Optimal planning of hybrid renewable energy systems using HOMER: A review

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ABSTRACT

World energy consumption is rising due to population growth and increasing industrialization. Traditional energy resources cannot meet these requirements with notice to their challenges, e.g., greenhouse gas emission and high lifecycle costs. Renewable energy resources are the appropriate alternatives for traditional resources to meet the increasing energy consumption, especially in electricity sector. Integration of renewable energy resources with traditional fossil-based resources besides storages creates Hybrid Renewable Energy Systems (HRESs). To access minimum investment and operation costs and also meet the technical and emission constraints, optimal size of HRES's equipment should be determined. One of the most powerful tools for this purpose is Hybrid Optimization Model for Electric Renewables (HOMER) software that was developed by National Renewable Energy Laboratory (NREL), United States. This software has widely been used by many researchers around the world. In this paper a review of the state-of-the-art of researches, which use HOMER for optimal planning of HRES, is presented.

Contents

1. Introduction ................................................................. 609
2. HOMER software description ........................................ 610
   2.1. Input data .......................................................... 611
       2.1.1. Meteorological data .............................................. 611
       2.1.2. Load profile ......................................................... 611
       2.1.3. Equipment characteristics ....................................... 611
       2.1.4. Economic data ..................................................... 611
       2.1.5. Technical data ..................................................... 612
       2.2. HOMER optimization procedure ............................... 613
           2.2.1. Simulation and optimization ................................. 613
           2.2.2. Sensitivity analysis ............................................ 613
3. Equipment modeled in HOMER ....................................... 614
   3.1. Loads ................................................................. 615
   3.2. Component .......................................................... 615
   3.3. Grid ................................................................. 615
4. Sensitivity analysis ..................................................... 616
5. Discussion on HOMER’s outputs ..................................... 617
6. Conclusion ............................................................... 618
References ........................................................................ 618

Abbreviations: EML, electrical machinery laboratory; TGS, thermal generation station; DRC, Democratic Republic of Congo; UAE, United Arab Emirates; K.S.A., Kingdom of Saudi Arabia; UK, United Kingdom; MACS, maximum annual capacity shortage; USA, United State of America; MREF, minimum renewable energy fraction; WEOR, wind energy operating reserve; PVEOR, PV energy operating reserve.

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1. Introduction

In recent years, population growth and technology development have resulted in increasing energy consumption, especially in electricity sector. Moreover, there are many rural and remote areas particularly in developing countries which have no access to electricity. In order to solve these problems, electricity generation should be increased. Nowadays, a large percentage of the world electricity is supplied by fossil fuel resources. However, these resources cannot meet the future electricity requirements because of their economic and environmental problems. Renewable energy resources have become efficient alternatives for fossil fuel resources. However, when these resources are used to supply the local loads individually, many problems are created such as high investment costs and low security of supply because of intermittent and uncertain nature of them. To solve these problems a new concept, namely Hybrid Renewable Energy Systems (HRESs) has emerged [1]. HRES is a combination of renewable, traditional energy resources, and energy storages to meet the load locally in both grid connected and standalone modes. HRESs are used in standalone mode in remote and rural areas. In this mode, due to uncertain nature of renewable resources, traditional energy resources and energy storages can be used as the back-up resources for them. In fact, during the periods in which the output of renewable resources is not enough to meet the load, remaining part of the load can be supplied by the back-up resources. On the other hand, when the renewable resources have extra generation, the excess energy can be absorbed by the energy storages. Therefore, HRESs have more reliability than only renewable energy systems in standalone mode. HRESs are used in grid connected mode in some places such as universities, hospitals, factories, and town. In this mode, when the grid electricity prices are low, the HRES meets the load from the grid and charges the energy storages with renewable resources. Then, during the periods in which the grid electricity prices are high, the HRES meets the load with its resources and sells the extra energy to the grid. In this manner, energy storages are discharged to meet the load or to sell energy to the grid. In this mode HRESs have more economical than only renewable energy systems. Therefore, HRES provides some advantages, e.g., increasing penetration of renewable energy resources, decreasing Cost of Energy (CoE), reduction of greenhouse gas emission, and providing access to electricity for people in remote and rural areas. These advantages meet all three criteria of Sustainable Development (SD) including economic, environmental, and social aspects.

