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Multi Attribute Investment Planning of a Grid-Connected Diesel/Wind/PV/Battery Hybrid Energy System

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ABSTRACT

Recently, along with the depletion of fossil fuels and growing electrical requirements, more attention has been paid to utilizing Renewable Energy Sources (RESs). Hence, the regulatory rules are in a way to expand the share of RESs in supplying microgrids energy demands. This study reports the optimum investment planning for electrical expansion of a grid-connected tourism complex including diesel/wind/PV/battery technologies. For the optimal planning of microgrid, an efficient simple-computational two-stage procedure is proposed. In the first stage, all of the feasible system configurations are determined using NREL's HOMER software which is a well-known and well-established optimal modeling environment. Subsequently, in the second stage based on Analytical Hierarchy Process (AHP) and simple additive weighting (SAW) method, the best configurations for hybrid system are determined through the Expert Choice software considering economical and environmental criteria. With the aim of providing a comprehensive decision-making capability, a sensitivity analysis is performed considering relative importance of each criterion. Simulation results demonstrate that for the considered complex, the best configuration is grid/diesel/wind hybrid system as it shows a uniform behavior for different cases.

Key words: Microgrids, Hybrid Energy Systems, Sustainable Electricity Planning, Analytical Hierarchy Process, Sensitivity Analysis.

1. Introduction

Today, world is facing with some challenging crisises including population growth, more energy requirements, looming fossil fuels, and also environmental concerns such as ongoing increase in green house gases (GHGs) and global warming. As a relieveing solution, renewable energy sources (RESs) such as wind and solar energy are catching more attention as clean and limitless energy resources apt to obviate the aforementioned concerns [1]. Hence, most governments are promoting sustainable expansion of grid-connected large-scale microgrids with hybrid RESs [2]. The term "hybrid" alludes to an electrical system that incorporates more than one type of generators such as a diesel engine,RES-based technologies including wind, and photovoltaic (PV), and also storage technologies like batteries [3].

Efficient and optimal usage of RESs in every location is directly related to the precise assessment of wind and solar potential and their

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availability. Hence, many scientists and researchers have focused on designing and assessing the hybrid RESs for sustainable electrification of different-sized microgrids. Shahid and Elhadidy [4] have considered PV/battery based hybrid energy system and carried out an economic analysis based on cost of energy (COE) criterion. They have proved the potential of solar energy in providing enough electricity and less pollution. Authors in [5] have determined the suitable hybrid configuration for a region in Marmara, Turkey. In their research, the PV-hydrogen system is determined as the most feasible solution. Dalton et al. [6] have focused on the feasibility evaluation of RESs for supporting the electrical demand of large hotels in Australia. The evaluation criteria include net present cost (NPC), renewable fraction (REF) and payback time. Nayar et al. [7] have concluded that a wind/PV/diesel hybrid system established in remote islands of Maldives is a good option to reach in a higher share of renewable energy in electrification process. Also, performance of a mixed PV/wind hydrogen energy system is reported in [8]. Celik [9], has proposed a small-scale renewable energy system to improve the quality of life in remote areas. In [10], Dihrab and Sopian have inferred that the use of hybrid energy system with grid-connection capability provides an economically and environmentally-friendly alternative to produce electric power. The vast body of available literature in this field emphasizes the importance of RESs as an electricity source nearly all over the world.

In the previous decades, the government's subsidies for energy carriers in Iran have hold the price of fossil fuels such as diesel and oil as well as other form of energy such as electricity to a level much lower than the global prices. However, partial removal of subsidies in 2011, raised the price of energy to a great extent and this trend will be realized more intensively in near future [11]. Therefore, with the aim of achieving a more economical plan, Renewable Energy Organization of Iran (SUNA), a section governed by Ministry of Power has initiated to develop hybrid RESs-based microgrids in a large scale [12]. In this context, some studies such as [3] have conducted feasibility study and application of RESs to meet the electrical requirements of remote villages in Iran. They have focused on selecting the best plan for different conditions of microgrid only based on NPC criterion and HOMER results. The absence of a new and effective methodology to cater both the economical and environmental issues is one of the main shortcomings of the aforementioned study which motivates us to establish a deeper analysis herein. Also, it is worth noting that the potential of renewable energy exploitation for the electrification of coastal tourism complexes in Iran has not yet been fully explored.

