Oman rural grid extension employing renewable energy technology

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Abstract— Today, the electrification of various locations is a significant challenge for governments in several countries because of many challenges, especially in desert areas far from the national grid. The paper discusses employing renewable energy sources as an alternative solution for the national grid to feed rural areas in Oman because air pollution is escalating due to the fast growth and the industrialization. The research has taken the load estimation in an Omani desert village called Yanqul, which necessitates about 40 MW. The paper has finalized that installing 12 units of the wind turbine 36 MW with 30 MW Solar Panels is feasible. The approach has included the module sizing calculations using the Power World Simulator, and HOMER Pro software for economic consideration and operational costs. The paper has encouraged using renewable energy as an alternative method over the traditional transmission system due to the technical issues connected with losses, power factor, synchronization, and pollution. The Levelized cost of renewable energy was found $1,366.56, which is cheaper than extending the national grid. This reduction has appeared on annual electricity bill per capita, which dropped to $581.3. Environmentally, the study has shown a reduction in CO₂ emissions by 22 tons, making value to air quality. The future study will discuss the reactive power compensation of the wind turbine technologies to improve power transmission.

Keywords – Solar panel, Fault analysis, Wind turbine, Contingency plan, Economic.

1. Introduction

The fast growth of the economy and the industrial revolution of the Sultanate of Oman have enhanced the quality of urban living standards, which have caused in turn massive air pollution. The contamination of energy generation plants, transportation, and industrial divisions is the primary source of pollution in Oman. The concentration of populations in coastal areas to protect biodiversity, urban existing and finding jobs is another problem; therefore, these problems aggravate air pollution complications. Sohar, the northern industrial city, is an example of Sulphur dioxide air contamination [1]. As air pollution is escalating in the country, the government has started pushing towards deployment the renewable technologies all over the country.

The electricity demand is increasing steadily due to the economy’s growth; thus, searching for different utilities becomes essential to meet the requirement. In 2023, the growth of demand estimated to be 5.5% of the Main Interconnected System in Oman (MIS) which is about 8006.1 MW [2]. The total generation capacity is 8932.5 MW included the power losses of the MIS system [3]. As Oman’s desert area is vast, the grid stations are slightly far from the load, creating technical issues while supplying the load and economic costs.

Therefore, the current solution is to employ renewable energy resources, supporting the overall power generation. Yanqul village is located at the north side in Oman, 23.5990° N, 56.5448° E. Yanqul has many tourism landmarks. It is famous for its natural beauty and heritage premises. This village is a connection of three governors: Al-Buraimi, North Al Batinah and AL Dhahriah.

This landmark place needs 40 MW power. The area has appropriate renewable resources which can use specific types of renewable energy components. Two available options are possible: Solar Photovoltaic Panels (PV) and Wind Turbine technologies (WT) can be utilized to provide Yanqul village grid station.

The paper illustrates the relevant approach of using both sources independently to feed Yanqul’s load, 40MW, which equals 50 MWh. The nearest national grid to feed this load was also taken into consideration. Power World Simulator (PWS) used to design and simulate the system implementation.
includes power flow analysis and relative features.

PWS is a commercial program used by many utilities worldwide, investigating how their system behaves in certain situations. The software engine can solve Power Flow Solution for systems over 60,000 buses. This makes the simulator quite useful as a stand-alone power flow analysis package. Therefore, a project can be modified, build from scratch and analyze quickly. PWS can build any power system model with a mouse click. The transmission lines are protected with circuit breakers that enable switching in or out of service for further investigation and future expansion. This facility is applied to other parts of the power system. The simulator's widespread usage of visual graphics and animation substantially expands the user's understanding of system characteristics, complications and constraints and how to remedy them [4, 5].

The simulator also delivers a medium for simulating the development of the power system. The change in load and generation can be visualized, and interchange schedule variations may be prearranged. This functionality is valuable, for instance, in exemplifying the issues connected with engineering restructuring [5]. The simulator additionally estimates economic dispatch, computation of the power transfer distribution factor (PTDF), analysis of short circuit and contingency plans. These structures are combined with being up and running within minutes of installation [4].

Hybrid Optimization Model for Multiple Energy Sources software (HOMER) has also been used for hourly assessment tool of renewable energy models. The free online application is functional to evaluate off-grid and on-grid power systems selections technically and financially [6]. Therefore, from the data inserted, HOMER determines the optimum power for the network.