One of the important issues in HRES is optimal planning of its component, e.g., number of Wind Turbines (WTs), Photo-Voltaic (PV) arrays, batteries, and capacity of generators and converters so that the objective functions are minimized/maximized and all constraints are satisfied. For this purpose, many software and optimization approaches are proposed in the literature. There are appropriate papers that have reviewed optimal planning and operation techniques of HRES from different viewpoints [1–9]. Different optimization methods and modeling of HRES's component are described in [2]. Design and control techniques reported in the literature to simulate and optimize the stand-alone and grid connected modes. HOMER requires six types of data for simulation and optimization including meteorological data, load profile, equipment characteristics, search space, economic and technical data. These data are described in details in the following subsections.

2. HOMER software description

HOMER software is a powerful tool for designing and planning of HRES in order to determine optimal size of its components through carrying out the techno-economic analysis. Many resources such as WT, PV array, fuel cells, small hydropower, biomass, converter, batteries, and conventional generators are modeled in HOMER. HOMER also considers HRES in grid-connected and stand-alone modes. Fig. 1 shows the typical configuration of HRES designed in HOMER. Required input data for simulation with HOMER and also a comprehensive framework to show how optimal sizes of HRES’s equipment is determined by HOMER are described in this section.

2.1. Input data

HOMER requires six types of data for simulation and optimization including meteorological data, load profile, equipment characteristics, search space, economic and technical data. These data are described in details in the following subsections.
2.1.1. Meteorological data
The meteorological data are wind speed, solar radiation, temperature, and stream flow which are fed into the software in the form of monthly averages or time series data. HOMER uses these inputs data to calculate the output power of WT, PV array and hydropower.

2.1.2. Load profile
Load profile of each region is the most important factor in the simulation and optimization. Some locations such as universities, hospitals, hotels, and industrial towns have real load consumption data, which are appropriate for simulation. These real data are fed into HOMER as time series data. However, in some regions especially remote and rural areas that the real load consumption data are not available, the load profile should be forecasted with notice to the specification of that region. These data are fed into HOMER as daily profile and HOMER uses them in power balance constraint.

2.1.3. Equipment characteristics
According to the characteristics of each equipment, which is modeled in HOMER, efficient operation of it in HRES is determined. The characteristics of HRES’s equipment are described in [11].

### Table 1
Search space for a hypothetical case study.

| Component | WT (number) | PV array (kW) | Battery (number) | Converter (kW) |
|-----------|-------------|---------------|------------------|----------------|
| Maximum   | 4           | 40            | 40               | 40             |
| Minimum   | 0           | 0             | 0                | 0              |
| Step      | 1           | 10            | 10               | 20             |

Fig. 2. The comprehensive framework of HOMER optimization procedure.
Table 2
Peak and types of different loads in the articles.