Keeping the foregoing discussion in mind, this study aims to present an exact and efficient sustainable expansion planning strategy for coastal tourism microgrids. A coastal tourism complex which is located in the coastal line of Orumieh is considered as the test bed here. This complex has been previously supplied via the main grid connection. With the aim of achieving the sustainable and a clean energy supply, RESs are considered in the planning stage of this microgrid. Commencing the procedure, environmental data such as wind speed and solar radiation are acquired through the measuring devices and also international databases such as National Aeronautics and Space Administration (NASA). Subsequently, forecasted electrical requirements of the tourism complex and also the costs related to the different technologies of RESs are provided. The large amount of publications and research works conducted based on NREL's HOMER software [1], [3], [10], [13-15], justifies its well performance to settle it as the modeling environment herein. HOMER initiates with the aim of finding the feasible solutions for the microgrid planning problem and ranks the plans based on minimum net present cost (NPC). Most of the presented works in the literature have sorted the feasible plans based on the NPC or renewable fraction (REF) and no clear strategy is presented to select the most suitable plan. In fact, one of the main shortcomings of the available methods is the lack of an exact mathematical model to select the best plan based on all criteria, namely both NPC and REF to be implemented. Hence, the main contribution of this work is to present a two-stage expansion planning strategy to determine the best configuration of tourism complexes microgrids. The first stage is implemented via the HOMER simulation results where NPC and REF for each plan are calculated. In the second stage, the analytical hierarchy process (AHP) is devoted to take into account the importance degree of each criterion. Taking into account the relative importance of each criteria such as NPC or REF, the AHP procedure determines the most suitable configuration for the considered microgrid. Consequently, it would be possible for the planners and investors to select a suitable plan based on the importance of each criteria. Also, a sensitivity analysis is conducted to scrutinize the behavior of each configuration in different cases. The plan with the most uniform behaviour in all of the importance degrees of criteria, would be known as the most robust plan for microgird implementation. Eventually, it is shown that the grid-connected diesel/wind hybrid energy system is the most suitable one for the considerd tourism complex.

2. Microgrid Plan Determination based on HOMER

This section is devoted to present the mathematical formulation for determination of feasible plans and their configuration for the considered microgrid. Then, the initial results are obtained based on HOMER platform and introduced in more detail.

2.1. Mathematical Formulation

2.1.1. Objective Function

For a specific microgrid, a plan with lower NPC results in a better economical condition while satisfying different constarints. Hence. for each plan, the objective is to minimize the total NPC which is calculated based on equation (1) as follows:

$$Minimize \quad NPC = C_{cap} + \sum_{n=1}^{N} [(C^n_{O\&M} + C^n_{repl} + C^n_{buy} + C^n_{sale} + C^n_{salvage} + C^n_{fuel}) / (1+i)^n] \tag{1}$$

In (1), i corresponds to the annual real interest rate, and N is the number of years. The different cost components in (1) are calculated as follows:

- **Total components capital cost:**

$$C_{cap} = \sum_{j=1}^{N_{com}} C^j_{cap} \tag{2}$$

where N_{com} is the number of components in each plan and C^j_{cap} is the capital cost related to each component ;

- **Operation and mainatnace cost:**

$$C^n_{O\&M} = \sum_{j=1}^{N_{com}} C^j_{O\&M} \tag{3}$$

in (3), $C^j_{O\&M}$ is the operation and mainatnace cost of each component in *n-th* year;

- **Replacement cost:**

$$C^n_{repl} = \sum_{j=1}^{N_{com}} C^j_{repl} \tag{4}$$

The repalcing costs of each component is represnetd by C^j_{repl} in *n-th* year;

- **Cost of purchased power from grid:**

$$C^n_{buy} = \sum_{t} \rho^t_{buy} . E^t_{buy} \tag{5}$$

where ρ^t_{buy} is the price of buying electricity from grid, and E^t_{buy} is the amount of electricity purchased from grid in every hour t in *n-th* year;

- **Revenue earned by selling power to grid:**

$$C^n_{sale} = \sum_{t} \rho^t_{sale} . E^t_{sale} \tag{6}$$

as a revenue, this term would be considered negative, ρ^t_{Sale} is the selling price of electricity to the grid, and E^t_{Sale} is the amount of electricity sold to the grid.

