* + 1. Key assumptions used throughout the study

2.4.1 Project parameters

The economic settings used were relative to the economic status of Yemen, the nominal interest rate was set to 27 %, the inflation rate to 13 %, the resulting real interest rate is 14 % [1]. The project lifetime was considered as 20 years for all scenarios. The lifetime of each system components is assumed as follow, Wind turbine (20 y), PV panel (25 y), diesel generator (10 y), open cycle gas turbine (OCGT) (30 y), battery (5 y), and converter (20 y). Hence, during the lifetime of the system, only batteries, and diesel generator 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.

2.4.1 System costs estimation

The considered economic parameters associated to system cost calculations included capital, installation, replacement, operation and maintenance (O&M), fuel, land, and salvage costs. A summary of the cost assumptions used for the economical calculation of the energy system components is illustrated in Table 1.

Table 1: Summary of the cost parameters used for the economical calculation of the system components. [2]

|  |  |  |
| --- | --- | --- |
| Parameter |  |  |
| Capital cost | USD | Depending on the type of energy system |
| Installation and related services | % | Depending on the type of energy system |
| Operating and maintenance costs | USD | Depending on the type of energy system |
| Natural gas price | USD/MMBtu | 12.5 |
| Diesel fuel price | USD/L | 1.38 |
| Replacement cost | USD | Depending on the type of energy system |
| Land cost | USD/m2 | 40 |
| Shipment and logistics costs | % | 15 % of system cost |
| Regional variations | % | 20 % of system cost |

2.4.2 Project Constraints

The simulation constraints for each simulation scenario are illustrated in Table 2.

Table 2: Summary of project constraints.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter |  |  | Constraints |
| Land constraints |  |  | Available land area was set to 300 km2 |
|  |  |  |  |
| Reliability constraint | Conventional  energy system | Case I: diesel generators  Case I: open-cycle gas turbines | Fully meet the load demand of 172 MW of electricity annually |
|  | Hybrid system | Case III: fully renewable energy system  (PV, wind turbines turbine and battery)  Case IV: hybrid energy system (PV,  wind turbine, battery, and diesel genset) | Allowed yearly capacity shortage is set to 2% |
| Renewable energy fraction constraint |  |  | Renewable energy fraction was set at 100% (Case III) and 75% (Case IV) |

* + 1. Excel-based model development

In the first phase, a Microsoft Excel-based model was developed, for more information see section 2.6 System sizing and design. In the second phase, the excel model was used to execute the energy systems simulation and optimization, w here the considered technologies are PV systems, wind turbines, battery storage, converter/inverter, diesel generators and open-cycle gas turbines. The model input that are introduced by the user are illustrated in Table 3. The model outputs are illustrated in Table 4.

Table 3: Input of the Excel model

|  |  |
| --- | --- |
| Input data | Description |
| General project factors | Financial parameter, project lifetime, and project constraints |
| Electricity demand | Hourly electricity demand over a year |
| Meteorological data | Hourly global solar radiation, ambient temperature, and wind speed over a typical year, obtained from NASA’s database |
| Technical details | Technical specifications of all energy technologies considered |
| System costing | Economical specifications of the system components |

Table 4: Output of the Excel model

|  |  |
| --- | --- |
| Input data | Description |
| All energy configuration | Type of technology |
| Number of components |
| System components costs, net present cost (NPC), and levelized cost of energy (LCOE) |
| Energy production, excess electricity, unmet load (hourly and yearly) and excess energy |
| Fuel consumption and costs |
| Land area required |
| Renewable Fraction |
| Carbon dioxide equivalent emissions (CO2-eq) |
| The least-cost system | Levelized cost of energy (LCOE) and Net present cost (NPC) |
| LCOE and NPC reduction compared to the conventional power systems |
| Reduction of fuel consumption compared to the conventional power systems |
| CO2-eq reduction compared to the conventional power systems |

* + 1. System sizing and design

Here is a summary of the key assumption and equation used for sizing and designing the energy systems.