| Ref. | Peak load (kWp) | Location | Country |
|------|-----------------|----------|---------|
| Primary | Deferrable | | |
| [14] | 498,000 | – | TGS | Canada |
| [15] | 4,73 | – | Remote area | Canada |
| [16] | 12 | – | Remote area | Cameroon |
| [17] | 356 | – | Remote area | Canada |
| [18] | 61 | – | Rural | Bangladesh |
| [19] | 8.3 | – | Remote villages | Cameroon |
| [20, 21] | 24 | – | Rural | Senegal |
| [22] | 7.5 | – | Village | Cameroon |
| [23] | Unknown | – | Village | Portuguese |
| [24] | 5.6 | – | Remote area | China |
| [25] | 16 | – | EML | Greece |
| [26] | 6 | – | Remote area | Jordan |
| [27] | 7109 | – | Island | Malaysia |
| [28] | 966 | – | Hotel | Australia |
| [29] | 11 | – | Residential area | Canada |
| [30] | 4 | – | Remote area | Greece |
| [31] | 4200 | – | Remote area | K.S.A. |
| [32] | 159 | – | Commercial building | K.S.A. |
| [33] | 13.4 | – | Village | Iran |
| [34] | 4231 | – | Village | K.S.A. |
| [35] | 966 | – | Hotel | Australia |
| [36] | 8080 | – | Island | Greece |
| [37] | 42 | 1.05 | – | Remote area | Ethiopia |
| [38] | 1183 | – | Rural community | Canada |
| [39] | 4370 | – | Village | K.S.A. |
| [40] | 0.626 | – | Rural areas | Algeria |
| [41] | 81 | 1.8 | – | Remote area | Ethiopia |
| [42] | 239 | – | University | Turkey |
| [43] | 7700 | – | Arid region | Algeria |
| [44] | 159 | – | Village | India |
| [45] | 31 | – | Remote areas | Bangladesh |
| [46] | 32 | – | Remote area | Bangladesh |
| [47] | 297.2 | – | Hotels | Australia |
| [48] | 77 | – | University | Malaysia |
| [49] | 9.97 | – | Hotel | Jordan |
| [50] | 36 | – | University | Turkey |
| [51] | 4400 | – | Remote area | K.S.A. |
| [52] | 265 | – | Residential district | Italia |
| [53] | 9.3 | – | Residential consumers | K.S.A. |
| [54] | 23 | – | Island | Bangladesh |
| [55] | 34 | – | Urban area | UK |
| [56] | 84 | – | Remote area | Malaysia |
| [57] | Unknown | – | Island | Brazil |
| [58] | 2.3 | – | Remote area | India |
| [59] | 4.2 | – | Kolkata city | India |
| [60] | 11.9 | – | Remote area | Malaysia |
| [61] | 15 | – | Remote area | South Africa |
| [62] | Unknown | – | Island | Thailand |
| [63] | Unknown | – | Remote area | Canada |
| [64] | 1030 | – | University | Iran |
| [65] | 7100 | – | University | Malaysia |
| [66] | 982 | – | Industry area | Malaysia |
| [67] | 197 | – | Island | Malaysia |
| [68] | 325 | – | Residential consumers | Hypothetical |
| [69] | 5300 | – | Island | USA |
| [70] | 91 | – | Island | Indonesia |
| [71] | 65.1 | – | Village | Iran |
| [72] | 9.6 | 133 | – | desert agricultural area | Egypt |
| [73] | 27 | – | Remote island | Hong Kong |
| [74] | 56 | – | Village | Indonesia |
| [75] | 1137, 2300 and 11,000 for three cases | – | Remote areas | UAE |
| [76] | 495 | – | Renewable energy site | Iran |
| [77] | 1.1 | – | Urban areas | India |
| [78] | 550 | – | Island | South Korea |
| [79] | 44.4 | – | Village | Bangladesh |
| [80] | 92 | – | Island | Scotland |
| [81] | 537 | – | Remote areas | Canada |
| [82] | 9.4 | – | Village | South Africa |
| [83] | 8 | – | Remote area | DRC |
| [84] | 83 | – | Remote areas | Ghana |
| [85] | 1.4 | – | Urban area | India |
2.1.4. Search space
Since HRES's components including WT, PV array, generator, battery, and converter have different sizes, there is a search space that is considered in simulation and optimization. For example, the equipment of a hypothetical HRES which have different sizes is illustrated in Table 1. So, the search space includes 5 × 5 × 3 = 375 plans (combination of different equipment) that the simulation and optimization stages will be done for each of them.

2.1.5. Economic data
Each equipment in HRES has some cost data such as operation and maintenance, capital, and replacement cost. Fuel price, price of transaction electricity with the grid, real interest rate, project lifetime, system fixed capital cost, system fixed operation and maintenance cost, and emissions penalty are the other economic data that can be considered in HOMER. These costs are considered in simulation and optimization stages and based on them, the Net Present Cost (NPC) of each plan is calculated.

2.1.6. Technical data
For simulation, HOMER requires some technical data including dispatch strategy, MACS, MREF, and operating reserve, which are described in [11].

2.2. HOMER optimization procedure
After the input data are fed into HOMER, which was described in previous section, optimal sizes of HRES’s equipment are determined in three stages including simulation, optimization, and sensitivity analysis as described in Fig. 2. These stages are introduced in the following subsections. Simulation and optimization stages are done simultaneously.

2.2.1. Simulation and optimization
For each plan from search space the optimization and simulation stages are done. The objective function is minimized subject to the constraints. The objective function of each plan is the total NPC which is the present value of the sum of costs minus the sum of revenues. The costs are the cost of energy purchased from the grid, initial cost, replacement cost, operation and maintenance cost as well as the fuel cost. The revenues are the revenue from energy sold to the grid and the salvage value. Constraints are power balance constraint, charging and discharging constraints of battery, constraints of transaction energy with grid, technical constraints of generators and so on. For the feasible plans the required output is calculated including the NPC, operation results of resources such as generator, battery, and converter in each time step, the energy transacted with the grid, and the emissions produced. Feasibility means that the power balance constraint is satisfied in each time step. In fact, the demand of each time step is supplied. At the end, the feasible plans are sorted according to the minimum NPC so that the first plan has the minimum NPC and is considered as the best plan.