The authors' contribution is to save the environment of the Sultanate of Oman theoretically and practically after the revolution of the industrialization has impacted the natural resources. This paper also demonstrates the commercial scale of energy generation using PV and WT farms in Oman. The study begins with load calculation and location topographies, e.g., natural resources availability and the nearest national grid. Finally, the approach provides the appropriate design of both mentioned renewable technologies. Likewise, economic analysis of the system operational cost, including maintenance, was studied.

2. Numerical Model and Design Description

2.1. Oman renewable energy (PV/WT) and its topography
Sultanate of Oman is located at the southeastern of the Arabian Peninsula. It is also presented with a massive desert with different natural resources. An average temperature of 36°C is close to the requirement of using solar panels operation as exposed in figure 1. Moreover, the average speed of wind which equals 7.5 Knots [7], is shown in figure 2. Sun Irradiation is also required to be estimated to ensure the area selected has the relevant solar panel operation requirement. The irradiation of Yanqul village has also estimated 2300 kW/h/m².

The data gives the impression that the manipulation of renewable energy technology is conceivable, especially for the two types of renewable energy technologies: PV solar panel and wind turbine. Due to the fact of nonviability of suitable water run, hydroelectricity energy is omitted. The share of renewable energy in Oman until now is 10% [3, 8].
2.2. Design Components Sizing

The selection and design components depend on the load necessity and climate conditions [2, 5]. Based on the average wind speed at Yanqul, Enercon-115 wind turbine was nominated. Enercon-115 Turbine could provide 3MW [10]. By choosing 12 units, an average of 36MW, outages are considered too [3]. The equation illustrates the expected output power from the wind turbine:

\[ P = \frac{1}{2} \times A \times \rho \times V^3 \]

Equation (1)

Where: 
P is a unit output Power.
A is swept speed
\( \rho \) is place density
V is the speed of the wind

Regarding Solar panels, they are selected to provide 30MW. They are featured with an appropriate rate of 2300kW/m² [11]. The Canadian CS6P260P solar panels were selected. These panels have decent efficiency, high performance at low irradiance above 96.5%, and vast temperature operating range. Same panels are supplied to the largest PV project at Netherlands [12]. As the village has a high temperature, the PV panels are supposed to provide high output rated power [13]. The following equation can calculate the efficiency of PV panels:

\[ \mu = \frac{P_m}{E \times A_c} \]

Equation (2)

Where: \( P_m \) is the panel output power
E sun irradiation at the area
\( A_c \) is the surface area.

Two parallel transmission lines were suggested to install as a back up to the system. The nearest
point from the grid has been found at 38.4 KM [2, 3]. The per-unit (p.u) transmission line impedance must be estimated. Therefore, line resistance for this feeder is:

\[ 0.04283 \times 38.4 = 1.644672 \, \Omega. \]

And line reactance for this feeder is:

\[ 0.2821 \times 38.4 = 10.83264 \, \Omega. \]

Dividing the line impedance parameters by the system base impedance to find out the p.u of the line impedance. It should be assumed that the system base 100MVA then, base impedance is:

\[ Z_{\text{base}} = \frac{V_{\text{system}}^2}{S} = \frac{132^2}{100} = 174.24 \, \Omega \]

\[ R_{\text{pu}} = \frac{174.24}{1.644672} = 0.00944 \]

\[ X_{\text{pu}} = \frac{174.24}{10.83264} = 0.0621 \]

Which gives p.u line impedance \((R + jX)\)

\[ Z_{\text{pu}} = 0.00944 + j0.0621. \]

Besides, per unit line impedance values are calculated for the whole system, as shown in Figure 3.