2.6.1 Photovoltaic Arrays

Solar photovoltaic (PV) system size and performance are highly dependent on weather factors like as solar radiation and surrounding temperature. All PV panels are assumed to operate at its Maximum Performance for all solar irradiance ambient temperatures at 10° tilt angle. The power generated variability resulted from their relative spacing is considered negligible. The Surface area required by each solar panel is calculated using the PV modules dimensions as shown in Figure 3. Table 6 and 7 show the technical economical parameters specifications of PV technologies considered. The maximum output power from the PV panel at any irradiance and cell temperature is given by following equation shown in Table 5.

Table 5: Summary of the equation used for sizing of the PV system.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | Parameters | Key equation |  |
|  |  | PV Maximum output power output, |  | (1) |
|  |  | PV module's temperature, |  | (2) |
|  |  | PV system's energy generated, |  | (3) |
|  |  | Surface area required by each solar panel, m2 |  | (4) |

where is solar irradiation (W/m2), is rated power of the PV module under standard testing conditions, (1000 W/m2), and (25 °C) are the standard test conditions for solar radiation, and ambient temperature. γ is the temperature coefficient of the PV module (%/°C), and is the efficiency of converter (%). is the inclination angle of the surface panel. is the nominal operation cell temperature which is measured under 800 (W/m2) of solar radiation, 20 °C of ambient temperature and 1 m/s of wind speed. is the system's net energy and representing the total number of photovoltaic panel of given type.

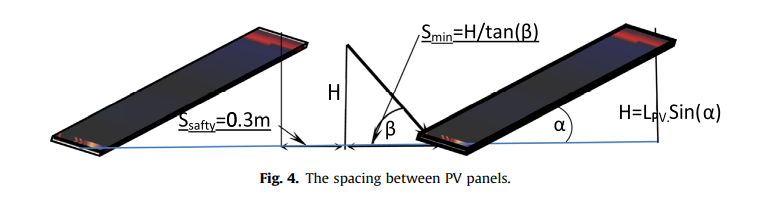


Figure 3: The spacing between PV panels. [3]

Table 6: Cost assumption used for the economical calculation for the PV system.

|  |  |  |
| --- | --- | --- |
| Parameter |  | Cost (2021 USD) [4] |
| Installation and related services |  | 0.19 USD/W |
| Variable operating and maintenance |  | 9.50 USD/kW/y |
| wiring cost |  | 0.13 USD/W |

Table 7: Technical and economical specifications of PV technologies considered.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Manufacturer | Model | Size  (W) | Unit Price  (2021 USD) | Avg. panel  efficiency  (%) | Temperature  coefficient  (%/°C) | Degradation  rate (%) | Dimension  L ˣ W  (m) | Ref. |
| SunPower1,2 | SPR-P6-540-COM | 540 | 146 | 21.1 | - 0.34 | 0.45 | 2.4 × 1.1 | [5],[6] |
| SunPower | SPR-X2-460-COM | 460 | 124 | 21.7 | - 0.29 | 0.25 | 2.1 × 1.1 | [5],[6] |
| Trina Solar | TSM-DEG19C.20 | 660 | 165 | 21.2 | - 0.34 | 0.45 | 2.4 × 1.3 | [7],[8] |
| Trina Solar | TSM-DEG21C.20 | 540 | 135 | 20.7 | - 0.34 | 0.45 | 2.4 × 1.1 | [7],[8] |
| Canadian Solar | CS7L-600MS | 600 | 144 | 21.2 | - 0.34 | 0.55 | 2.2 ˣ 1.3 | [9],[10] |
| Jinko Solar | JKM600N-78HL4 | 600 | 150 | 21.4 | - 0.30 | 0.40 | 2.5 ˣ 1.14 | [11],[10] |
| JA Solar | JAM72S30 | 540 | 135 | 20.9 | - 0.35 | 0.55 | 2.3 ˣ 1.14 | [12],[10] |

2.4.1 Wind Turbine

The main parameters that influence the generated power of a wind turbine are the hub wind speed, wind turbine's rated power, cut-in speed, rated speed, and cut-off speed. All turbines are assumed to operate at its Maximum Performance for all wind speed at a specific hub height, and the power generated variability resulted from their relative spacing is considered negligible. The Weibull shape parameter (k) was set to 2. The Surface area required by each wind turbine is calculated using the turbine dimensions as shown in Figure 4. Table 9 and 10 show the technical economical parameters specifications of the technologies considered. The maximum output power from the wind turbine at any wind speed is given by following equation shown in Table 8.