2.2.2. Sensitivity analysis
In optimal sizing procedure of HRES's equipment, some parameters such as fuel cost, wind speed, solar radiation, electricity price, and components cost have not deterministic values. So, the uncertainty of these parameters has effect on simulation and optimization stages. These parameters are fed into HOMER with different values. When the simulation and optimization stages are done and the feasible plans are sorted according to the minimum NPC, the sensitivity analysis is done as shown in Fig. 2. For each uncertain parameter the simulation and optimization stages are repeated and the new feasible and best plans may be obtained. To
Table 3
Components considered in different articles.

| Ref. | Non-dispatchable resources | Dispatchable resources | Converters | Storages |
|------|-----------------------------|------------------------|------------|----------|
|      | PV | WT | Hydro | Gen. | Boiler | Grid | Converter | Electrolyzer | Battery | Hydrogen tank |
| [14] | – | ✓ | – | ✓ | – | – | – | – | – | – |
| [15] | ✓ | – | – | ✓ | – | – | ✓ | ✓ | ✓ | ✓ |
| [16] | ✓ | – | – | ✓ | – | – | – | – | – | – |
| [17] | – | ✓ | – | ✓ | – | – | – | – | – | – |
| [18] | ✓ | ✓ | – | – | – | – | – | – | – | – |
| [19] | – | – | ✓ | ✓ | – | – | – | – | – | – |
| [20,21] | ✓ | – | – | ✓ | – | – | – | – | – | – |
| [22] | ✓ | – | – | ✓ | – | – | – | – | – | – |
| [23] | ✓ | – | – | – | – | – | – | – | – | – |
| [24] | ✓ | ✓ | – | – | – | – | – | – | – | – |
| [25] | ✓ | – | – | ✓ | – | – | – | – | – | – |
| [26] | ✓ | – | – | – | – | – | – | – | – | – |
| [27] | ✓ | – | – | – | – | – | – | – | – | – |
| [28] | ✓ | – | – | – | – | – | – | – | – | – |
| [29] | ✓ | – | – | – | – | – | – | – | – | – |
| [30] | – | – | – | – | – | – | – | – | – | – |
| [31] | ✓ | – | – | – | – | – | – | – | – | – |
| [32] | – | – | – | – | – | – | – | – | – | – |
| [33] | ✓ | – | – | – | – | – | – | – | – | – |
| [34] | – | – | – | – | – | – | – | – | – | – |
| [35] | ✓ | – | – | – | – | – | – | – | – | – |
| [36] | ✓ | – | – | – | – | – | – | – | – | – |
| [37] | ✓ | – | – | – | – | – | – | – | – | – |
| [38] | ✓ | – | – | – | – | – | – | – | – | – |
| [39] | – | – | – | – | – | – | – | – | – | – |
| [40] | ✓ | – | – | – | – | – | – | – | – | – |
| [41] | ✓ | – | – | – | – | – | – | – | – | – |
| [42] | – | – | – | – | – | – | – | – | – | – |
| [43] | ✓ | – | – | – | – | – | – | – | – | – |
| [44] | ✓ | – | – | – | – | – | – | – | – | – |
| [45] | – | – | – | – | – | – | – | – | – | – |
| [46] | ✓ | – | – | – | – | – | – | – | – | – |
| [47] | – | – | – | – | – | – | – | – | – | – |
| [48] | ✓ | – | – | – | – | – | – | – | – | – |
| [49] | ✓ | – | – | – | – | – | – | – | – | – |
| [50] | – | – | – | – | – | – | – | – | – | – |
| [51] | – | – | – | – | – | – | – | – | – | – |
| [52] | – | – | – | – | – | – | – | – | – | – |
| [53] | – | – | – | – | – | – | – | – | – | – |
| [54] | – | – | – | – | – | – | – | – | – | – |
| [55] | – | – | – | – | – | – | – | – | – | – |
| [56] | – | – | – | – | – | – | – | – | – | – |
| [57] | – | – | – | – | – | – | – | – | – | – |
| [58] | – | – | – | – | – | – | – | – | – | – |
| [59] | – | – | – | – | – | – | – | – | – | – |
| [60] | – | – | – | – | – | – | – | – | – | – |
| [61] | – | – | – | – | – | – | – | – | – | – |
| [62] | – | – | – | – | – | – | – | – | – | – |
| [63] | – | – | – | – | – | – | – | – | – | – |
| [64] | – | – | – | – | – | – | – | – | – | – |
| [65] | – | – | – | – | – | – | – | – | – | – |
| [66] | – | – | – | – | – | – | – | – | – | – |
| [67] | – | – | – | – | – | – | – | – | – | – |
| [68] | – | – | – | – | – | – | – | – | – | – |
| [69] | – | – | – | – | – | – | – | – | – | – |
| [70] | – | – | – | – | – | – | – | – | – | – |
| [71] | – | – | – | – | – | – | – | – | – | – |
| [72] | – | – | – | – | – | – | – | – | – | – |
| [73] | – | – | – | – | – | – | – | – | – | – |
| [74] | – | – | – | – | – | – | – | – | – | – |
| [75] | – | – | – | – | – | – | – | – | – | – |
| [76] | – | – | – | – | – | – | – | – | – | – |
| [77] | – | – | – | – | – | – | – | – | – | – |
| [78] | – | – | – | – | – | – | – | – | – | – |
| [79] | – | – | – | – | – | – | – | – | – | – |
| [80] | – | – | – | – | – | – | – | – | – | – |
| [81] | – | – | – | – | – | – | – | – | – | – |
| [82] | – | – | – | – | – | – | – | – | – | – |
| [83] | – | – | – | – | – | – | – | – | – | – |
| [84] | – | – | – | – | – | – | – | – | – | – |
| [85] | – | – | – | – | – | – | – | – | – | – |
| [86] | – | – | – | – | – | – | – | – | – | – |
| [87] | – | – | – | – | – | – | – | – | – | – |
evaluate the effect of uncertain parameters on the results, two criteria including robust planning and risk of planning are proposed in [12,13]. These criteria can be calculated by the researchers according to the methodologies which are described in [12,13] and HOMER software is not able to calculate them. HOMER also produces appropriate figures to show how the best plans’ output will be changed with uncertain parameters.

