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Optimal Energy System for Repowering Yemen's Cities

Mohammed Abdulrahman Saleh Almurisi[a], Jeng Shiun Lim[b,*]

[a]School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia.
[b]Process Systems Engineering Centre (PROSPECT), Research Institute for Sustainable Environment, Universiti Teknologi Malaysia (UTM), 81310 UTM Johor Bahru, Johor, Malaysia.
jslim@utm.my

As a result of the ongoing conflict in Yemen, the country's energy infrastructure and supply deficiency has worsened dramatically from its pre-existing poor levels, creating significant consequences for the population's essential needs. Recent estimates revealed that approximately 90 % of the people in Yemen had lost access to public power by 2020 leaving most of the country's population in complete darkness. This study aims to design a cost-effective, and reliable energy supply system to repower Taiz city, in which the considered technologies are photovoltaic (PV), wind turbine (WT), diesel generator (DG), open cycle gas turbine (OCGT), battery (Bat), and converter. The developed energy system planning model was built in Microsoft Excel and employed to simulate and optimize four different energy system configurations. The resulting least-cost energy system comprises a 131.51 MW wind system, a 152.13 MW photovoltaic system, a 16.92 MW diesel generator, and 66,321 batteries (16,580 strings) with an associated levelized cost of energy (LCOE) of USD 0.166/kWh achieving 90 % carbon dioxide equivalent emissions (CO_2-eq) reduction, and 40 % LCOE reduction compared to the conventional power system.

1. Introduction

The ongoing Yemen crisis has imposed severe consequences on the country's energy sector; power supply lines have been affected across the country, causing 8 % of the public grid to be permanently destroyed while 55 % of public power utilities have faced damages that rendered them unusable, leaving most cities in complete darkness (World Bank Group, 2020). The total installed capacity in Yemen is 1.67 GW, barely meeting 40 % of power demand at approximately 200 kWh/capita/y making Yemen's energy production the lowest in the Arabian Peninsula (Ansari et al., 2019). Access to the public energy sector dropped from 60 % in 2014 to 10 % by the end of 2017 (World Bank Group, 2020). Because of the energy system's existing issues in Yemen, various researchers have examined the viability of renewable energy systems, identified barriers, developed solutions, and performed an analysis of data. These studies have limitations, including lacking consideration of different energy system configurations and a lack of analysis of a broad range of relevant parameters (Mubaarak et al., 2020).

The ongoing efforts for a cost-effective reconstruction of the country's energy infrastructure to restore electricity services in Yemen require rebuilding and updating the power sector better and smarter and encouraging low-carbon growth of the country's power grid. Fossil fuels have been a key generator of electricity in Yemen accounting for 99.91 % of electricity despite the country's high renewable energy potential (Mubaarak et al., 2020). The Yemen crisis is a chance to transition away from fossil fuels; renewable energy technologies offer a short-term solution for power generation, particularly in areas where the power supply system has been destroyed, or connection to the grid is infeasible (Ahmad et al., 2019). Renewable energy technologies advancement and rapid decrease in cost made them more appealing to investors because they are less susceptible to attacks on fuel supplies and networks compared to conventional systems, which require a continuous supply of fuel (Sufian, 2019). Yemen's geographical location on the global sunbelt makes renewable energies abundant, according to Qasem (2018), Yemen averages at 9 - 11 h/d of sunshine with an average 5.2 - 6.8 kW/m^2/d of solar radiation and has an estimated 4.1 h/d of full-load wind due to its long coastline and high altitudes.

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In this case study, the city of Taiz alone could produce 1.8 GW of power and the average annual wind speed is 6.9 m/s. The purpose of this study is to propose a repowering solution in the city of Taiz and evaluate the techno-economic feasibility of renewable energy, setting a precedent for the entire country.

2. Methodology

In this study the energy system planning started with a resource potential evaluation for a specific area, followed by technology evaluation and selection, and energy system simulation and optimization. This study adopted a framework of three phases for planning an energy system, shown in Figure 1.

