# INVESTIGATION OF OFF-GRID INTEGRATED RENEWABLE ENERGY SYSTEM

**Ph.D. THESIS**

***by***

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# INVESTIGATION OF OFF-GRID INTEGRATED RENEWABLE ENERGY SYSTEM

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# ABSTRACT


Energy is fifth essential need of the human being after air, water, food and shelter, thus becomes the strategic need of almost all the countries for socio-economic development. Among the various forms of energy, electrical energy which is easy to handle and transport is the most convenient form of energy for variety of end-use applications. Presently, the major contribution to the electrical power generation is from the conventional energy resources. The conventional energy sources such as crude oil, coal, gas and nuclear are depleting drastically in the world and expected to be exhausted in the coming future. Further, enormous use of these resources has increased concentration of carbon dioxide in the atmosphere significantly. On the other hand, the renewable energy (RE) sources such as sunlight, wind, biomass, etc. are naturally replenished and environmentally benign. They can generate electrical power with the negligible emission of the greenhouse gases and other pollutants.

In the developing countries, two-third of the total population lives in the rural areas. Generally, the human population in urban areas have access to energy in many different forms such as electricity, cooking, heating, etc., while the isolated rural communities of many developing countries are still struggling for their energy needs. According to International Energy Agency, more than 84% people live without access to electricity in rural areas. In the un-electrified rural areas, the activities of people are usually limited to daylight hours. Providing electricity access satisfies not only the lighting and household needs but also offers opportunities to conduct activities related to the education, farming, social, health, safety, communication and employment beyond the daylight hours.

The electricity access to un-electrified areas can be provided mainly by three options: (i) by grid extension, (ii) by using fossil fuel based generator, and (iii) by RE based system. Providing electricity access by extending nearby power grid is the best solution, if it is techno-economically feasible; however, the grid extension to remotely located hilly areas is quite difficult and economically prohibitive due to the poor load density and uneven terrain. In the remote rural areas, the fossil fuel-based generator is commonly used for electrical power generation; however, this option has certain disadvantageous as: (i) high transportation, storage and supply costs, (ii) adverse environmental impact, (iii) noisy operation, and (iv) high maintenance cost. A new pathway for off-grid rural electrification has come up due to innovation in RE based technologies. The use of locally available RE

sources can be explored in two ways: (i) single RE based system and (ii) integrated system. Due to the stochastic nature of major RE sources, a single RE based system cannot provide uninterrupted supply of electricity; hence, to attain the high energy security, it is necessary to oversize the rating of the generating system, which in turn increases the overall cost of the system. On the other hand, the integrated renewable energy system (IRES), which employs potential of two or more RE sources to satisfy various energy demands, offers a better option than a single RE system in terms of efficiency, reliability and cost.

Various studies show that the optimal configuration of the IRES should satisfy and compromise between two main objectives: (i) overall cost and (ii) power reliability. A reasonable compromise between the cost and power reliability of the system can be achieved by using different optimization techniques. The long-term system performance is one of the most imperative design criteria for the off-grid integrated energy system. It has been indicated in the literature that the performance of the off-grid IRES mainly depends on the performance of the individual system components accommodated in it. If the system components perform well, the final combination will automatically be the cost-effective and reliable. Therefore, in order to have the cost-effective and reliable off-grid IRES design, the system components used in building the IRES must be cost-effective and capable to contribute more to the power reliability of the IRES.

Further, in the remote rural areas, the loads are generally scattered in nature and the electrical distribution network needs to be developed. In the developing countries, the distribution loss (DL) accounts around 13% of the generated energy. Many studies show that the distribution losses have a direct impact on the overall economy and efficiency of the system. Hence, it is necessary to consider the losses occurred in the distribution network while designing the off-grid IRES based power generation system.

Based on the comprehensive literature review, it has been found that in most of the previous studies, the optimal configuration of the integrated system has been identified without considering the alternatives of system components**.** The optimal results may vary in case, various alternatives of system components are considered in the analysis. Further, the concept of the optimal component selection, by evaluating and comparing the performance of various equipment considered in the analysis has been presented by very few researchers. They used a value of the capacity factor (CF) for selection of the best components. Although this method gives sufficient information about energy generation by the equipment over a specific time period, it is incapable to evaluate the performance of the equipment in terms of their effect on the overall cost and power reliability of the off-grid IRES. Moreover, in the previously published works, the effect of DL on the power reliability, economy and size of the off-grid IRES has not yet been identified.

