 and \$92.9 million, for an increase of 1 km² available land, was observed for the PV(+CHP) and CSP(+CHP) configurations, respectively.

In the cases without the CHP technology, the most significant carbon emissions were observed for the wind technology. A decrease of around 8.13 Mton was observed at an added cost of about \$8.90 million and 1 km² available land. In contrast to the wind(+CHP) configuration, a continual increase in wind contribution was observed as the available land increases. This is due to the sole contribution of the boiler toward meeting heat requirements. Thus, the wind contribution will continue to increase with an increase in the available land until all electrical power requirement is met by the wind technology. Similarly, CSP and PV configurations tend to produce fewer carbon emissions with increased available land. Yet, their mitigation of carbon emissions is less significant as compared to that by the wind technology. Solar PV results in 1.43 Mton less emissions per 1 km² increase in available land for an added cost of \$3.23 million. However, solar CSP yields 1.67 Mton less emissions per 1 km² increase in available land for an additional cost of \$9.30 million. CSP technology was also considered to provide heat instead of electricity. However, it was observed to be the most expensive option, as evident from Figures 4 to 6.

3.4. Electricity. In the absence of the CHP technology, as evident from previous analyses, the refinery meets its electricity requirement mainly from the grid. This is true even in the presence of renewable energy technologies. In the initial case, an industrial tariff of \$0.10/kWh was assumed. The following analysis studies the impact of changes in the electricity price on the total project cost.

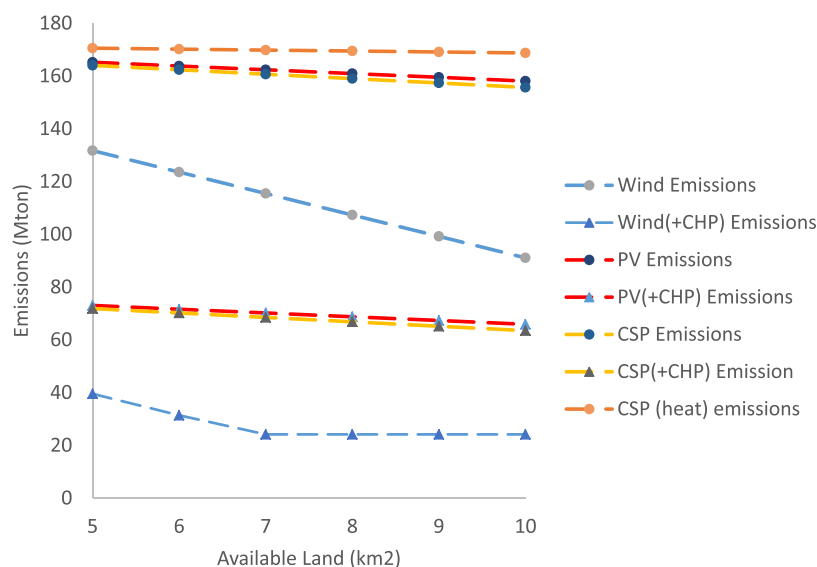


Figure 7. Sensitivity analysis on available land against emissions.

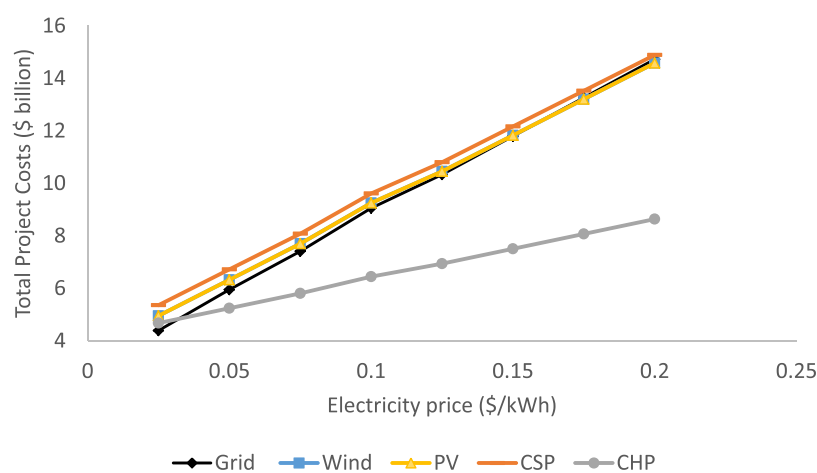


Figure 8. Sensitivity analysis of electricity price versus total project costs.