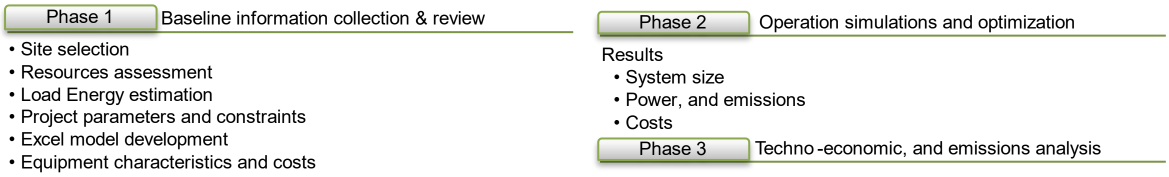

Figure 1: Block diagram of the research methodology

2.1 Background of the studied area

The proposed site is in Al Mocha town, Taiz on the Red Sea and is approximately 300 km^2 in area with a typical annual temperature of 30 °C. The average annual rainfall is 26.7 mm, with most of the rain falling in the winter and spring. There are no coastal fogs in the region, despite the high humidity (Al-Barashi et al., 2015). Taiz is the top third densest city in Yemen with a population of 3.4 million and it served as a key centre for industrial and commercial growth prior to the 2015 conflict. The city was a source of various economic staples such as food processing, packing, cementing, among others (UN Habitat, 2020).

2.2 Meteorological data

The study considered hourly metrological data over a typical year at the proposed location, which include solar radiation, wind speed, and temperature, obtained from NASA's database. The average yearly solar radiation recorded on NASA's database was 6.15 kWh/m^2/d. The annual average ambient temperature was determined to be 28.65 °C, which is in the range at which solar panels perform at their peak efficiency. The yearly average wind speed was determined to be 6.9 m/s. NASA's database of wind speed shows significant potential in all months which were all greater than the yearly average except June and September. The greatest value is 8.47 m/s in January, while the lowest value was 4.47 m/s in September (Sparks, 2018).

2.3 Load demand estimation

The average load of Taiz city is estimated to be 172 MW and its annual average electricity consumption is estimated to be 4,131 MWh with an hourly peak of 510 MW (Hadwan, interviewed by author, 2021). In this study, an hourly data interval is considered. To generate a realistic hourly load profile in kWh/h over a year, the load random variability was set to 20 % day-to-day and 15 % hour-to-hour. Figure 2 provides an example of the synthesized hourly demand for a typical day.

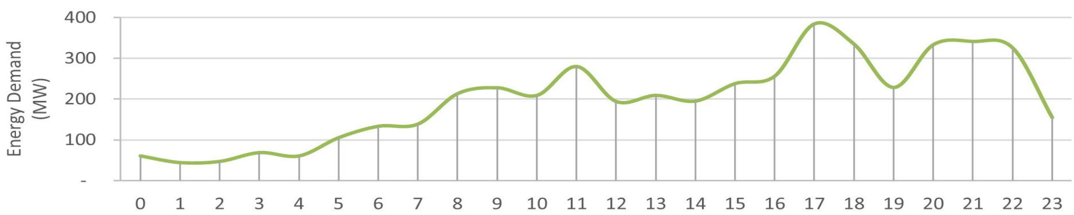

Figure 2: An example of the synthesized hourly demand profile for a typical day

2.4 Energy systems simulation and optimization

This study examines two simulation scenarios with four different configurations, summarized in Table 1, to find the best energy system configuration for Taiz with the lowest investment cost to meet an average demand of 172 MW with an hourly peak equal to 510 MW. In this work, the following scenarios are evaluated and compared:

- Conventional energy system; in this scenario, a list of commercially available gensets was evaluated to minimize the total cost of the system and emissions generated.

- Hybrid energy system; in this scenario, a list of commercially available technologies was evaluated to implement renewable energy infrastructure in the city of Taiz and minimize the total cost of the systems.