Table 8: Summary of the equation used for sizing of the wind turbine system.

|  |  |  |
| --- | --- | --- |
| Parameters | Key equation |  |
| Wind turbine maximum power output, kW |  | (5) |
| Wind speed at the hub height, , m/s |  | (6) |
| Wind system's overall energy generated, , kW |  | (7) |
| Installation area required by each set of wind of turbines (3 WT), , m2 |  | (8) |

Where, is the hub wind speed (m/s) at a hub height of H (m), , and refer to cut-in, rated and cut-out wind speed (m/s), and is the wind turbine rated power (kW). refers to wind speed at a 10 m reference height (m/s), is a value between 0.14 and 0.25 due to ground roughness, and is rotor diameter (m). is an optimization variable representing the total number of wind turbines of given type.

Table 9: Cost assumption used for the economical calculation for the wind turbine system.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter |  | Cost (2021 USD) | Reference |
| Installation and related services |  | 12 % of system’s total capital cost | [13] |
| Operating and maintenance |  | 36.00 USD/kW/y | [14] |

5 times the distance of the rotor diameter

Figure 4: The spacing between wind turbines.

Table 10: Technical and economical specifications of wind turbine technologies considered.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Manufacturer,  WT model | Size  (MW) | Price  (2021 USD/MW) | Hub Height  (m) | Rotor Diameter  (m) | Swept Area  (m2) | Cut-In Speed  (m/s) | Rated Speed  (m/s) | Cut-Off Speed  (m/s) | Reference |
| Enercon E92 | 2.35 | 0.92 | 78-138 | 92 | 6,648 | 2 | 13 | 25 | [15], [16] |
| Vestas V90 | 2 | 1.01 | 80-125 | 90 | 6,362 | 4 | 13.5 | 25 | [15], [17] |
| Siemens SWT 2.3 | 6.6 | 0.89 | 68-153 | 93 | 10,207 | 1.5 | 9 | 25 | [15], [18] |
| General Electric 2.75 | 2.75 | 0.976 | 75-123 | 103 | 8,332 | 3 | 13 | 25 | [15], [16] |
| Nordex N100 | 2.5 | 0.84 | 75-100 | 100 | 7,823 | 3 | 12 | 20 | [15], [19] |

2.4.2 Battery Bank

In this study, only the lead acid batteries were considered because their commercial popularity and cost advantages over other storage technologies. The battery bank is configured to be in strings and there are 4 batteries in each string. The initial state of charge was assumed to be 70 % and the battery charge efficiency and discharge efficiency are both assumed 85 %. The battery lifetime is strongly influenced by the Depth of Discharge (DOD), the lowest level a battery hits in each discharging-charging cycle was set to 30%. However, the lifetime assumed for lead-acid batteries to be 10 y. The batteries are assumed to be mounted with (1.3 cm) spacing minimum. The percentage of the battery capacity available per hour is compared to the needed load capacity. If the energy generated by renewable resources at time t exceeds the demand, the excess power is sent to the batteries. If the electricity provided by renewable sources at time t is less than the demand, the battery is discharged and maintains the shortfall demand.

Table 12 and 13 show the technical economical parameters specifications of battery technologies considered. The percentage of the battery capacity available at time t can be estimated using the following equation shown in Table 11.

Table 11: Summary of the equation used for sizing the battery system.

|  |  |  |
| --- | --- | --- |
| Parameters | Key equation |  |
| State of charge of battery bank at any hour t at |  | (9) |
| State of charge of battery bank at any hour t at |  | (10) |
| Battery bank system's overall energy discharged at time t, |  | (11) |
| Battery bank over-discharge constraint |  | (12) |
| Area required by one unit |  | (13) |

where, refers to the state of charge of the battery bank at any hour t (%), refers to the previous state of charge at time t-1 (%), refers to the hourly self-discharge rate. is energy demand at time t (kW), is the efficiency of converter (%), refers to charge efficiency of the battery storage (%), is the total number of batteries, is the nominal capacity of a battery (kWh), and refers to discharge efficiency of the battery storage (%). Where, is the maximum depth of discharge (%).