- **Salvage cost:**

$$C^n_{salvage} = \sum_{j=1}^{N_{com}} C^j_{repl} \cdot \frac{R^j_{rem}}{R^j_{com}} \tag{7}$$

as an income, this term should be considered negative. R^j_{rem} and R^j_{com} are the remaining and nominal lifetime of each component respectively.

- **Fuel cost:**

$$C^n_{fuel} = \sum_{t} \rho^t_{diesel} . L^t_{diesel} \tag{8}$$

where ρ^t_{diesel} and L^t_{diesel} are the price and consumption amount of diesel in every hour t in *n-th* year respectively;

2.1.2. Running Constraints

The objective function introduced in (1) is subjected to the following equality and inequailty constraints:

- **Power flow limitation of each componenet:**

$$P_j^{\min} \le P_j^{com} \le P_j^{\max} \quad (9)$$

This constraint is to observe the power flow limitation for each component. $P_j^{\min}$ and $P_j^{\max}$ are respectively the minimum and maximum posible power flow in each component.

- **Power balance:**

$$P_{buy} + P_{components} = P_{load} + P_{sell} + P_{loss} \quad (10)$$

This equation guarantees the power balance at each hour in a year, P_{buy} is the purchased power from the external grid, $P_{components}$ relates to the produced power by different technologies in micrigrid such as wind turbine and PV pannels, P_{load} represents microgrid electrical demand, P_{sell} demonstrates the power sold to the external grid, and P_{loss} accounts for the lossess inside the microgrid.

2.1.3. Share of Renewables in Each Plan

REF for each plan is the fraction of the energy delivered to the load originated from renewable power sources [16]. For a specific plan, the *REF* is determined by equation (11).

$$REF = 1 - \left(\frac{E_{nonren} - E_{grid,sales}}{E_{served}}\right) \quad (11)$$

Herein E_{nonren} is the non-renewable electricity production, $E_{grid,sales}$ is the energy sold to the grid and E_{served} represents the total electrical load served in a year. The more the *REF* is, the less diesel or grid generation would be; hence, less pollutant emissions would be produced.

2.2. Obtained Results based on HOMER Optimization

2.2.1. Studied Microgrid

As presented earlier, the considered tourism complex is located in the coastal line of Orumieh, (37°58′35.15″ N, 45°25′85.14″ E), West-Azerbaijan, Iran where Figure 1 shows the geographical location of this tourism complex. The considered complex has been recognized as a tourism complex and there are many installations and equipment that are being installed for this purpose. This complex comprises a medium-sized hotel and also some small rooms to be rent near the coast. As it is going to be accomplished in the near future, it is very fruitful to determine the best RESs technologies to be installed in this microgrid. Hence, diesel, wind turbine, PV arrays and batteries along with the grid-connected feature are put under investigation herein. The aim is to determine the best plan for the considered microgrid to be implemented.

Fig. 1. Location of considerd tourism complex in Iran.

2.2.2. Assumptions and Model Inputs

As described in the previous subsection, in the considered grid-connected microgrid different technologies namely diesel, wind turbine, PV arrays, and batteries are envisaged. Figure 2 depicts microgrid's setup which has been used for simulation studies and further analysis. In the previous sections, it was mentioned that the NREL's HOMER software is considered as the base optimization simulator. Working with HOMER, needs to provide some input data about the electrical load demand, environmental information such as wind speed and solar radiation, and economical inputs such as fuel cost. In the following, the required input data are provided in a different part.