In the first phase, a Microsoft Excel-based model was developed and in the second phase, the excel model was used to execute the energy systems simulation and optimization where the considered technologies are PV systems, wind turbines, battery storage, converter/inverter, diesel generators and open-cycle gas turbines. The model inputs that are introduced by the user are hourly load and meteorological (solar radiation, surrounding temperature, and wind speed) data for the studied location, project parameters and constraints, and the technical and economical specifications of energy technologies being considered for implementation. The model output for each energy configuration includes the type of technology and number of components, the system's costs, energy production, and emissions generated. A detailed model description, insight about the key equation used in developing the excel model, and the technical and economical inputs for each component can be viewed in Almurisi (2022).

Table 1: Summary of the simulated scenarios, and energy system configurations and technologies

Scenario	Configuration	Diesel generators (DG)	Open-cycle Gas turbines (OCGT)	Solar photovoltaic (PV)	Wind turbine (WT)	Battery bank (Bat)
Conventional system	Case I	✓				
	Case II		✓			
Hybrid system	Case III			✓	✓	✓
	Case IV	✓		✓	✓	✓

The system cost calculations included capital, installation, replacement, operation and maintenance, fuel, land and salvage costs. For this purpose, the economic settings used were relative to Yemen's economic status, the interest rate was set to 14 %, the diesel fuel price was set to 1.38 USD/L, the natural gas price was set to 12.5 USD/MMBtu, and the project lifetime was 20 y, for all scenarios. The lifetime of each of the systems' components is as follows, Wind turbine (20 y), PV panel (25 y), diesel generator (10 y), open cycle gas turbine (30 y), battery (5 y), and converter (20 y). Within these two decades, only batteries, and diesel generators are replaced. The batteries are replaced three times in the 5th, 10th, and 15th year, while the diesel generators are replaced once in the tenth year.

Excel Solver was then used for the systems operation and capacity optimization, to determine the cost-effective number and type of components. The objective function used is to minimize the system total cost subject to the following constraints; the technology's type and capacity limitation, reliability, minimum renewable energy fraction, and land limitation. The final model of the optimization problem is presented in Eq(1) and Eq(2).

$$\text{Objective function} = \text{Minimize TAC} = \sum_{i \in \{PV,WT,Bat,DG,OCGT\}} (\text{TAC}_i) \tag{1}$$

$$\textbf{s.t.} \begin{cases} \mathbf{N_i} = \text{Integer}, i \in \{PV, WT, Bat, DG, OCGT\} & \text{variable constraints} \\ 0 \leq N_i \leq N_{i-Max}, i \in \{PV, WT, Bat, DG, OCGT\} & \text{bound constraints} \\ \text{LPSP} \leq \text{LPSP}^* & \text{Reliability constraint} \\ \text{REF} \geq \text{REF}^* \min & \text{renewable energy fraction constraints} \\ \sum_i N_i \times A_i \leq A^* \max & \text{land constraints} \\ \sum_i x_i \geq 1 & \text{binary constraints} \end{cases} \tag{2}$$

where i ∈ I equipment, TAC is the system's annualized cost (USD/y), N_i is the total number of equipment i (unit), LPSP represents the loss of power supply probability (%), REF is renewable energy fraction (%), A_i is the area of land required by equipment i (m^2), and X_i represents the existence of a given type of equipment.

2.5 System performance assessment

In the third phase, this study analysed the four simulated system feasibility based on technical, economic, and environmental standpoints. In the technical analysis, the power output and reliability of each system are investigated and presented in terms of loss of power supply probability as indicated in Eq(3).

$$\text{LPSP} = 1 - \frac{\sum_{t=1}^{T} \text{LPS}_t}{\sum_{t=1}^{T} E_{d,t}} \ (\%) \tag{3}$$

where i ∈ T time, LPSP is the loss of power supply probability (%), $E_{d,t}$ is the electricity demand at time t (kWh), and $LPSP_t$ is the loss of power supply at time t (kWh).