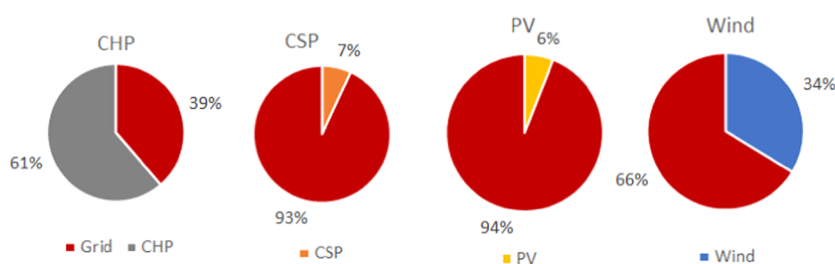


Figure 9. Share of energy generation technologies in different configurations.

The total project cost is observed to increase as electricity tariffs increase, as shown in Figure 8. As evident from Table 2, CHP and RER technologies in the absence of CHP are complemented by the grid significantly. The lowest cost increase is observed for the CHP configuration as the electricity price increases. This is because the share of CHP in electricity generation is 39%, as shown in Figure 9. Thus, the change in the tariff does not affect the total project cost as significantly as it does in the other configurations.

The next lowest is the base case where all of the electricity requirements are met by the grid. It is noteworthy that the grid has a lower project cost than CHP for an electricity price of

\$0.025/kWh. The project costs for these configurations seem to cross at around \$0.03/kWh, implying that purchasing electricity from the grid will be the most economic option if electricity was sold at a price lower than that. Nevertheless, considerable emissions are prevented by adopting the CHP technology as opposed to the grid. Following them are the configurations PV and wind, which seem to coincide. Although the share of wind is 34% in electricity generation, the high cost of PV relative to wind seems to mask the difference. Lastly, the configuration of CSP heat yields the highest cost and has a slightly higher share as compared to PV and reduces a further 1 Mton than it.

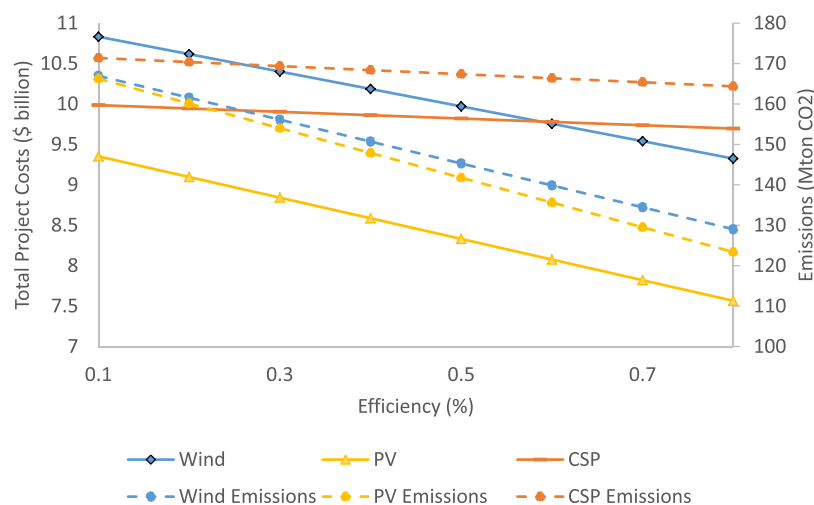


Figure 10. Sensitivity analysis of efficiency against total project costs and emissions.

3.5. Efficiency. For renewable energy technologies, there are several factors that contribute to the overall efficiency of the equipment. If the overall efficiency is improved, it can have a significant effect on the ability to yield energy, thereby resulting in more gains.

In the analysis depicted in Figure 10, it can be seen that the project costs and emissions decrease with increasing efficiency. As observed, the lowest emissions observed are that of solar PV. The initial efficiency considered for the solar PV module in this study was 14%, as reported by the manufacturer. However, during operation, such modules can reach an efficiency of up to 42%. For an increment of 10% in efficiency, the PV configuration prevents 6.13 Mton of emissions from being produced while saving \$255 million. Wind, on the other hand, has a total electrical efficiency usually within the 60–70% range. In this case, wind experiences a slightly less gain, preventing 5.42 Mton while saving \$215 million. Lastly, the CSP technology is able to prevent 1 Mton of emissions and saving \$41.4 million. Most CSPs have an efficiency between 10 and 25%.

