Optimization of a renewable energy supply system on a remote area: Berlenga Island case study

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Abstract: HOMER software was used to technical and economically assess two renewable energy supply (RES) system configurations – PV-only (80 kW) and PV (34 kW)/WT (36 kW), both with a three day storage capacity and requiring 11kW of electric power – proposed by a partnership project responsible for the implementation of sustainable measures on a Portuguese small island. HOMER calculation showed insufficient storage capacity for both RES system proposed, so extra storage capacity should be added. Economically, life cycle cost (NPC) of the cheaper configuration (PV/WT) resulting from HOMER calculation was significantly lower (20%) than the one advanced by the project. On a second stage, HOMER was used to compute an optimal RES system configuration to attend water desalination and street lighting electric additional loads. The optimal configuration – PV (25 kW)/WT (18kW) – costs 18% less than the equivalent PV/WT system proposed by the project when the same additional load is considered. Sensitivity analysis on the electric load showed the cost difference between project's and HOMER's proposals fading as the load increased. Variation on wind speed average demonstrated the significance of data accuracy: using NASA's average wind speed data the NPC increased on 15% compared to using wind speed values revealed on a monitoring campaign on the island.

Keywords: *Remote off-grid energy systems, Optimization software, Sensitivity analysis*

1. Introduction

Decentralized energy generation systems have become a recent trend on the development of energy systems. Concerns related to energy security and climate change have been fostering the implementation of projects that allow the production of power and heat closer to the point of use [1], as the current and dominant approach of centralized energy production, based on fossil fuels, lead to inequities, external debts and significant environmental degradation [2]. Sustainability of energy systems is based on the energy hierarchy principles: top priority is energy conservation, next the adoption of renewable resources for energy production, and last the use of fossil resources [3].

Planning energy systems represents a major issue on the development process of our society. Available computational energy models can support energy planners to decide the best configuration for an energy supply system, as they allow simulating different solutions and working conditions, and checking their technical and economical feasibility in an early stage of the decision process. Optimization models, namely linear programming mathematical models, are usually used to solve cost minimization problems subject to specific technological, political and demand satisfaction constraints given by energy models [4]. This is the case of HOMER®, a software developed by the US National Renewable Energy Laboratory to address the need for a hybrid system design tool accurate enough to predict energy system performance. It has been used on several situations all over the world: a feasibility study for the implementation of a zero home energy in a Canada's city [5]; study of wind penetration into an existing diesel plant of an Saudi Arabia village [6]; analysis of the technical and financial viability of grid-only, renewable energy supply (RES)-only and grid/RES hybrid power supply configurations for a large-scale grid-connected Australian hotel [7].

2. Methodology

2.1. HOMER Software

HOMER is primarily an optimisation software package which simulates different RES system configurations and scales them on the basis of net present cost (NPC), which is the total cost of installing and operating the system over its lifetime. Depending on the input data and constrains imposed by the user, HOMER firstly assesses the technical feasibility of the RES system (i.e. whether the system can adequately serve the electrical and thermal loads and any other constraints imposed by the user), and then estimates the system's NPC [7]. Besides the electric load to attend, the user has to specify the "search space", i.e., the sizes and/or quantities of the different components of the RES system (wind generators (WT), photovoltaic array (PV), batteries, inverters, electrolyser, generator…) that will be used to calculate the optimal system design. It also performs sensitivity analysis to evaluate the impact of a change in one or more of the input parameters.

HOMER was used on this paper with three purposes: first, to assess the technical and economical performance of two predetermined RES system configurations; second, to optimise a RES system based on wind and solar resources on the Berlenga Island; and third, to assess the impact of the variation on electric load and the average wind speed has on the optimal RES system configuration.

2.2. Case Study: Berlenga Island

The Berlengas Archipelago is located 6 miles away from the Carvoeiro cape on Western Portugal, and has approximately 100 ha. Its island is called Berlenga Island. There is no resident population on this small group of islands, which contributed for the preservation of singular species of flora and fauna. Despite the absence of resident population, there is some human activity on Berlenga Island all year long: lighthouse workers are present on the island 24H/7day during all year. They work on rotation teams and spend several days in a row all year long; some Peniche's municipality workers spend some periods of time on the island form March to November; from May to October nearly 30 fisherman and restaurant workers stay full time on the island. Besides these "permanent" residents, there is a legal limitation of 350 islands visitors [8].