The systems' economic feasibility was evaluated based on the levelized cost of energy (LCOE) and the net present cost (NPC) indicators. The NPC is the present value of the system costs through its lifecycle as denoted in Eq(4).

$$\mathrm{NPC} = \frac{\mathrm{TAC}}{\mathrm{CRF(r,n)}}\ (\mathrm{USD}) \quad (4)$$

where TAC is the system's annualized cost (USD/y) and CRF(r,n) is the capital recovery factor as denoted in Eq(5).

$$\mathrm{CRF(r,n)} = \frac{\mathrm{r(1+r)^n}}{\mathrm{(1+r)^n - 1}} \quad (5)$$

where n is the project lifetime (y), and r is the yearly real interest rate (%) which can be calculated using Eq(6).

$$\mathrm{r} = \frac{\mathrm{r_{nominal} - f}}{\mathrm{1+f}} \quad (6)$$

where $r_{nominal}$ stands for the nominal interest rate and f stands for the annual inflation rate.
The LCOE calculates the unit costs of energy over the project's entirety and is used extensively to assess the project's viability and competitiveness in comparison to alternative technologies. LCOE is determined by dividing the system's lifecycle costs by the system's lifetime energy generation as denoted in Eq(7).

$$\mathrm{LCOE} = \frac{\mathrm{TAC}}{\mathrm{E_{served}}} = -\frac{\sum_i(\mathrm{TIC_i + TOC_i - Salvage})}{\sum_{t=1}^{T} \mathrm{D_{m,t}} - \sum_{t=1}^{T} \mathrm{LPS_t}}\ (\mathrm{USD/kW}) \quad (7)$$

where E_{served} represents the useful power served by the system (kW), TIC_i represents the total investment cost as indicated in Eq(8), TOC_i refers to the total operating costs as indicated in Eq(9), and $Salvage_i$ is the worth value of component i at end of project lifetime as indicated in Eq(10).

$$\sum_i \mathrm{TIC_i} = \mathrm{CRF(r,n)} \times (\mathrm{CC_i + IC_i + LC_i + RC_i})\ (\mathrm{USD/y}) \quad (8)$$

where CC_i, IC_i, LC_i, RC_i are, the capital, installation, land, and replacement cost of the component i (USD).

$$\sum_i \mathrm{TOC_i} = \mathrm{O\&MC_i} . \sum_{t=1}^{8760} \mathrm{E_i(t)} + \mathrm{FC_i}\ (\mathrm{USD/y}) \quad (9)$$

where $O\&MC_i$ refers to the operating and maintenance costs (USD), $E_i(t)$ represents the technology's energy production at time t (kWh), and FC_i refers to the fuel costs (USD/y) which can be calculated using Eq(11).

$$\mathrm{Salvage_i} = \mathrm{CC_i} \times \frac{\mathrm{L_r - n}}{\mathrm{L_i}}\ (\mathrm{USD}) \quad (10)$$

where CC_i is capital cost, L_r is remaining life (y) and L_i is lifetime (y) of the component i.

$$\sum_i \mathrm{FC_i} = \mathrm{F_{price\_i}} \times \sum_{t=1}^{8760} \mathrm{F_i(t)}\ (\mathrm{USD/y}) \quad (11)$$

where F_{price_i} refers to fuel price and $F_i(t)$ stands for technology's fuel consumption at time t.
For the environmental impact, the carbon dioxide equivalent emissions (CO_2-eq) is used to highlight the environmental friendliness of the system which can be estimated using Eq(12).

$$\mathrm{CO_2\text{-}eq_{fuel}}\ (\mathrm{t}) = \mathrm{F_i(t)} \times \left(\mathcal{F}_{\mathrm{CO_2}} + \mathcal{F}_{\mathrm{CH_2}} \times 25 + \mathcal{F}_{\mathrm{N_2O}} \times 298\right)\ \ (\mathrm{kg\ CO_{2-eq}}) \quad (12)$$

where CO_2-eq_{fuel}(t) is the CO_2-eq emissions generated by a given fuel (kg CO_2-eq), $F_i(t)$ is amount of fuel combusted per type of technology (GJ), $\mathcal{F}_{CO_2}$, $\mathcal{F}_{CH_2}$, $\mathcal{F}_{N_2O}$ are default emission factors of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) for a given fuel (kg/GJ).