3. Equipment modeled in HOMER

In this section, various HRES’s equipment modeled in HOMER and used in different articles is presented. Loads, components, and grid are three types of the HRES’s equipment, which are modeled in HOMER.

3.1. Loads

HRES should meet the load requirements in each time step. Electrical, thermal, and hydrogen loads are modeled in HOMER. Electrical loads are primary and deferrable loads. Primary loads are the electrical load that must be met in certain time while deferrable load is the electrical load that must be met within some time period, but the exact time is not important. Peak and types of different loads that are used in different articles are listed in Table 2. Also, Table 2 shows the locations and countries which are considered in each article. Locations that are listed for each article, such as remote area, rural, and village are exactly mentioned in the same article. Since there are some peak loads data that have not mentioned in the articles, these data are shown in Table 2 as unknown data.

Table 2 shows that the wide range of the peak loads from 0.626 kW to 2,213,000 kW are modeled in the articles. The most loads that are modeled in the articles are electrical loads; while thermal and hydrogen loads are modeled in few ones.

Fig. 3 shows the percentage of the articles published in different continent of the world. As illustrated in Fig. 3, the most articles are done in Asia. Sixty percent of the world population is living in Asia and 57.8% of these people are living in rural and remote areas and also most countries of the Asia are developing countries. So, these countries have severe need for electrical energy. Taking these issues into account, large number of the researches about HRES is done in Asia especially in remote areas.

3.2. Component

In HOMER, each part of HRES that can produce, deliver, convert, or save energy is named as a component. Ten components are modeled in the HOMER. WT, PV, and small hydropower are three renewable energy and non-dispatchable resources. Generators, grid, and boiler are three dispatchable resources. Converter and electrolyzer are components that convert electrical energy to other forms. AC and DC power are converted to each other using converters and electrolyzers consume AC or DC power and generate hydrogen through electrolyzing water. Batteries and hydrogen tanks are components that store energy. HRES that are modeled in the articles have used different components for simulation as given in Table 3. In some articles, fuel cells are used as generators. These HRES with fuel cell have electrolyzer as converter and hydrogen tank as energy storage as illustrated in Table 3.

Since different combinations of the component that are considered in the articles are listed in Table 3, this table can be used by each researcher who intends to design HRES with a specific combination in his/her regions. PV is the most common resource from non-dispatchable resources in HRESs that are used in 91.2% of the studies. In recent papers new resources are considered such as biogas is used as the fuel resource for generators in [96,102] and flywheel is used as energy storage in [93].

3.3. Grid

Grid is modeled in the HOMER in three modes, namely, grid-connected, stand-alone, and compare stand-alone system with grid extension. Table 4 shows different modes of HRESs used in the articles. In grid connected mode price and sell back of electricity should be fed into HOMER in two types, real time prices and scheduled rates. In compare stand-alone system with grid extension mode, breakeven grid extension distance will be calculated using three inputs including capital, operation and maintenance cost and grid power price. The breakeven grid extension distance
is the minimum distance from the grid that makes a stand-alone system cheaper than extending the grid. As illustrated in Table 4, most of HRESs in the articles are simulated in standalone modes.