| Line | No. of circuit s | Voltage level | Line Length (in km) | Type of Conductor (in mm²) | kV | kV | Line resistance (in Ohms) | Line Reactance (in Ohms) | Rectangular Line Impedance (p.u) | Rating (in MVA) | Comment |
|------|-----------------|---------------|---------------------|---------------------------|--|---|------------------------|------------------------|-----------------------------|----------------|---------|
| Ibn-Dank | 2 | 132 kV | 55.4 | YEW x2 | 0.0423 | 0.2621 | 2.5757 | 15.6234 | 0.0136 + j0.090 | 293 | - |
| Wadi Sa’ir- Dank | 2 | 132 kV | 58.4 | 725 AAAC x2 | 0.0423 | 0.2621 | 2.50127 | 15.47464 | 0.01435 + j0.090 | 89 | Line MVA rating is small comparing with other lines of project because it’s wooded pool line but other lines are steel tower. |
| Darbi- Yampal | 2 | 132 kV | 38.4 | YEW x2 | 0.0423 | 0.2621 | 1.646472 | 10.83264 | 0.00944 + j0.0621 | 293 | - |
| Yampal- Alhayl | 2 | 132 kV | 20.0 | YEW x2 | 0.0423 | 0.2621 | 0.8366 | 5.642 | 0.00944 + j0.0621 | 293 | - |
| Renewable Source generation- Yampal | 2 | 132 kV | 2.7 | YEW x2 | 0.0423 | 0.2621 | 0.115641 | 0.70167 | 0.00944 + j0.0621 | 293 | - |
| Darbi- Alhayl | 2 | 132 kV | 51.8 | YEW x2 | 0.0423 | 0.2621 | 2.218594 | 14.61278 | 0.0127 + j0.0838 | 293 | This feeder is an old because it was used before adding Yampal 132kV grid station as new load to system and that is connected to renewable Energy station as well |

Figure 3: Per-unit calculated parameters of the power network on 132 kV.

2.3. Energy Storage System

The DC voltage produced by the PV panels is stored in batteries. Then, an inverter DC to AC is required. Different sorts of batteries were considered, like Lead-acid Lithium-ion and Saltwater battery type. The study concluded that Lithium-ion type is the best option, but they are expensive compared to the other two options [14]. Accordingly, the Lead-acid was chosen because it has minimum Depth of Discharge (DoD) [15], and due to the reliable performance and the cost-effective are better than the rest [14]. The lead-acid energy storage system cost is $549 per kWh (total project cost), approximately $27,450,000 for 50MWh [16, 17].

The Lead-Acid batteries have two tasks in the system. These tasks are called charging and saving operation and discharging operation to feed the load. Sizing the battery bank of the storage system is indispensable. Therefore, correctly measuring the power of the system becomes essential. It also becomes imperative to select the maximum battery cycle count since it distresses the battery lifetime [18]. More the number of cycles generate more charge and discharge operation of the battery. Depth of Discharge (DoD): is an essential feature while choosing batteries because it relates to the battery's lifecycle. DoD is typically shown at percentage value; therefore, the highest DoD per cent represents a
higher use to the energy stored in a specific battery [19, 20].

Besides, over and under-voltage protection was studied as this condition may cause shortness the battery's life. It is provided to isolate the system's faulty element, so it helps run the rest of the equipment safely. Overvoltage and under-voltage protection devices can be used at the input and output side of the batteries. Those protection devices are designed with circuit breakers to send a trip single to the breaker for isolating the system.

3. RESULTS

3.1. Power Flow

Figure 4 shows the power flow stability of the designed system that implements a renewable source to feed a specific load under decent condition. The total power generated by both renewable energy stations is 58 MW which is matching the load requirements. The power production is divided evenly by the PV Panels and Wind Turbines. However, the wind turbines' reactive power is about 21Mvar, which equals approximately 1/3 of total power generated by both stations. It should be noted there is no turbine at the PV panels, so they are not producing reactive power. The PWS demonstrates the total MW losses of the whole system, which are 0.477MW; this value could increase while using long overhead transmission lines [21].

![Figure 4: Solar and Wind Renewable Technologies are feeding the load with the national grid.](image)

3.2. Contingency Plan

Contingency plan of the system investigated and found there are violations. All the transmission lines are paralleled to ensure the implementation of n-1 criterion to secure the system reliability [22]. This also means the redundancy of design is good if any of the line or transformer fails. During the daytime, the PV panels' operation can provide a direct supply to the load. However, during the night, the stored energy is used to manage the supply's availability. The proper contingency plan supports the unavailability of the power during abnormal conditions; hence, penalty to the power operator or producer. Therefore, the contingency plan will reflect the operating system's continuity to sustain reliability [23]. Monitoring the remaining loads of the system under that condition is the leading cause of the plan.

As part of the contingency plan, two parallel lines were applied as back up to Yanqul grid in case renewable energy grid fails to produce power. Those two parallel lines were extended from Dank 132kV grid station, which is about 38.4 KM from Yanqul grid. Those parallel lines will sustain abnormal condition scenarios' reliability like a failure in equipment or any related issues. Using renewable energy to the system, PWS shows 0.477 MW of total power system losses. On the other hand, while using the national grid extension to supply the same load, more power losses were about 1.362 MW, as shown in figure 4. This increase in losses is because of using long transmission lines.
Moreover, the reactive power increased while using the national extension due to the long transmission lines' nature. While using the national extension, the power factor values have approximately decreased at some points of grid stations. For example, in Yanqul 33kV bus station, the power factor declined to 0.92. So, it may need to provide compensation to improve it.