- **Electrical Load**

The considered tourism complex is a new one which is on the way of development; hence, exact estimation of its electrical demand is postponed to the near future when it is nearly fulfilled. Consequently, a similar electrical consumption pattern depicted in Figure 3 is speculated here. The maximum amount of hourly electricity consumed by complex is about 100 kWh which occurs at 18 PM in summer. For the other seasons, including spring, autumn and winter, the electrical demand is taken to be 65% of the summer values. Also, 15% of daily noise and 20% of hourly time-step noise is considered in the load pattern [16]. As a result, the maximum hourly load of complex is seen to be equal with 164 kWh throughout the year.

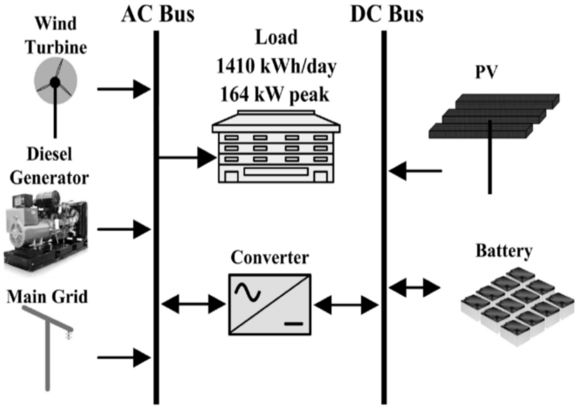

Fig. 2. The studied microgrid setup.

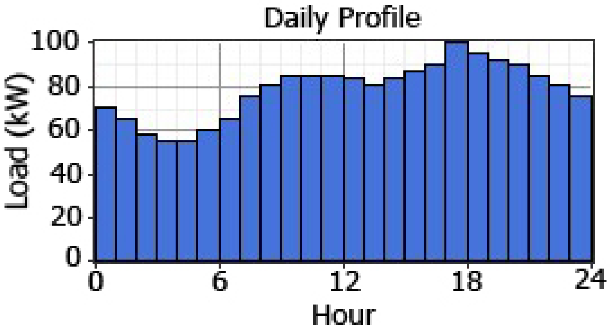

Fig. 3. Hourly electrical load profile of the examined microgrid.

- **Wind Speed**

The wind speed for Orumieh is directly acquired through the synoptic meteorological stations provided by I.R of Iran Meteorological Organization (IRIMO) [17]. But, there is no access to the real values for wind speed in the coastal line. However, it is obvious that the wind speed in the coastal line is to somewhat greater than the wind speed in the lands far away [18-19]. Hence, wind speed in the coast is considered to be 1 m/s greater than the values obtained by the IRIMO for Orumieh city. Figure 4 demonstrates the wind speed profile in one year period.

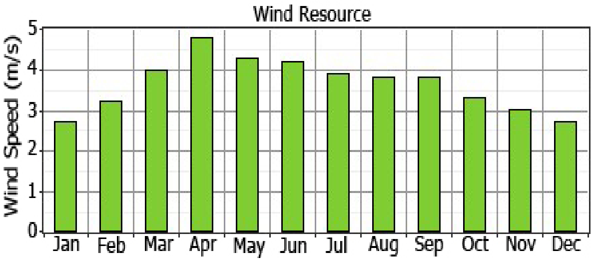

Fig. 4. Wind speed profile for the considered microgrid.

The annual average wind speed for this area equals 3.64 m/s. There are some parameters concerning the wind speed distribution in the HOMER. The parameter Weibull *k* relates to the long term distribution of wind speed in a year. The auto-correlation factor models hour-to-hour random behavior of the wind speed. The dependency of the wind speed on the time of the day is modeled via the diurnal pattern strength [16]. Based on the introduced parameters, HOMER is able to calculate the wind speed for each hour of the year. In the considered system, the presented three parameters namely, Weibull (*k*), the auto-correlation factor, and the diurnal pattern strength are supposed to be 2, 0.85, and 0.25 respectively. The wind turbine model is PGE 20/25 for which the cost related information is provided in Table 1.