Table 12: Cost assumption used for the economical calculation for the battery system.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter |  | Cost (2021 USD) | Reference |
| Installation and related services |  | 2 % | [4] |
| Operating and maintenance |  | 5 USD/kWh/year | [20] |
| Replacement |  | 95 % of unit cost | [20] |

Table 13: Technical and economical specifications of battery technologies considered.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Manufacturer | Unit Price  (2021 USD) | Rated Capacity @  20-hour rate (AH) | Energy  (kWh) | Nominal  voltage (V) | Cycles @  50 % DOD | Dimensions  (cm) |  |  |  | Ref. |
| Surrette Rolls 6 CS 25P | 1,124 | 820 | 6.94 | 6 | 0 | 55.9 x 28.6 |  |  |  | [21] |
| Rolls Surrette 6CS 27P | 1,227 | 929 | 7.19 | 6 | 0 | 55.9 x 28.6 |  |  |  | [21] |
| Trojan SIND 06 1225 | 1,152 | 942 | 7.35 | 6 | 0 | 68.9 x 26.5 |  |  |  | [22] |
| Trojan SIND 06 920 | 897 | 708 | 5.52 | 6 | 0 | 56.7 x 26.2 |  |  |  | [22] |

2.4.3 Converter

A power converter is a crucial component of a hybrid energy system for converting direct current (DC) to alternate current (AC) or AC to DC. In our setup, a bi-directional DC-AC converter was selected to convert DC from the PV and batteries to AC and to convert the AC excess electricity generated by wind turbines and diesel generators to DC and stored in a battery, to supply it back when necessary. Table 14 show the economical parameters considered for the converter. The rated power of converter needed, is defined in Eq(14).

|  |  |
| --- | --- |
|  | (14) |

where, The rated power of converter needed (kW), is the energy peak demand (kW), and is the efficiency of converter (%).

Table 14: Cost assumption used for the economical calculation for the converter system.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter |  | Cost (2021 USD) | Reference |
| Capital cost |  | 210 USD/kW | [23] |
| Installation and related services |  | 2 % | [4] |
| Operating and maintenance |  | 6 USD/kW/y | [23] |
| Replacement |  | 190 USD/kW | [23] |

2.4.4 Diesel Generator

The main parameters of the diesel generator are its maximum and minimum electrical power output, its expected lifetime, and its fuel curve, which relates the quantity of fuel consumed to the electrical power produced. A constraint to limit the minimal power output of the DG to 30% of its rated capacity is included to model the minimum operation limit. The generators are assumed to be mounted within a minimum spacing equal to 1.3 times generator’s dimension (L x W). Table 17 and 18 show the technical economical parameters specifications of diesel generator technologies considered. The generated power can be estimated using the following equation shown in Table 15.

Table 15: Summary of the equation used for sizing the diesel genset system.

|  |  |  |
| --- | --- | --- |
| Parameters | Key equation |  |
| The required power from the diesel generator at |  | (15) |
| The loss of power supply, |  | (16) |
| The power generated from the diesel generator, |  | (17) |
| Hourly fuel consumption of the diesel generator, |  | (18) |
| Load ratio constraint |  | (19) |
| Area required by one generator |  | (20) |
| CO2-eq Emission, kg |  | (21) |

where, the required power from the diesel generator (kW), is energy demand at time t (kW), and is the efficiency of converter (%). is the loss of power supply (kW), and is the rated power of the generator (kW). is the power generated from the diesel generator (kW). is the hourly fuel consumption of the generator (L), is the fuel curve slope, and is the fuel curve intercept (L/kW h). is the minimum load ratio (%). , , are emission factors for CO2, CH4, and N2O shown in Table 16.