3.3. Sensitivity
Sensitivity evaluates the amount of injected power to the network. The system Power factor's increment is almost the same; it has a negligible quantity, proving the entire bus system is in the same condition. As the power factor measures are low, the probability of avoiding transient conditions becomes higher, and the system's reliability improves [23]. Figure 2 demonstrates reactive power (Q) values and active power (P) at the grid's buses under operation mode. The figure shows the highest values recorded at the busses 14 and 15, where an injection of real power and reactive power of full system buses happened. It also evaluates the suitable location of providing power compensation to captivate the reactive power and recover the overall system power factor. The power factor was measured to be 0.982 in Yanqul. Consequently, the approach has achieved the optimal power flow by calculating the perfect power factor and relative parameters [3, 4, 24]. However, the power factor was dropped to 0.92 when the national grid fed the load.

![Figure 5: The sensitivity of the grid.](image)

3.4. Fault Analysis
Fault analysis is an essential part of all electrical power systems. Moreover, it analyzes how the system behaves under such faults, increasing the overhead power transmission capability and selecting the proper protection devices to safeguard the system [25]. For many different reasons like heavy storms, massive rains, and improper installation of the system, equipment and lightning could lead to faults. The approach has taken into consideration the symmetrical and asymmetrical faults conditions. Regarding the asymmetrical faults, phase-phase fault was simulated, as shown in Figure 4. During the fault time, as the voltage between the two phases Y and B has decreased, the per-unit fault current has increased. Which imitates the real behaviour of how the single-phase voltage and current parameters act [23]. The location of the fault was selected on 50% of the transmission line length. As part of the protection system, the values of voltage and current helps to find out the location of line faults by following the formula: $Z = \frac{U}{I}$. 


Figure 6: Fault calculation phase to phase (Y-B).

In Figure 7, three-phase symmetrical faults simulation on bus system used. This kind of faults happens rarely, but it is severing on the system if it happens. Since it is a balanced fault, all three-phase voltages and currents are equal, and the phase displacement is 120 degrees between them.

Figure 7: Fault calculation of the three-phase system.

3.5. Economic Results
Optimal power flow of any system can be achieved by obtaining maximum power production from the lowest generation cost. This includes the construction of new grid station while considering a national extension to the rural area. Alternatively, it can be achieved by applying the technology of renewable energy in the same area. Also, the operation and maintenance cost were studied. Likewise, lowest power system losses could save more of power generated; hence, save more money [26]. HOMER Pro software used to estimate the cost of renewable energy, operation and maintenance. Correspondingly, it helps optimize and simulate the power system even if it is hybrid for different loads [6, 27]. The natural sources like wind speed and sun irradiation have automatically loaded into the software by identifying the location. The simulation came out with two possible solutions, and the lowest price has selected to operate the system as simulation results shown in Table 1.

The installation cost for new grid station 132kV/33kV in Oman is approximately $27 million [28].
The operation and maintenance cost of natural gas turbine generation is $44/kWh, making $2,200,000 for 50MWh to feed Yanqul Village. Alternatively, the energy storage system's operation and maintenance cost using lead-acid batteries are $0.03/kWh per year [29, 30].

The renewable energy stations support to avoid the long transmission lines from the national grid. Consequently, power losses may achieve. The fuel/gas prices used to generate power from the national grid are going up during the long term due to international fuel prices fluctuation. Which means producing electrical power by using standard method generators can cost more after a couple of years [31, 32]. The Levelized of cost (LCOE) for renewable energy is $1,366.56 per Homer Pro software results.

Maintenance of PV panels usually needs fewer efforts. It is sometimes required because of panel crack caused by sunlight and the dust storms. Consequently, washing panels from dust will improve PV arrays' efficiency. Then maximum energy output from PV panels improves by 6% to extend system lifetime [33, 34]. Regarding the wind turbines, regularly checkup to the units is required, such as physical checkup and gearbox inspection concerning the amount of power produced by individual wind units.