3.6. Pareto Front. As the model was solved to minimize the multiobjective function, a pareto front was generated to obtain a range of values on which optimality lies. The extremities of this function denote the minimum emissions and cost, respectively (Figure 11).

As shown in Figure 4, the lowest carbon emissions were observed for the wind(+CHP) configuration, marking one extremity of the front. CHP, the most economic option from the remaining configurations, marks the other end of this front. The front aids in decision-making when a trade-off needs to be analyzed. In this case, as the cost of the CHP and grid-connected electricity mainly constitutes its fuel price while small wind turbines are utilized, a linear front is obtained. This particular front denotes a change of 8.02 Mton emissions with an \$8.78 million change in the project cost. After choosing to install the CHP technology within the refinery, the refinery can be installed with a limited set of wind turbines and still benefit from optimality.

4. CONCLUSIONS

In this study, a model was developed to optimally integrate renewable energy technologies within a refinery to attain economic and environmental gains. With the help of the

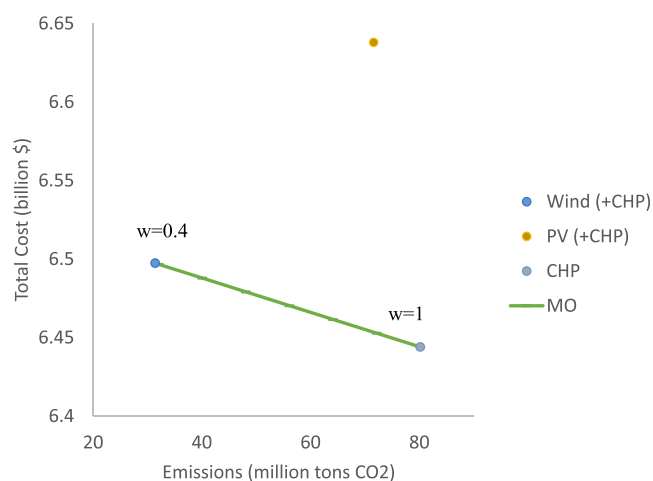


Figure 11. Pareto front plotted along with the PV(+CHP), wind(+CHP), and CHP configurations.

developed model, the total project costs and carbon emissions realized over the lifetime of the project were obtained. Moreover, the monthly operating costs were analyzed to see the economic load on the refinery if it were to receive a government incentive to gain capital for the energy generation technologies. Various factors such as the available land, electricity tariffs, and the efficiency of units were studied to observe the effect of such factors on the overall cost and emissions. Based on the findings, the wind energy coupled with CHP energy system was found to be the most environmentally friendly option. On the other hand, CHP alone was determined to be the most economic option. Through the epsilon constraint method, a front was generated through which the decision-making process can be made easy. Since this profile was linear, investments in wind turbines will result in proportional carbon emission reduction.

Refineries consume a tremendous amount of energy and generate emissions that have adverse effects on social health and the environment. Thus, more work needs to be carried out to make the refining process sustainable through alternative resources and technologies. Although the energy hub approach can incorporate energy storage modeling, this was not considered within the scope of this study. However, storage technologies can be studied in the integration process to

maximize gains, especially from intermittent sources of energy (i.e., solar), and tackle any reliability issues. Excess energy was restricted in this study; yet, further work can be carried out to allow excess to be fed back to the grid or power neighboring settlements. Data clustering methods can also be utilized to tackle uncertainty issues with weather data. Furthermore, stochastic parameters pertaining to the refinery market such as varying product prices can be tied in with the overall costs to understand the profit margin of such refineries. Oil will be around for at least a few more decades and steps need to be taken to make its operations sustainable.

AUTHOR INFORMATION

Corresponding Author

Ibrahim H. Alhajri – Chemical Engineering Department,
College of Technological Studies, PAAET, Shuwaikh 70654,
Kuwait; orcid.org/0000-0002-5225-362X;
Email: ih.alhajri@paaet.edu.kw

Author

Syed Taqvi – Chemical Engineering Department, University of
Waterloo, Waterloo, Ontario N2L 3G1, Canada

Complete contact information is available at:
<https://pubs.acs.org/10.1021/acsomega.1c02461>

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

NOMENCLATURE

Indices

i type of output energy carrier
j type of input energy carrier
s, b particular energy hub
t time period