Table 16: Diesel emission factors for CO2, CH4, and N2O [24]

|  |  |
| --- | --- |
| Parameters, | kg/GJ |
| Emission factor CO2 | 74.1 |
| Emission factor CH4 | 0.003 |
| Emission factor N2O | 0.0006 |

Table 17: Cost assumption used for the economical calculation for the diesel genset system.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter |  | Cost (2021 USD) | Reference |
| Installation and related services |  | 10 % of system’s total capital cost | [25] |
| Operating and maintenance |  | 0.02 USD/kW/y | [25] |
| Replacement |  | 95 % of unit cost | [25] |

Table 18: Technical and economical specifications of diesel genset technologies considered.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Manufacturer | Make model | ISO power rating  (MW) | Unit Price  (2021 USD) | Reference |
| Caterpillar | 3516E – 3500 kVA -50Hz | 2.8 | 580,000 | [26], [27] |
| Caterpillar | C175-16 - 3000 kVA - 50Hz | 2.4 | 471,500 | [26], [27] |
| Caterpillar | 3516B – 2500 kVA - 50Hz | 2 | 325,000 | [28], [29] |
| Cummins | QSK60-G4 – 2250 kVA - 50 Hz | 1.8 | 327,750 | [30], [31] |

2.4.3 Gas Turbine

In this study the open-cycle gas turbines (both the aero-derivative and the large industrial) were included because the ministry of energy Yemen (MOE) planned to utilize more natural gas in future project, and the assumed unit size (MW) is at standard conditions, at 25 °C, 110 m, and 60 % relative humidity. At site conditions, 10 % reduction of OCGT net output was assumed. List of commercially available OCGT is evaluated to determine the least cost technology with high reliability and better efficiency and fewer fuel consumption and emissions to fully meet the load demand to Taiz the load at any time over the project life. The required land area for each of the technology options considered was assumed 20,000 m2. Table 21 and 22 show the technical economical parameters specifications of OCGT technologies considered. Simple calculation is used for sizing of the peaking power plant, to estimate the generated power, fuel consumption, and related costs, as shown in Table 19.

Table 19: Summary of the equation used for sizing the OCGT system.

|  |  |  |
| --- | --- | --- |
| Parameters | Key equation |  |
| The required power from the gas generator at any hour t |  | (22) |
| The loss of power supply, |  | (23) |
| The power generated from the gas generator, |  | (24) |
| Hourly fuel consumption of the gas generator, |  | (25) |
| Load ratio constraint |  | (26) |
| CO2-eq Emission, kg |  | (27) |

where, is energy demand at time t (kW), and is the net power output of the gas turbine (kW). is the hourly fuel consumption of the gas turbine (MMBtu), is the net heat rate of gas turbine (Btu/kWh), is net efficiency of gas turbine, and is the minimum load ratio (%)., , are emission factors for CO2, CH4, and N2O shown in Table 20.

Table 20: Natural gas emission factors for CO2, CH4, and N2O [24]

|  |  |
| --- | --- |
| Parameters, | kg/GJ |
| Emission factor CO2 | 56.1 |
| Emission factor CH4 | 0.006 |
| Emission factor N2O | 0.0001 |

Table 21: Cost assumption used for the economical calculation for the OCGT system.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter |  | Cost (2021 USD) | Reference |
| Installation and related services |  | 30 % of capital cost | [32] |
| Fixed Operating and maintenance |  | 21.25 USD/kW | [14] |
| Variable operating and maintenance |  | 5.25 USD/MWh | [14] |

Table 22: Technical and economical specifications of OCGT technologies considered.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Manufacturer | Make model | Net output  (MW) | Unit Price  (2021 M USD) | Heat rate  (Btu/kWh, LHV) | Net Efficiency  (%, LHV) | Ref. |
| General Electric | GE 9F.05 | 299 | 108.3 | 8,810 | 38.7 | [32], [33] |
| General Electric | LM 6000 PF | 49 | 33.5 | 8,281 | 41.2 | [32], [33] |
| General Electric | LMS100PA | 103 | 45.4 | 7,830 | 43.6 | [32], [33] |
| Siemens | SGT5 2000E | 175 | 50.5 | 9,349 | 36.5 | [34], [35] |
| Siemens | SGT 800 | 54 | 27.2 | 8,916 | 38.3 | [34], [36] |

* + 1. Energy systems simulation and optimization

This study examines two simulation scenarios with 4 different configurations, summarised in Table 23, to find the best energy system configuration with the lowest investment cost to meet an average demand of 172 MW with hourly peak equal to 510 MW to Taiz.