- **Solar Radiation**

For the case of solar radiation, data for the considred complex is obtained from National Aeronautics and Space Administrative (NASA) 22-year average monthly database [20]. Figure 5 exhibits the solar radiation data for the considered microgrid over a one-year period. As it is seen, the solar radiance ranges from 2.11kWh/m^2/day to 7.70kWh/m^2/day. The annual average solar radiance is 4.95kWh/m^2/day. For the PV arrays, a de-rating factor of 90% representing 10% reduction in power production, modeling the temperature and dust effect is considered. Also, no tracking system is taken for the PV panels. The cost related information for PV arrays is provided in Table 1.

- **System Economics along with Components Specifications**

This part addresses the microgrid components specifications and cost related information. The main project lifetime is assumed to be 25 years and the annual real interest rate is considered to be 10%. The grid power price is equal to \$0.1/kWh [3] which is expected to increase by the total removal of subsidies in Iran in near future. Hence, for this research the grid power price is set on an average of \$0.15/kWh. Also, the current fuel price for the case of diesel is about \$0.32/liter which would experience higher values in the near future. The emissions penalty is set to be \$15/ton to limit the use of pollutant fossil fuels. Other required data regarding the components economic and technical specifications is presented in Table 1.

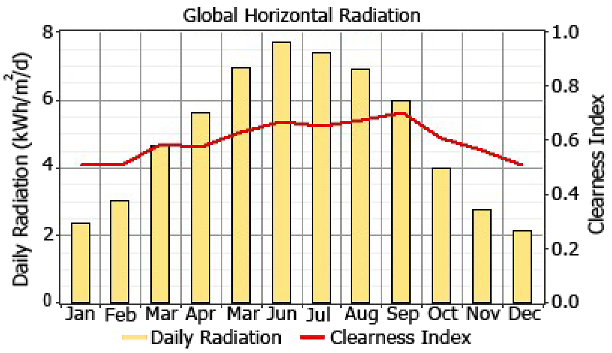

Fig. 5. Solar radiation for the considered microgrid.

2.2.3. Optimal Results Obtained based on HOMER

Table 2 presents the simulation results obtained by HOMER software and ranked based on the NPC. As it is seen, different configurations for the microgrid namely grid/diesel (Plan1), grid/diesel/wind(Plan2), grid/diesel/wind/battery (Plan3) and grid/diesel/wind/battery/PV (Plan4) are determined. As it is observed, HOMER ranks the feasible plans based on their NPC all over the project lifetime [16]. It is worth noting that as the solar radiation and intensity in the coast is relatively lower than wind speed, the combination of PV/Grid/Diesel/battery has a very high NPC to be implemented and has not been placed among the top plans to be implemented.

Table 1. Economical and technical specifications of components.

Description	Specification
1. Diesel generator	
Generator model	Cummins Generator
Sizes to consider	0 kW-175kW with an interval of 25kW
Capital cost [3]	\$1000/kW
Replacement cost [3]	\$900/kW
Operation and maintenance cost	\$0.02/hour
Lifetime	15,000 operating hours
2. Wind turbine	
Type of wind turbine	PGE 20/25
Rated power	25 kW
Numbers to consider	0-50 with an interval of 10
Capital cost [21]	\$100,000
Replacement cost [21]	\$60,000
Operation and maintenance cost	\$100/year
Lifetime	15 years
3. PV array	
Sizes to consider	0 kW-175kW with an interval of 25kW$_p$
Capital cost [3]	\$6,000/kW
Replacement cost [3]	\$5,000
Operation and maintenance cost	\$10/year
Lifetime	25 years
4. Batteries	
Type of battery	Surrette 6CS25P (6 V, 1156 Ah, 9645 kWh)
Batteries per string	10
Sizes to consider	0-25 string with an interval of 5
Capital cost [22]	\$1100 per single cell
Replacement cost [22]	\$1000 per single cell
Operation and maintenance cost	\$10/year
5. Converter	
Sizes to consider	0 kW-175kW with an interval of 25 kW
Capital cost [3]	\$900/kW
Replacement cost [3]	\$800/kW
Operation and maintenance cost	\$10/year
Lifetime	15 years
Conversion efficiency	95%

Table 2. Different configurations for microgrid determined by HOMER.