### 4. Sensitivity analysis

To evaluate the effect of uncertain parameters on optimal sizing of HRES's equipment, sensitivity analysis should be done. Uncertain parameters may differ with notice to the location and type of the components. Uncertain parameters considered in different articles are listed in Table 5. Wind speed, solar radiation, fuel price, component cost, and primary load are the most uncertain parameters considered in the researches.

In most articles the effect of uncertain parameters on NPC, operation results of resources, production of emissions and other parameters of best plans are evaluated. Moreover, sensitivity analysis is done in details in recent papers. Effects of real interest rate, fuel price, and primary load on output results is investigated through different scenarios in [89]. The simultaneous effects of wind speed and solar radiation on CoE is studied in [103]. To investigate the effect of uncertain parameters on the NPC, an appropriate spider graph is presented in [98]. However, as mentioned before, to evaluate uncertain parameters and their effect on optimal sizing of HRES's equipment, two appropriate criteria including robust planning and risk of planning should be considered as proposed in [12, 13]. Scenario technique is one of the appropriate approaches in dealing with the uncertainties in planning of HRES. To this end, at first, uncertain parameters and their different values that may occur in the future is determined and based on them, the scenarios can be constructed. For example, in one project the uncertain parameters and their different values may be considered as shown in Table 6. As illustrated in Table 6, there are three uncertain parameters with different values.

Considering these different values, there are 5 × 6 × 4 = 120 scenarios that should be considered in HOMER. The first scenario will occur when the wind speed is 4, diesel price is 0.2 and solar radiation is 4.5 and the last scenario will occur when wind speed is 8, diesel price is 0.7 and solar radiation is 6. Simulation and optimization stages are repeated for each scenario.

When each scenario is considered, even the best plan may differ. So, the best plan in base scenario may be changed into other scenarios. The robust plan is the one with the minimum NPC in most scenarios [12, 13].

When one plan is considered as the best one in base scenario, its parameters such as NPC and production of emissions in other

| Table 4 | Grid modes in the articles. |
|---------|-----------------------------|
| Ref.    | Grid connected | Stand-alone | Breakeven grid extension distance (km) |
|---------|----------------|-------------|----------------------------------------|
| [14]    | –              | ✓            | –                                      |
| [15]    | –              | ✓            | –                                      |
| [16]    | –              | ✓            | 37.4 and 15.4 for two cases             |
| [17]    | ✓              | –            | –                                      |
| [18]    | –              | ✓            | 17                                     |
| [19]    | –              | ✓            | 12.9 and 15.2 for two cases             |
| [20, 21] | –             | ✓            | –                                      |
| [22]    | –              | ✓            | 3.3                                     |
| [23]    | ✓              | –            | 31.6                                    |
| [24]    | –              | ✓            | –                                      |
| [25]    | –              | ✓            | –                                      |
| [26]    | –              | ✓            | –                                      |
| [27]    | –              | ✓            | –                                      |
| [28]    | ✓              | –            | –                                      |
| [29]    | ✓              | –            | –                                      |
| [30]    | –              | ✓            | –                                      |
| [31]    | –              | ✓            | –                                      |
| [32]    | –              | ✓            | –                                      |
| [33]    | ✓              | ✓            | 5.92                                   |
| [34]    | –              | –            | –                                      |
| [35]    | –              | ✓            | –                                      |
| [36]    | –              | ✓            | –                                      |
| [37]    | –              | ✓            | –                                      |
| [38]    | ✓              | –            | 153                                    |
| [39]    | –              | ✓            | –                                      |
| [40]    | –              | –            | –                                      |
| [41]    | –              | ✓            | –                                      |
| [42]    | ✓              | –            | –                                      |
| [43]    | ✓              | –            | –                                      |
| [44]    | –              | –            | –                                      |
| [45]    | –              | –            | –                                      |
| [46]    | –              | ✓            | 10.10                                   |
| [47]    | –              | –            | –                                      |
| [48]    | –              | ✓            | –                                      |
| [49]    | ✓              | –            | –                                      |
| [50]    | ✓              | –            | –                                      |
| [51]    | –              | ✓            | –                                      |
| [52]    | ✓              | –            | –                                      |
| [53]    | –              | –            | –                                      |
| [54]    | ✓              | –            | –                                      |
| [55]    | ✓              | –            | –                                      |
| [56]    | –              | –            | –                                      |
| [57]    | –              | –            | –                                      |
| [58]    | –              | –            | –                                      |
| [59]    | –              | –            | –                                      |
| [60]    | –              | –            | –                                      |
| [61]    | –              | ✓            | 3.07                                    |
| [62]    | –              | –            | –                                      |
| [63]    | –              | –            | –                                      |
| [64]    | ✓              | –            | –                                      |
| [65]    | –              | ✓            | –                                      |
| [66]    | ✓              | –            | –                                      |
| [67]    | –              | ✓            | –                                      |
| [68]    | ✓              | –            | –                                      |
| [69]    | –              | –            | –                                      |
| [70]    | –              | –            | –                                      |
| [71]    | –              | –            | –                                      |
| [72]    | –              | –            | –                                      |
| [73]    | –              | –            | –                                      |
| [74]    | –              | –            | –                                      |
| [75]    | –              | ✓            | 31, 38 and 180 for three cases         |
| [76]    | –              | –            | –                                      |
| [77]    | –              | ✓            | –                                      |
| [78]    | ✓              | –            | –                                      |
| [79]    | –              | –            | –                                      |
| [80]    | –              | –            | –                                      |
| [81]    | –              | –            | –                                      |
| [82]    | –              | ✓            | 1.1 for the best plan                  |
| [83]    | –              | –            | –                                      |
| [84]    | –              | –            | –                                      |
| [85]    | ✓              | –            | –                                      |
| [86]    | –              | –            | –                                      |
| [87]    | –              | ✓            | 1.76 and 1.1 for two cases             |
| [88]    | –              | –            | –                                      |
| Table 4 (continued) | Grid modes in the articles. |
| Ref.    | Grid connected | Stand-alone | Breakeven grid extension distance (km) |
|---------|----------------|-------------|----------------------------------------|
| [89]    | –              | ✓            | –                                      |
| [90]    | –              | ✓            | –                                      |
| [91]    | –              | ✓            | –                                      |
| [92]    | ✓              | –            | –                                      |
| [93]    | –              | ✓            | –                                      |
| [94]    | –              | ✓            | –                                      |
| [95]    | –              | ✓            | –                                      |
| [96]    | –              | ✓            | –                                      |
| [97]    | –              | ✓            | –                                      |
| [98]    | –              | ✓            | –                                      |
| [99]    | –              | ✓            | –                                      |
| [100]   | –              | ✓            | –                                      |
| [101]   | ✓              | –            | –                                      |
| [102]   | –              | ✓            | –                                      |
| [103]   | –              | ✓            | –                                      |
| [104]   | –              | ✓            | –                                      |
| [105]   | –              | ✓            | –                                      |
Table 5
Type of uncertain parameters considered in different articles.