Table 23: Summary of simulation energy system configurations.

|  |  |  |
| --- | --- | --- |
| Scenario | Configuration | Objective |
| Conventional energy system | Case I: diesel generators  Case I: open-cycle gas turbines | With the objective to minimize the total cost of the system and emissions generated, list of commercially available genets is evaluated to determine the cost-effective number and type of units to fully meet the load demand to Taiz. |
| Hybrid system | Case III: fully renewable energy system (solar PV, wind turbines turbine and battery bank) | To bring renewable energy infrastructure to the city of Taiz, the objective is to minimize the total cost of the systems, that satisfy the considered constraints (technology’s type and capacity limitation, system reliability, minimum renewable energy fraction, and land limitation) |
| Case IV: hybrid energy system (solar PV,  wind turbine, battery bank and diesel genset) |

* + 1. Hybrid system dispatch strategy

In this study the load following strategy is followed to effectively manage the energy flow to and from each system and ensure that the hybrid system is reliable to fulfill the energy demand. In load following strategy, at each hour (t) over year, the model checks the energy demand (Ed) and checks if the energy generated by solar PV system (EPV) and wind turbine system (EWT) are enough to meet the demand and utilize the excess energy in charging the batteries. If the solar PV system and wind turbine system cannot supply the required energy demand, the model checks the battery state of charge (SOC) to control the operation of the battery bank and the genset to assist in meeting the energy demand, by discharging the stored energy or running the genset or doing both. The dispatching strategy is illustrated in Figure 5.