Plan							Wind Turbine (number)	Battery (Strings)	PV (kW)	Total NPC ($)	Renewable Fraction (REF)
Plan1	✓	✓	-	-	-	-	0	0	0	808,575	0
Plan2	✓	✓	✓	-	-	-	10	0	0	1,525,529	0.51
Plan3	✓	✓	✓	✓	✓	-	10	5	0	1,587,370	0.56
Plan4	✓	✓	✓	✓	✓	✓	10	5	25	1,708,424	0.6

As it is seen from Table 2, a smaller NPC does not necessarily coincide with a high REF and environmentally friendly plan. Hence, for a specific plan, having only a smaller NPC does not justify its qualification to be implemented. In the majority of related literature, there is a lack of suitable strategy to determine the microgrid configuration to be implemented considering more impressive aspects including both economical and environmental attributes. Hence, the subsequent subsection talks about the application of AHP method in selecting the microgrid configuration. The second stage is a mathematical model based on AHP to take into account more features in selecting an expansion plan for the studied microgrid.

3. Analytical Hierarchy Process (AHP) to Determine the Microgrid Configuration

As described earlier, proper quantitative criteria must be evaluated to determine the most suitable plan among the feasible plans to be implemented for the microgrid. To this end, the multi attribute decision making (MADM) techniques would be very effective. AHP as one of the MADM techniques, is used commonly in the situations facing with more than one effective criterion (attribute). The AHP method works based on the degree of importance for the criteria namely their weights [23]. In the following, the proposed method is presented in more detail.

3.1. Quantitative Criteria

In this research, two criteria are of great importance to sort the plans:

a) Economical criterion: NPC is considered as the best economic index in the period of planning.

b) Environmental criterion: REF is the share of renewable sources in the total load serving and is considered as a good index of environmental state of the plan.

The Expert choice software [24] is considered for performing the AHP method. For this work, the hierarchical view implemented by the Expert choice software is depicted in Figure 6.

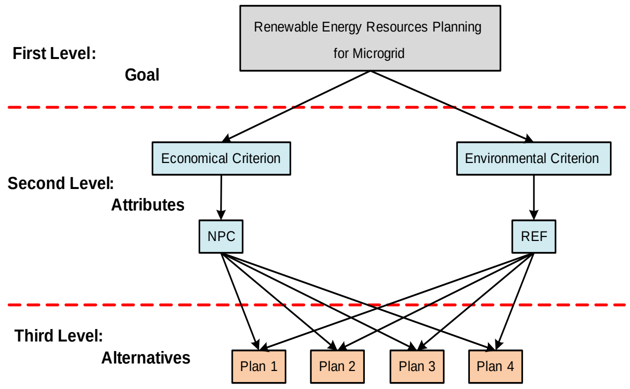

Fig. 6. Hierarchical view for microgrid configuration selection process based on AHP.

3.2. Utility Function

A utility function should be defined to obtain a net quantitative criterion. It is obvious that for a specific plan, the less NPC and more REF are desirable. In this work, a normalizing system is utilized so that a plan having the least NPC has the most value of NPC (U_{NPC}) of unity and the other NPCs are mapped to lower positive values accordingly. In the case of REF, the plan having the most REF has the most value of REF (U_{REF}) of unity and the other REFs are mapped to lower positive values accordingly. The utility function for Planj (U_{Planj}) is a weighted sum of the U_{NPC} and U_{REF}.

$$U_{Plan_j} = W_{NPC} \, .U_{NPC}(P_j) + W_{REF} \, .U_{REF}(P_j) \qquad (12)$$

where P_j represents the *j-th* plan, U_{Planj} is the net quantitative utility of the *j-th* plan, and finally W_{NPC} and W_{REF} are the importance degree of the NPC and REF respectively.