3. Results and discussion

Two simulation scenarios with four different configurations were evaluated to determine the most economical solution to meet an average demand of 172 MW with an hourly peak equal to 510 MW. Table 2 illustrates the technical and economic results of the four simulation cases. Assessing the renewable energy participation perspective from Table 2, Cases I and II are 100 % fossil-fuel-based systems. Case III and Case IV systems are 100 % and 94.37 % renewable-based energy systems. From an environmental perspective, the PV/WT (Case III) system has the lowest carbon dioxide equivalent emissions. The PV/WT/DG (Case IV) follows, then the natural gas-based (Case II) system, and finally, the diesel-based (Case I) system is ranked last.
Taking the economic perspective, the LCOE and NPC were used in the assessment of the four energy configurations. It can be noted in Table 2 that LCOE and NPC of the PV/WT/DG system in Case IV are the lowest cost. Case II is a runner-up, but this kind of system includes significant costs caused by the gas turbines and the use of natural gas. The third system is shown in Case III; this requires a 100 % renewable-based

energy system which is more costly at the beginning of the investment. Finally, Case I has the highest cost resulting from fuel and maintenance costs.

Diesel generators and gas turbines in Cases I and II are more reliable and affordable to install and but they can be costly to operate. In Taiz, the cost of energy fluctuates in accordance with the price of fuel which can mean an incapability in meeting electricity needs. The energy systems with renewable energy, Case III and Case IV, implement solar and wind energy. They are sourced at no cost and are environmentally friendly through their reduction of pollution. The disadvantages of renewable-based systems are that they are generally unreliable for meeting full-day electricity demand due to the intermittent nature of renewable resources and have high initial investment costs which result in a higher levelized cost of energy. The energy system in Case III needs to add extra capacities in terms of PV or wind turbines and batteries to balance the intermittent nature of renewable resources resulting in an increase in the system cost. Case III's energy system is not preferable because it shows comparatively low technical performance and has higher LCOE.

Table 2: Simulation and optimization results of the four simulated cases

Case	DE (I)	GT (II)	PV + WT (III)	PV + WT + DE (IV)
Power generation (%)	DE (100 %)	OCGT (100 %)	19.8 % WT+ 80.2 % PV	49 % PV + 43 % WT + 5 % DE
CO_2-eq (M kg/y)	1,085	281	-	106
LPSP (%)	0	0	1.97	1.15
Renewable fraction (%)	-	-	100.00	94.37
NPC (M USD)	1,720	1,107	1,206	1,021
LCOE (USD/kWh)	0.277	0.178	0.197	0.166
NPC and LCOE savings compared to case I (%)	-	35.6	28.4	39.9
CO_2-eq savings compared to case I (%)	-	74	100	90

Case IV's energy system has the lowest LCOE and demonstrates better technical performance compared to the energy system in Case III because the DG backup system can provide power at times when renewable energy is insufficient, with a cost that is usually considered as marginal and that consumes very little fuel since it runs few hours per year. The emission reduction potential in Table 2 shows the PV/WT/DG energy system in Case IV would lead to a saving of 978,652,301 kg CO2-eq/y in comparison to the diesel-based system in Case I and 174,656,516 kg CO2-eq/y in comparison to the gas-based system in Case II. This configuration guarantees that the 20-year-round total system cost is minimized while the load demand is fully covered with an acceptable reliability of supply, share of renewables and low level of emissions. Case IV's energy system meets all the criteria and can be considered as an efficient repowering solution to meet the city's electricity demand. Table 3 shows Case IV's system capacity and annual energy production.