SETS

I set of output energy carrier
J set of input energy carrier
S set of energy hubs
T time period (30 years)

PARAMETERS

A_{swept} area swept by a blade in the wind turbine technology ($\pi r_{\text{rotor}_{\text{WT}}}^2$), m^2
 $\text{aperture}_{\text{SCA}}$ aperture of a solar collector assembly in the CSP technology (6), m
 area_{PV} area of a solar photovoltaic (PV) module (1.94), m^2
 area^{max} maximum area allocated for the technology at a particular energy hub, m^2
C coupling matrix
 C^{cap} capital cost per unit of power for a particular energy carrier, \$/kW
 $C^{\text{fixed O\&M}}$ fixed operating cost per unit energy produced for a particular energy, \$/kWh
 C^{fuel} fuel cost per unit energy, mass, or volume for a particular energy, \$/kWh

$C^{\text{var O\&M}}$ variable operating cost per unit energy produced for particular input energy carrier, \$/kWh
CF capacity factor of a particular energy production technology, %
 CO_2 carbon emissions produced per unit of energy demanded or produced, gCO_2/kWh
CRF capital recovery factor
D discount rate aka interest rate, %
 D_{PV} depreciated present value
DNI direct normal irradiance exposed to the CSP technology, W/m^2
GHI global horizontal irradiance per surface area, W/m^2
h number of operating hours in a year, hours
LEC levelized energy cost for a particular energy production technology, \$/kWh
LHV low heating value of a particular fuel, J/m^3
 $\text{length}_{\text{SCA}}$ length of a single solar collector assembly in the CSP technology (150), m
 P^{min} minimum energy production capacity of the input energy carrier at energy hub *s*, kWh
 P^{max} maximum energy production capacity of the input energy carrier *j* at a particular energy hub, kWh
 $\text{power}_{\text{PVP}}$ power rating of a single solar photovoltaic (PV) module (300), W
 $\text{power}_{\text{CSP}}$ power rating of a single CSP solar collector assembly (32 000), W
 power_{WT} power rating of a single wind turbine (1500), W
prod volume of production, bbl/h
PR performance ratio of a particular energy production technology (accounts for all losses due to system defects, unclean modules, etc.)
 rotor_{WT} rotor diameter of the blades of a single wind turbine (1.82), m
T tax rate, %
 V^{fuel} volume of fuel used for an energy production technology using natural gas/oil, m^3
 β matrix defining the connections between energy hubs
 ρ_{air} density of air, $1.225 \text{ kg}/\text{m}^3$

CONTINUOUS VARIABLES

$\text{capital}_{\text{energy}}^{\text{T}}$ total capital cost of energy production technologies, \$
 $\text{cost}_{\text{energy}}^{\text{T}}$ total cost of energy produced from energy production technology, \$
D load energy demand by a particular energy hub, kWh
E energy demand by a particular energy hub per unit product, kWh
L load demand by a particular energy hub, kWh
land land area occupied by a particular energy hub for a certain technology, km^2
 $\text{O\&M}_{\text{energy}}^{\text{T}}$ total operational and maintenance costs of energy production technologies, \$
P input energy carrier, kWh
Tr energy flowing out of a particular energy hub to all energy hubs, kWh
*z*₁ total economic cost incurred during the lifetime of a project, \$
*z*₂ total amount of carbon dioxide emitted during the lifetime of a project, gCO_2

■ INTEGER VARIABLES

- N_{PV} number of Suntech STP 300-24/Ve polycrystalline silicon photovoltaic modules
- N_{SCA} number of ASTRO Abengoa Solar collector assemblies with Flabeg RP3 mirrors
- N_{WTA} number of Honeywell WT6500 small wind turbines

■ BINARY VARIABLES

- γ indicates whether a particular energy production technology is being used (1), or otherwise (0)