| Ref. | Sensitivity analysis |
|------|----------------------|
| [14] | Wind speed – Fuel price |
| [15] | Wind speed – Solar radiation – Fuel price – Component cost |
| [16] | – |
| [17] | – |
| [18] | – |
| [19] | Component cost |
| [20,21] | – |
| [22] | Solar radiation |
| [23] | Sellback rate – Component cost |
| [24] | Wind speed – Solar radiation – Primary load |
| [25] | Fuel price – Solar radiation – Primary load |
| [26] | Solar radiation – Fuel price – MREF – MACS – PVEOR |
| [27] | Fuel price |
| [26] | Emission penalty – Electricity price – Component cost – Rate of return |
| [29] | Wind speed – Primary load |
| [30] | Fuel price – Component cost |
| [31] | – |
| [32] | – |
| [33] | – |
| [34] | Wind speed – Fuel price – MREF – MACS – WEOR |
| [35] | Battery efficiency – Payback time – Number of battery |
| [36] | – |
| [37] | – |
| [38] | – |
| [39] | Wind speed – Solar radiation |
| [40] | – |
| [41] | – |
| [42] | Component cost – MACS – Electricity price |
| [43] | Wind speed – Solar radiation – Electricity price |
| [44] | Fuel price – Wind speed – Flow rate |
| [45] | Solar radiation – MACS – MREF – Wind speed – Fuel price |
| [46] | Wind speed – Solar radiation |
| [47] | Carbon tax – Fuel price |
| [48] | – |
| [49] | Electricity price |
| [50] | – |
| [51] | – |
| [52] | – |
| [53] | – |
| [54] | – |
| [55] | – |
| [56] | Solar radiation – Fuel price |
| [57] | – |
| [58] | – |
| [59] | Solar radiation |
| [60] | – |
| [61] | – |
| [62] | – |
| [63] | – |
| [64] | Primary load – Solar radiation – Wind speed – Fuel price – Interest rate – CO2 penalty |
| [65] | – |
| [66] | – |
| [67] | Solar radiation – Wind speed – Fuel price |
| [68] | – |
| [69] | – |
| [70] | Primary load – Fuel price |
| [71] | – |
| [72] | – |
| [73] | Solar radiation – Wind speed – Primary load |
| [74] | – |
| [75] | Solar radiation – Wind speed – Fuel price |
| [76] | – |
| [77] | Capacity shortage |
| [78] | Solar radiation – Wind speed – Fuel price |
| [79] | – |
| [80] | Primary load |
| [81] | Wind speed – Fuel price |
| [82] | – |
| [83] | – |
| [84] | Solar radiation – Wind speed – Fuel price |
| [85] | Component cost |
| [86] | – |
| [87] | – |
| [88] | Primary load – Fuel price – Annual interest rate – Stream flow |
| [89] | Primary load – Fuel price – Annual interest rate |
| [90] | Investment costs – Biogas production rate |
| [91] | Solar radiation – Fuel price – Annual interest rate – Component cost |
| [92] | Photovoltaic array size – Converter size |
| [93] | – |
| [94] | – |
| [95] | Fuel price |
| [96] | Component size |
| [97] | Maximum CO2 emission |
| [98] | Primary load – Wind speed – Solar radiation – Fuel price – Component cost |
| [99] | Primary load – Wind speed – Solar radiation – Fuel price |
| [100] | Primary load – Solar radiation – Fuel price – Annual interest rate |
| [101] | Wind speed – Solar radiation – Grid electricity price |
| [102] | – |
| [103] | Wind speed – Solar radiation – Component cost |
| [104] | – |
| [105] | Wind speed – Solar radiation – Annual interest rate |