Table 3 presents the selected best plans for studied microgrid configuration for different values of W_{NPC} and W_{REF} highlighted in darker gray. It is seen that when the NPC as the economical criterion, is of the greater importance, Plan1 with the minimum NPC is selected and when the REF as the environmental criterion is of the greater importance, the other plans with greater REFs are selected.

Table 3. Influence of NPC and REF weights on configuration selection.

Weights		U_{Planj}			
W_{NPC}	W_{REF}	Plan1	Plan2	Plan3	Plan4
1	0	0.398	0.211	0.202	0.189
0.7	0.3	0.270	0.241	0.246	0.243
0.5	0.5	0.189	0.261	0.278	0.272
0.3	0.7	0.111	0.279	0.298	0.312
0	1	0	0.305	0.335	0.360

For example, for the case where only the REF is in the center of attention (W_{REF}=1, W_{NPC}=0), the Plan4 with the maximum REF=0.6 (60%) is going to be selected. However, although this methodology provides a good decision making capability for the investors or owners, it is not absolutely perfect. For example if a greater attention is given to Table 3, it can be seen that the column corresponding to Plan2 (column in lighter gray) has a uniform utility for different values of weights. Hence, a sensitivity analysis is performed to determine the best plan for the the examined microgrid.

4. Sensitivity Analysis for the Best Plan Selection

As discussed in the previous section, it was inferred that the plan selection process is dependent to the importance degree of criteria. But, a good plan is the one that with the change of weights, its utility does not vary in a wide range, i.e. it has a relatively acceptable utility in all cases. Hence, a sensitivity analysisshould be performed with the change of weights. Consequently, W_{NPC} and W_{REF} are varied in the range of 0-1 with interval of 0.1. Fig. 7 shows the sensitivity results for considered plans through the AHP process obtained based on equation (12).

With the aim of achieving to the most robust plan for the microgrid, robustness criterion is defined hereunder. A robust plan is the one that for different sets of weights would have the minimum variation in its utility, namely U_{Planj} presented in the Table 3 and Figure 7. Hence, the utility non-uniformity factor (UNUF) for *j-th* plan namely $\text{UNUF}_{\text{Planj}}$ is defined as below:

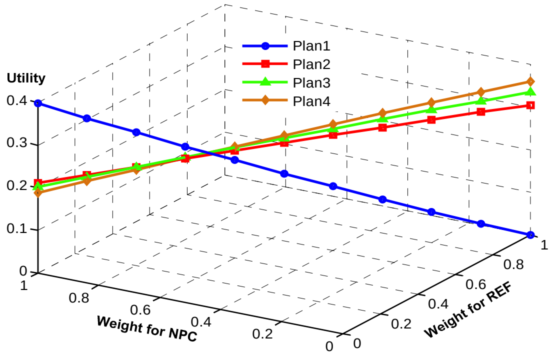

Fig. 7. Sensitivity analysis performed for the plans Plan1-Plan4.

$$UNUF_{Plan_j} = \frac{Max \; U_{Plan_j} - Min \; U_{Plan_j}}{\bar{U}_{Plan_j}} \qquad (13)$$

where $\bar{U}_{Planj}$ is the average value of all utility values for the *j-th* plan. Again a normalizing system is utilized so that a plan having the least $\text{UNUF}_{\text{Planj}}$ has the most value of robustness; hence, it is mapped to the highest value of unity and the others are mapped to the lower positive values accordingly. Fig. 8 provides utility of each plan considering the robustness criterion.

Figure 8 illustrates that Plan 2,i.e. grid/ diesel/ wind configuration is the most robust candidate for all sets of weights (W_{NPC}, W_{REF}). Consequently, it shows more robustness against the uncertainty regarding the weights of criteria and is the best configuration for considered microgrid. Thus, investors will be more confident about the economical and environmental efficiency of microgrid configuration to be implemented. In the initial obtained results for the evaluation of plans, Plan1 seemed to be the best configuration as it shows the minimum total net present cost among the feasible plans presented in Table 2. Also Plan4 was taken to be the best plan when the environmental criterion was concerned. However, with respect to Figure 8, it can be inferred that Plan1 and Plan4 respectively show the minimum robustness to be implemented. Also, Fig. 8 reveals that Plan3 is the other good option for microgrid configuration as it has a relatively acceptable robustness in with different degrees of importance for criteria.