■ REFERENCES

- (1) Alanne, K.; Saari, A. Distributed energy generation and sustainable development. *Renewable Sustainable Energy Rev.* **2006**, *10*, 539–558.
- (2) Anderson, R.; Anderson, R. C. Southern Ships in the Middle Ages. In *A Short History of the Sailing Ship*, 1st ed.; Dover Publications Inc.: Mineola, 2003; pp 98–115.
- (3) Taqvi, S. T.; Maroufmashat, A.; Fowler, M.; Elkamel, A.; Khavas, S. S. Optimal Design, Operation, and Planning of Distributed Energy Systems Through the Multi-Energy Hub Network Approach. In *Operation, Planning, and Analysis of Energy Storage Systems in Smart Energy Hubs*; 1st ed.; Mohammadi-Ivatloo, B.; Jabari, F., Eds.; Springer Cham: New York, 2018; pp 365–389.
- (4) International Energy Agency Data and Statistics. <https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy%20supply&indicator=TPESbySource> (accessed Dec 21, 2020).
- (5) Absi-Halabi, M. A.; Al-Qattan, A.; Al-Otaibi, A. Application of solar energy in the oil industry—Current status and future prospects. *Renewable Sustainable Energy Rev.* **2015**, *43*, 296–314.
- (6) Taqvi, S. T.; Alkatheri, M.; Elkamel, A.; Almansoori, A. Generic modeling framework of Multi-Energy Systems (MES) within the Upstream Oil Supply Chain (USOSC) network. *Comput. Chem. Eng.* **2019**, No. 106523.
- (7) Martin, N. J.; Rince, J. L. Developing renewable energy supply in Queensland, Australia: A study of the barriers, targets, policies and actions. *Renewable Energy* **2012**, *44*, 119–127.
- (8) Lazard. *Lazard's Levelized Cost of Energy Analysis*; Lazard: New York, NY, 2014. https://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf (accessed July 07, 2021).
- (9) Perera, P.; Hewage, K.; Alam, M. S.; Merida, W.; Sadiq, R. Scenario-based economic and environmental analysis of clean energy incentives for households in Canada: Multi criteria decision making approach. *J. Cleaner Prod.* **2018**, 170–186.
- (10) Wee, H. -M.; Yang, W. -H.; Chou, C. -W.; Padilan, M. V. Renewable energy supply chains, performance, application barriers, and strategies for further development. *Renewable Sustainable Energy Rev.* **2012**, *16*, 5451–5465.
- (11) Pepermans, G.; Driesen, J.; Haeseldonckx, D.; Belmans, R.; D'haeseleer, W. Distributed generation: definition, benefits and issues. *Energy Policy* **2005**, *33*, 787–798.
- (12) Kumar, M. Social, Economic, and Environmental Impacts of Renewable Energy Resources. In *Wind Solar Hybrid Renewable Energy System*, 1st ed.; Okedu, K. E., Ed.; IntechOpen: London, 2020; pp 1–11.
- (13) Forsberg, C. W. Sustainability by combining nuclear, fossil, and renewable energy sources. *Prog. Nucl. Energy* **2009**, *51*, 192–200.
- (14) Saavedra, M. M. R.; Fontes, C. H. D. O.; Freires, F. G. M. Sustainable and renewable energy supply chain: A system dynamics overview. *Renewable Sustainable Energy Rev.* **2018**, *82*, 247–259.
- (15) Szklo, A.; Schaeffer, R. Alternative energy sources or integrated alternative energy systems? Oil as a modern lance of Peleus for the energy transition. *Energy* **2006**, *31*, 2513–2522.
- (16) Alnifro, M.; Taqvi, S. T.; Ahmad, M. S.; Bensaida, K.; Elkamel, A. In *Optimal Renewable Energy Integration into Refinery with CO2 Emissions Consideration: An Economic Feasibility Study*, 2nd Interna-

tional Conference on Green Energy Technology (ICGET), Rome, 2017.

(17) Dhaheri, N. A.; Diabat, A. In *A Mathematical Programming Approach to Reducing Carbon Dioxide Emissions in the Petroleum Refining Industry*, Second International Conference on Engineering System Management and Applications, Sharjah, 2010.

(18) Philibert, C. *Renewable Energy for Industry: From Green Energy to Green Materials and Fuels*; International Energy Agency: Paris, 2017. https://iea.blob.core.windows.net/assets/48356f8e-77a7-49b8-87de-87326a862a9a/Insights_series_2017_Renewable_Energy_for_Industry.pdf (accessed July 07, 2021).

(19) Wang, J.; O'Donnell, J.; Brandt, A. R. Potential solar energy use in the global petroleum sector. *Energy* **2017**, *118*, 884–892.

(20) Alhajri, I.; Elkamel, A.; Albahri, T.; Douglas, P. L. A nonlinear programming model for refinery planning and optimisation with rigorous process models and product quality specifications. *Int. J. Oil, Gas Coal Technol.* **2008**, *1*, 283–307.