The present study has been carried out to develop a methodology for investigation of the off-grid IRES for stand-alone power generation with the following objectives:

(i) To identify and consider an un-electrified area for investigation of the IRES-based off-grid power generation

(ii) To formulate different off-grid IRES models using various alternatives of system components, which allow performance evaluation of various equipment considered in the analysis.

(iii) To develop a methodology to identify the optimal components, among a list of commercially available equipment, based on their effect on the overall cost and power reliability of the off-grid IRES, and to validate the veracity of the proposed method using the existing methodology available in the literature.

(iv) To identify the optimal configuration of the off-grid IRES for the study area and to investigate the effect of DL on the power reliability, economy and size.

(v) To suggest the most economical option for providing electricity access to the study area by comparing the most optimal configuration of the off-grid IRES with the conventional grid-extension option.

(vi) To perform a sensitivity analysis to investigate the effect of key variables on performance of the system.

In order to fulfil the above mentioned objectives, a semi-isolated small hamlet, Khatisitara, situated in the hilly region near the border of the Gujarat and Rajasthan states in India has been considered as a study area. The grid-based electrical supply is not available in this area due to the poor load density and uneven terrain. The hamlet consists of 123 scattered households with a total population of 745. The selected study area is rich in terms of the availability of the solar, wind and bio-energy resources; hence, the IRES model has been configured using the solar photovoltaic (SPV) generator, wind turbine generator (WTG), biomass generator and biogas generator. An extensive field survey was carried out for assessment of the potential of RE resources and estimation of the electricity demand of the study area. The annual potential of the solar radiation, wind speed, agro-forest biomass and biogas from the cattle dung has been estimated as 1607 $kWh/m^2$/year, 1572 $kWh/m^2$/year, 66 tons/year and 16950 $m^3$/year respectively. Total daily electricity demand of the study area for the summer and winter seasons have been estimated as 348 kWh/day and 211 kWh/day respectively. The annual total electricity demand has been estimated as 110523 kWh/year.

To implement the proposed method of modeling the IRES-based off-grid power generation, the commercially available SPV modules of 0.1 $kW_p$, 0.2 $kW_p$ and 0.3 $kW_p$, WTGs of 1 kW, 3.3 kW and 5 kW, and the batteries of 360 Ah and 150 Ah have been considered for the analysis. Total 18 possible combinations of the off-grid IRES model have been configured using various alternatives of components. The mathematical modeling for all combinations of the IRES has been developed to evaluate the performance of various equipment considered in the analysis. In the mathematical modeling, the number of SPV module, number of WTG, output of biomass generator, output of biogas generator, and number of battery are considered as decision variables, and the life cycle cost (LCC) and energy index of reliability (EIR) are considered as performance indicators of the system.

Initially, a random sample of decision variables has been generated and the corresponding value of the rating of bi-directional converter with charge controller, LCC and EIR has evaluated; hence, a row vector of 8 data points is produced. Finally, 1000 numbers of such random samples of decision variables have been generated, which produce a feature data matrix of size $1000_{row}\times8_{column}$. Then, the multi-variable linear regression (MVLR) with gradient descent algorithm (GDA), an error-based machine learning technique, has been used to determine the impact of individual system components on the overall cost and power reliability of the IRES. In the MVLR analysis, the decision variables have been considered as predictor variables and performance indicators have been considered as response variables. Two MVLR models as the cost model and power reliability model have been formulated and the impact of different components on the LCC and EIR have been evaluated separately.

Once the impact assessment of different components on the LCC and EIR is accomplished, the best component has been selected by performing a trade-off between their impacts on the LCC and EIR of the IRES using an analytical hierarchy process (AHP) technique. In the AHP problem formulation, the impacts of system components on the LCC and EIR are considered as basic selection criteria and the combinations of the IRES are considered as alternatives. Finally, the local priority vector and global priority vector of the alternatives for both selection criteria have been evaluated, and different equipment have been ranked using their global priority. To validate the results obtained using the above methodology, a value of the CF of the SPV modules and WTGs were determined.