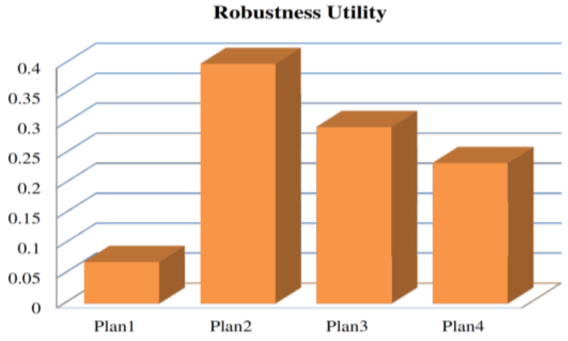

Fig. 8. Robustness utility for different plans.

Figure 9 exhibits the electric power production for the case of Plan2. As it is seen, wind turbine and grid connection have the most shares in supplying the electrical load. Also, the diesel generator is producing the remained electricity need for the grid.

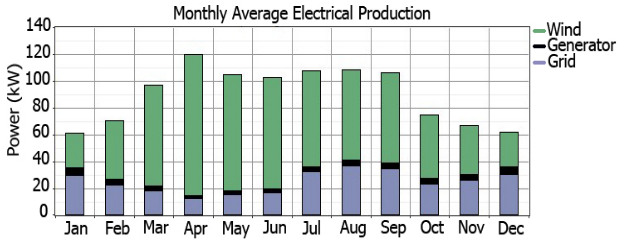

Fig. 9. Power production for the case of Plan2

Figure 10 demonstrates the annual cash flow for Plan 2 over the project lifetime. It is seen that the largest cost component corresponds to capital and replacement costs while the operating and fuel costs have the minimum share in raising NPC. The diesel generator experiences a replacement cost in a twelve-year cycle because of its 15000 hours operating life. Also a constant yearly cost of fuel and operation is observed.

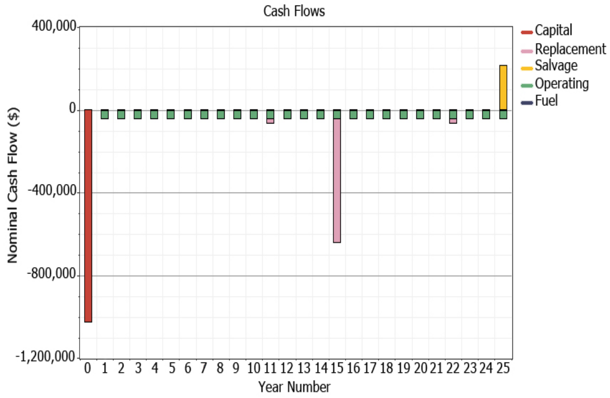

Fig. 10. Nominal cash flow details for Plan2 configuration.

5. Conclusions

This study intended to present an efficient two-stage investment planning selection methodology for microgrids. Firstly, by providing input data, the well-known HOMER software was utilized to determine feasible configurations for the examined tourism complex microgrid. In the second stage, besides the NPC, the REF of each plan was considered as the evaluation criteria. The proposed AHP method based on NPC and REF criteria has been considered for assessing the available plans. It was shown that for different degrees of importance for criteria, different plans get higher priority for implementation. This observation highlighted the importance of the proposed methodology taking into consideration the different aspects for evaluating the possible microgrid configurations. The proposed sensitivity analysis paved the way to determine the more robust plan considering all of the importance weight sets for the criteria. It was seen that Plan2 shows a more uniform utility against the change in weights. Hence, this plan was selected as the best and most robust plan for the considered coastal microgrid. Also, it was shown that a plan with the minimum implementation cost, such as the case of Plan1 in this study, is not necessarily the best plan for a microgrid expansion.

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