(21) Alhajri, I.; Saif, Y.; Elkamel, A.; Almansoori, A. Overall Integration of the Management of H₂ and CO₂ within the Refinery Planning Using Rigorous Process Models. *Chem. Eng. Commun.* **2013**, *200*, 139–161.

(22) Joly, M.; Moro, L. F. L.; Pinto, J. Planning and Scheduling for Petroleum Refineries Using Mathematical Programming. *Braz. J. Chem. Eng.* **2002**, 207–228.

(23) Lababidi, H. M.; Kotob, S.; Yousuf, B. Refinery advanced process control planning system. *Comput. Chem. Eng.* **2002**, *26*, 1303–1319.

(24) OPEC's Annual Statistical Bulletin. <https://asb.opec.org/> (accessed July 07, 2021).

(25) Al-Salem, S. Carbon dioxide (CO₂) emission sources in Kuwait from the downstream industry: Critical analysis with a current and futuristic view. *Energy* **2015**, *81*, 575–587.

(26) Kuwait Energy Outlook. https://www.undp.org/content/dam/rbas/doc/Energy%20and%20Environment/KEO_report_English.pdf (accessed July 01, 2020).

(27) Ramadhan, M.; Hussain, A. Kuwait Energy Profile for Electrical Power Generation. *Strategic Plann. Energy Environ.* **2012**, *32*, 18–25.

(28) Altaneeb, S. In *Development of Renewable Energy in Kuwait*, SPE Kuwait Oil & Gas Show and Conference, Mishref, 2019.

(29) International Energy Agency. *World Energy Balances: Database Documentation*; IEA: Paris, 2020. http://wds.iea.org/wds/pdf/WORLDBAL_Documentation.pdf (accessed July 07, 2021).

(30) Mancarella, P. In *Smart Multi-Energy Grids: Concepts, Benefits and Challenges*, IEEE Power and Energy Society General Meeting, San Diego, 2012.

(31) Maroufmashat, A.; Taqvi, S. T.; Miragha, A.; Fowler, M.; Elkamel, A. Modeling and Optimization of Energy Hubs: A Comprehensive Review. *Inventions* **2019**, *4*, No. 50.

(32) Adamek, F.; Arnold, M.; Andersson, G. On decisive storage parameters for minimizing energy supply costs in multicarrier energy systems. *IEEE Trans. Sustainable Energy* **2014**, *5*, 102–109.

(33) Hemmes, K.; Zachariah-Wolf, J. L.; Geidl, J. L.; Andersson, G. Towards multi-source multi-product energy systems. *Int. J. Hydrogen Energy* **2007**, *32*, 1332–1338.

(34) Geidl, M.; Andersson, G. Optimal Power Flow of Multiple Energy Carriers. *IEEE Trans. Power Syst.* **2007**, *22*, 145–155.

(35) Ouyang, X.; Lin, B. Levelized cost of electricity (LCOE) of renewable energies and required subsidies in China. *Energy Policy* **2014**, *70*, 64–73.

(36) Parrado, C.; Girard, A.; Simon, F.; Fuentealba, E. 2050 LCOE (Levelized Cost of Energy) projection for a hybrid PV (photovoltaic)-CSP (concentrated solar power) plant in the Atacama Desert. *Energy* **2016**, *94*, 422–430.

(37) Nassar, Y. F.; Abdunnabi, M. J.; Sbeta, M. N.; Hafez, A. A.; Amer, K. A.; Ahmed, A. Y.; Belgasim, B. Dynamic analysis and sizing optimization of a pumped hydroelectric storage-integrated hybrid PV/Wind system: A case study. *Energy Convers. Manage.* **2021**, No. 113744.

(38) dos Reis, M. M. L.; Mazetto, B. M.; da Silva, E. C. M. Economic analysis for implantation of an offshore wind farm in the Brazilian coast. *Sustainable Energy Technol. Assess.* **2021**, No. 100955.

(39) Sharif, A.; Almansoori, A.; Fowler, M.; Elkamel, A.; Alrafea, K. Design of an energy hub based on natural gas and renewable energy sources. *Int. J. Energy Res.* **2014**, *38*, 363–373.

(40) Wizelius, T. *Developing Wind Power Projects: Theory and Practice*; Earthscan, 2007.

(41) Kuwait Weather History Webpage. <https://www.wunderground.com/history/daily/kw/airport/OKBK/date/2019-1-14> (accessed July 07, 2021).