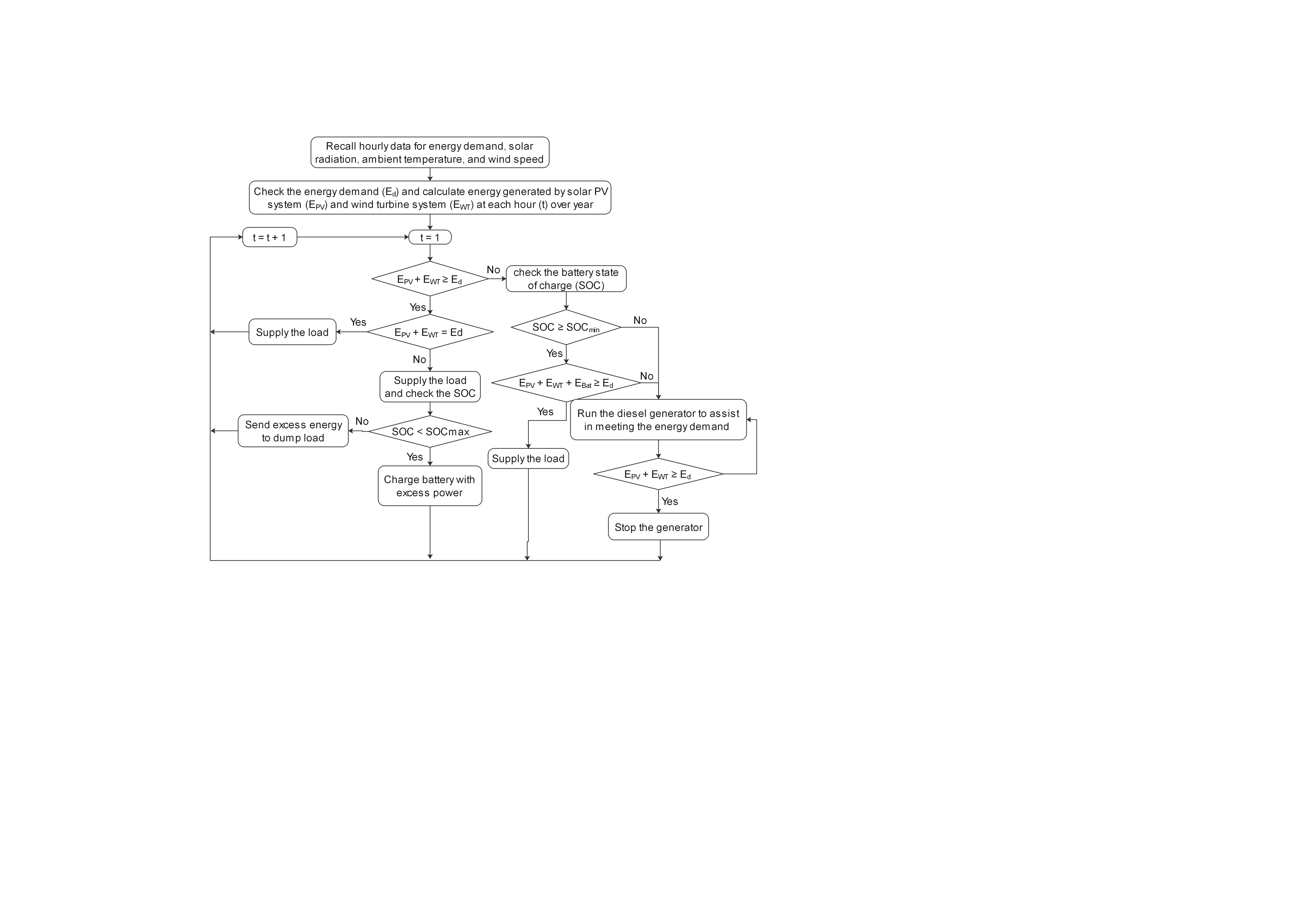


Figure 5: flowchart of the dispatching strategy.

* + 1. System optimization

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(28) and Eq(29).

|  |  |
| --- | --- |
|  | (28) |
|  | (29) |

where equipment, is the system’s annualized cost (USD/y) is the total number of equipment i (unit), represents the loss of power supply probability (%), and is renewable energy fraction (%), is area of land occupied by equipment i (), and represents existence of a given type of equipment.

* + 1. 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 were investigated. The reliability of the energy system is the total unsatisfied load divided by total load demand and is presented in terms of loss of power supply probability (LPSP), as indicated in Eq(30)

|  |  |
| --- | --- |
|  | (30) |

where, is the loss of power supply probability (%), is the electricity demand at time t (kWh), and is the loss of power supply at time t (kWh). In this study, T is equal to 8760 h (1 year).

The economic analysis to evaluate the system's feasibility was mainly based on the levelized cost of energy (LCOE) and the net present cost (NPC) indicators. The present cost (NPC) is the total present value of a cash flow the system cost through its lifecycle, as denoted in Eq(31).

|  |  |
| --- | --- |
|  | (31) |

where is the system’s annualized cost (USD/y), and is the capital recovery factor which can be calculated using Eq(32).

|  |  |
| --- | --- |
|  | (32) |

where *n* describes the project lifetime (y), and r represents the yearly real interest rate (%) which can be calculated using Eq(33).

|  |  |
| --- | --- |
|  | (33) |

where rnominal is the nominal interest rate and f is 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 indicated in Eq(34).

|  |  |
| --- | --- |
|  | (34) |

where, represents the useful power served by the system, represents the total investment cost, as indicated in Eq(35), refers to the total operating costs, as indicated in Eq(36), and is the worth value of component i at end of project lifetime, as indicated in Eq(37).

|  |  |
| --- | --- |
|  | (35) |

where are, the capital cost, installation cost, land cost, and replacement cost of the component i.

|  |  |
| --- | --- |
|  | (36) |

where refers to operating and maintenance cost and represents technology’s energy production at time t (kWh), and refers to the fuel costs which can be calculated using Eq(38).

|  |  |
| --- | --- |
|  | (37) |

where is the capital cost of the component i, , its remaining life, and , is the component i lifetime, and is the project lifetime.

|  |  |
| --- | --- |
|  | (38) |

where refers to fuel price (diesel USD/L, natural gas USD/MMBtu) and represents technology’s fuel consumption at time t.

For the environmental impact, the carbon dioxide equivalent emissions (CO2-eq) used to highlight the environmental friendliness of the system which can be estimated using Eq(39) (IPCC.

|  |  |
| --- | --- |
|  | (39) |

Where CO2-eq,fuel is the carbon dioxide equivalent emissions (CO2-eq) by a given fuel (kg CO2-eq), amount of fuel combusted per type of technology (GJ), , , are default emission factors of CO2, CH4, and N2O by a given fuel (kg/GJ).

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