Table 5 (continued)

| Ref. | Sensitivity analysis |
|------|----------------------|

Table 6
Different scenarios for a case study.

| Uncertain parameter | Different values |
|---------------------|-----------------|
| Wind speed (m/s)    | 4, 5, 6, 7, 8   |
| Diesel price ($/Liter) | 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 |
| Solar radiation (kWh/m²/day) | 4.5, 5, 5.5, 6 |

scenarios may be changed. So, to evaluate these changes an appropriate criterion, namely risk assessment should be considered. Risk of planning is evaluated via NPC in base scenario and in other scenarios [12, 13].

5. Discussion on HOMER’s outputs

After all required data are fed into HOMER and the simulation and optimization stages are done, the results of each plan including the NPC ($), the initial capital cost ($), the operation cost ($/yr), renewable fraction (percent), CoE ($/kWh), and emissions produced (kg/yr) are calculated. Although best plan is determined according to the minimum NPC by HOMER, the best plan may be selected with notice to the other criteria considering the investors’ perspective. This issue is discussed in details in [79].

CoE is an appropriate criterion to choose the best plan that is used in the literature. This criterion indicates the average cost per kWh of each plan to supply the demand. Table 7 shows the CoE for best plans which are obtained in the literature. Since in some articles the value of CoE for the best plans is not mentioned, these data is shown in Table 7 as unknown data. The CoE is high in some cases due to high investment cost of component, high fuel prices, high distance from the main grid and so on. For electrification to remote and rural areas which have high distance from the main grid, there are two main solutions including the extension of the main grid and using of HRESs. Although extension of the main grid may lead to lower NPC in comparison with HRES, it has several disadvantages including power losses, low power quality, and high operation and maintenance cost. Moreover, in some cases the grid extension in not possible with notice to the topography of region. On the other hand, in urban areas the CoE for best plans is higher than the grid electricity prices. Therefore, to encourage the private investors to invest on HRESs in rural and urban areas, the governments should determine attractive regulations to give more
incentives to investors. These issues are discussed in recent papers and appropriate solutions are introduced [75,79,80,90,96,103].

6. Conclusion

HRESs are appropriate solution to meet the local loads in rural, remote, and special urban regions, e.g., universities and hospitals. Determining the optimal sizes of HRES’s equipment is the major concern of researchers. HOMER software is a powerful tool used by many researchers around the world for optimal planning of HRES. According to the ability and widespread use of this software, the present paper reviewed those articles that have used HOMER for the optimal planning of HRES. The most remarkable conclusions from this review are listed as follows:

- The software has been used in developing countries other than regions, especially in remote and rural areas.
- The software has been used for wide range of load from 0.626 kW to 2,213,000 kW.
- Many combinations of dispatchable/Non-dispatchable resources, storages and converters have been modeled in the articles.
- PV is the popular resource considered by many researchers.
- HRESes have been modeled in stand-alone mode more than grid connected mode.
- Wind speed, solar radiation, fuel price, component cost, and primary load are the most uncertain parameters referred to in the articles.

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