Regarding the project's environmental division, the estimated Carbon Dioxide (CO₂) saved by using renewable technology is 445g for each kWh of electricity production [34, 35]. Therefore, more than 22 tons can be saved from this study. Therefore, this value is supporting the atmosphere and improving the quality of air in Oman. Besides, there is no noise produced by PV panels technology. However, more noise sounds are caused by a different type of generators, which can be considered one reason why generation stations are located far away from the consumers.

**Table 1:** Estimated cost from HOMER pro for installing renewable technologies in Yanqul.

| Item                              | Renewable Energy | Extension Grid |
|-----------------------------------|------------------|----------------|
| 30 MW Solar Farm                  | $ 63,000,000     | -----          |
| 36 MW Wind Farm                   | $135,000,000     | -----          |
| Lead-Acid Energy Storage          | $ 27,450,000     | -----          |
| Connection to grid Cost           | $2,000,000       | -----          |
| Extension The national grid only  | $27,450,000      | $27,000,000    |
| Total cost                        | $227,450,000     | $27,000,000    |

**Table 2:** Estimated cost of maintenance, operation and production [17, 36].

| Item                              | Maintenance and Operation Cost | Energy Production Cost |
|-----------------------------------|-------------------------------|------------------------|
| Batteries                         | $0.03/kWh × 500000 = $1500    | Saved by solar panels  |
| Solar                             | $0.01 × 30000 = $300          | $0.06/kw × 30000 = $1800 |
| Wind Turbine                      | $0.01 × 36000 = $360          | $0.05/kw × 36000 = $1800 |
| Grid + Gas power station          | $ 44/kWh × 50,000 kW = $2,200,000 | $0.3/kWh × 50000 = $15,000 |
|                                    | Conventional = $ 2,200,000    | Conventional = $10,000 |
|                                    | Renewable = $ 2,160           | Renewable = $3,600     |
| Production and Maintenance Cost   | Renewable = $ 5760            | Conventional = $ 2,210,000 |

**Table 3:** Estimated Annual Electricity Bill per capita [37].

| Item                              | From renewable | From extension the grid |
|-----------------------------------|----------------|-------------------------|
| Annual electricity bill per capita| $0.1/kWh × 5813 kwh = $581.3 | $0.5/kWh × 5813 kwh = $2906.5 |

Analysis of the above data shows that establishing the new renewable energy system has a higher
cost. However, the maintenance and operation cost has reduced by 380 times using renewable technologies, especially with escalating oil and gas prices the figure showed above could be worsen. The electricity bill per capita has witnessed another improvement; the reduction was about five times. This reduction will support families’ savings. Besides, renewable energy managed to reduce the greenhouse by 22 tons in Yanqul area. Power transmitting losses have also eliminated from 1.362 MW to 0.477 MW, which improves transmission efficiency. The power factor was improved from 0.9 to 0.955. Moreover, the government can benefit from exporting unused fuel.

4. Conclusion
This study demonstrates the commercial scale of energy generation using PV and Wind Turbine farms in Oman. The work also clarifies why these technologies cannot be established cheaply in some countries. The approach designates the significance of the PV and WT farms' location in terms of investment costs and reinforcement obligation. Based on the analysis, the paper has come to the use of renewable energy in Oman is feasible in Oman due to the following bulletins:

• The data of the natural resources of Yanqul village, especially sun irradiation, to operate PV solar and speed average to operate the wind turbine is feasible.
• Technically, the use of long transmission lines to the same area can cause more power system losses about 1.362MW and other issues connected with synchronizing the transmission line.
• Economically, international fluctuation of fuel and gas costs used to produce electrical power has affected the cost of energy production, and the massive cost is paying on maintenance and operation of the power plants. Therefore, installing 12 units of the wind turbine 36 MW integrated by 30 MW Solar Panels is feasible. The Levelized cost of renewable energy is $1,366.56, which is much cheaper than extending the national grid. This reduction has appeared on annual electricity bill per capita which dropped from $2906.5 to $581.3
• Environmentally, the amount of CO₂ emissions in Yanqul can be reduced by using renewable technology. The project saves about 22 tons of greenhouse, which makes value to air quality.

5. Future work (reactive power compensation)
For compensation purposes, the application of reactors in the network is compulsory to be sized and installed. This type of components is connected in parallel to the high voltage system. Most of the system used is AC transmission line especially while total system supplied by national extension grid. This is encouraging to absorb reactive power (Var) hence, improve the power factor of the system as the following equation shows: \[ Q = S \times \sin\theta \]

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