Table 3: Detailed results of Case IV

System	Manufacturer and Model	Number of Units	Rated Power (kW)	Energy Production (MWh/y)	Capacity factor (%)
PV Array	SunPower SPR-X21-460-COM	81,545	0.46	1,336,311	49
Wind Turbine	Enercon E92/2350	153	2,300	1,155,183	43
Diesel Generator	CAT-3516E-3500kVA-50Hz	55	2,800	148,668	5
Battery	Surrette Rolls 6 CS 25P	66,321	6.9	-	3
Converter	-	-	535,152	-	-

Based on the load demands, all or part of the generated electricity is sent to meet the site's load at each time step while the excess electricity is efficiently stored in the batteries or sent to a dump load. From Figure 3a, it can be seen that August is the most diesel-saving month. The participation of the renewable energy systems was significant in meeting the load demand in July and August. This indicates that renewable systems are a critical component in meeting electricity demands in Taiz which can resolve electrification challenges in Yemen as a whole. Figure 3b gives an overview of the cost structure of the energy system in Case IV. The recent renewable energy technologies advancement and rapid decrease in cost which is expected to continue in the near future would make them more competitive and offer much lower fossil fuel dependency for a comparable cost.

The techno-economic and emissions analysis shows that Case IV's system (PV/WT/DG) is the most cost-effective, reliable, and environmentally friendly, and the study supports it for Taiz's investment.

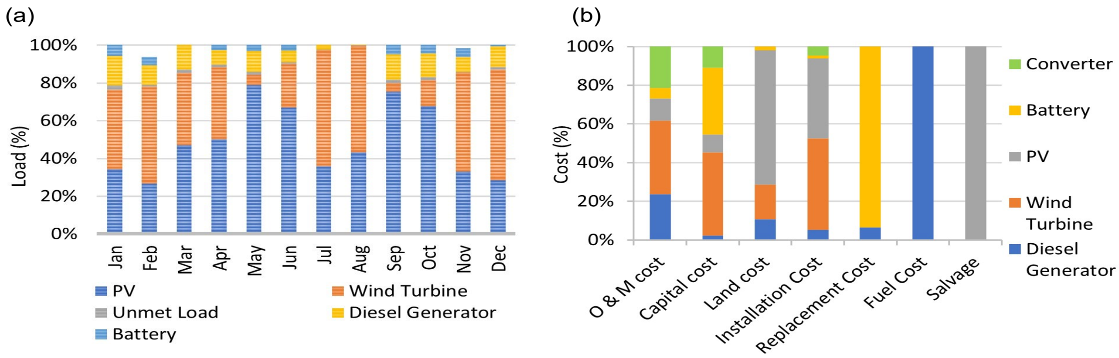

Figure 3: Illustration of Case IV's (a) monthly participation of the energy systems in meeting the load demand, and (b) components costs percentage to the total system cost

4. Conclusions

In this study, four cases of energy systems to repower Taiz were evaluated. The simulation-based optimized results found that under the defined constraints, a combination of a 131.51 MW wind system, a 152.13 MW solar system, a 16.92 MW for diesel generator, and 66,321 batteries (16,580 strings) is an economically feasible, reliable, and environmentally friendly solution to immediately restore electricity services to various user categories in the city of Taiz. This system would supply 94 % of the city's electricity demand through renewable energy at USD 0.166/kWh energy cost and achieve a 90 % CO_2-eq emission reduction when compared to the country's conventional energy system in Case I. The findings indicate that Yemen has high renewable energy potential, especially through the solar and wind resources, providing a solution to the issue of insufficient energy supply and providing a promising alternative to electricity generation fulfilling the Yemeni government's commitment to the Paris Climate Accords and the Kyoto Protocol to reduce the onset of global warming.

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