In the optimization problem, the minimization of the LCC has been considered as an objective function. The optimal configuration of each combination of the IRES has been identified by using the genetic algorithm (GA) and particle swarm optimization (PSO) algorithm at three different power reliability levels, i.e. 90%, 95% and 100%. The most optimal configuration of the IRES has been identified based on the lowest value of the LCC. Further, the effect of distribution losses on the power reliability, economy and sizing of the most optimal off-grid IRES has been investigated.

Finally, the break-even analysis for grid-extension distance has been conducted to investigate the economic feasibility limit of the proposed off-grid IRES in the study area against the conventional grid supply option. The break-even point is estimated by comparing the LCC of the off-grid IRES and grid extension. Also, the effect of DL on break-even point has been examined.

To investigate the effect of variation in the most influencing system parameters, the sensitivity analysis was conducted by changing the value of following variables: (i) the solar radiation and wind speed, (ii) capital cost of the IRES components. Further, the effect of increasing the cost of the raw fuel (agro-forest biomass and cattle dung) has also been investigated.

From the MVLR analysis, the non-dominated combinations of the IRES in which the SPV module, WTG and battery have the lowest impact on the LCC and/or the highest impact on the EIR have been identified.

From the AHP analysis, it has been found that the combination consisting of the SPV module of 0.2 $kW_p$, has the highest global priority of 38.83%. Similarly, the combination consisting of the WTG of 3.3 kW and battery of 150 Ah have the highest global priority of 39.28% and 21.28% respectively. From these results, it is concluded that the SPV module of 0.2 $kW_p$, WTG of 3.3 kW and battery of 150 Ah are the optimal choice for the selected site, and it will formulate the cost-effective and reliable off-grid IRES.

The value of CF for the SPV modules of 0.1 $kW_p$, 0.2 $kW_p$ and 0.3 $kW_p$ are obtained as 14.92%, 15.05% and 14.75% respectively. The value of CF for the WTGs of 1 kW, 3.3 kW and 5 kW are obtained as 26.23%, 27.75% and 26.23% respectively. The SPV module of 0.2 $kW_p$ and WTG of 3.3 kW possess the highest value of CF which indicates that these equipment are the best choice, among the available options. These results validate the optimal results obtained using the MVLR and AHP analysis.

For the formulated optimization problem, the PSO algorithm converges more efficiently for all combinations of the IRES at all power reliability levels. The lowest value of the LCC has been observed in the combination consisting of the SPV module of 0.2 $kW_p$, WTG of 3.3 kW and battery of 150 Ah. For the EIR value of 90%, 95% and 100%, the optimal value of the LCC is obtained as INR 12.32 million, INR 14.14 million and INR 16.20 million respectively.

The power reliability of the most optimal off-grid IRES would be compromised by 3.13%, if it is designed without considering the DL of 10%. To compensate 10% DL, the additional 44 SPV modules of 0.2 $kW_p$, 2 WTGs of 3.3 kW, and 9 batteries of 150 Ah are required to satisfy the estimated electricity demand compared to the DL free optimal IRES. Further at 10% DL, the system is economically oversized by 11.38% with respect to the DL free optimal IRES.

From the analysis for grid-extension distance, the break-even point for the DL free optimal IRES and optimal IRES with 10% DL are obtained as 4.668 km and 5.668 km respectively. This result shows that the break-even point is affected by the DL. The analysed IRES model is found economically feasible for rural electrification in the study area against grid extension provided its LCC remains below INR 22.34 million.

From the sensitivity analysis, it has been observed that the optimal results are sensitive to the increment in solar radiation. At 20% increment in the solar radiation, the most optimal configuration of the IRES is found in the combination consisting of the SPV module of 0.1 $kW_p$, WTG of 3.3 kW and battery of 150 Ah. For the variation in capital cost of the IRES components, the optimal configuration of the IRES remains unchanged. Further, the LCC of the optimal IRES varies from INR 16.31 million to INR 16.74 million for the increment in biomass cost from 10% to 50% respectively. The LCC of the optimal IRES varies from INR 16.45 million to INR 17.48 million for the increment in cattle dung cost from 10% to 50% respectively. It is found that the proposed IRES model is more sensitive to variation in the cost of the cattle dung as compared to the cost of biomass.

The methodology developed for investigation of the off-grid IRES in this study is generic and can be used for any other site and data. It will be beneficial to the system developers, decision and policy makers and researchers working in the area of stand-alone power generation using RE sources.