Before 2007, when a partnership program called "Berlenga – Sustainability Lab" (from now on called Berlenga Project) started, electricity generation was based on diesel generators (130 kW), producing 30 MWh/year and consuming nearly 15000 L/year (roughly 40 ton CO_2 emissions/year) [9]. This system had several drawbacks: high O&M diesel costs due to the aggressive environment on the island; limited energy supply schedule; island development compromised due to electrical limitations (water treatment systems) [9-10]. As so, Berlenga Project intended to develop a zero CO_2 emission electric system to supply the Berlenga Island. Two possible configurations were proposed: Configuration A – PV/WT system; Configuration B – PV-only system. Accordingly to Berlenga Project, Configuration A is less expensive than Configuration B (600 k€ and 750 k€, respectively), however it has an higher environmental impact (mainly because of WT's visual impact and sound pollution) [10].

2.2.1. Berlenga Project Electric Load

In an early stage of Berlenga Project, island's electric monthly load profile was monitored – Fig. 1. Island's electric load profile shows irregular electricity consumption due to the "tourist invasion" during summer months. This domestic electric load profile refers to electricity use on households only. From December to February the only residents on the island are the lighthouse workers. The lighthouse already had a PV array installed and that justifies the absence of electric load on those months. To perform a HOMER simulation, a monthly load profile is not accurate enough. It is required an hourly electric load profile. For that purpose it was used a typical household hourly load profile – Fig. 2 – in order to calculate an hourly load for an average day of each month of the year. The maximum electric power considered was 11 kW and the electric load is subject to 5% standard deviation on daily averages and 10% deviation between the difference of hourly data and the average daily profile.

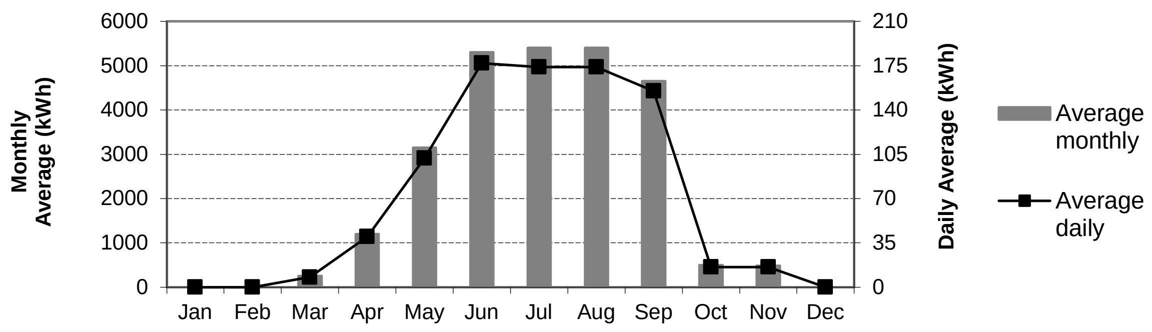

Figure 1. Monthly and daily average domestic electric load profile – adapted from [9].

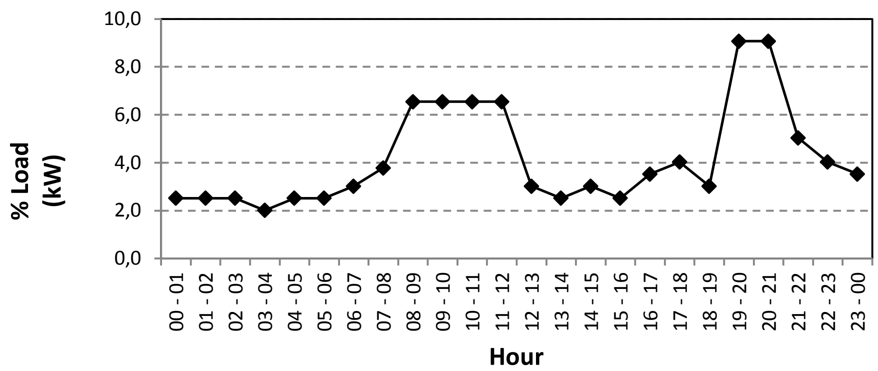

Figure 2. Hourly load percentage distribution during a typical day – adapted from [11].

2.2.2. Additional Electric Loads

Installation of street lighting on the island was assessed on this study. The street lighting system should include 10 street lamps with 125W each working on average 10h/day (3650 hours/year). During winter (Oct-Mar) street lightning works 12 hours/day (from 19:00 to 07:00) and on summer period (Apr-Sep) only 8 hour/day (from 22:00 to 06:00).

The island doesn't have fresh water reserve aquifers. Fresh water is supplied to the island through an 8 m^3 container, by the ship that takes the visitors to the island [12]. According to the last report on this matter [12], fresh water consumption on the island during high season (July and August) was 3 m^3/day and 2 m^3/day on 2007 and 2008 respectively. The fresh water load and electric load required to produce it using a reverse osmosis equipment, are shown on Fig. 3. This electric load was considered as a *deferrable load*, i.e. electrical load that must be met within some period of time, but the exact timing is not important.

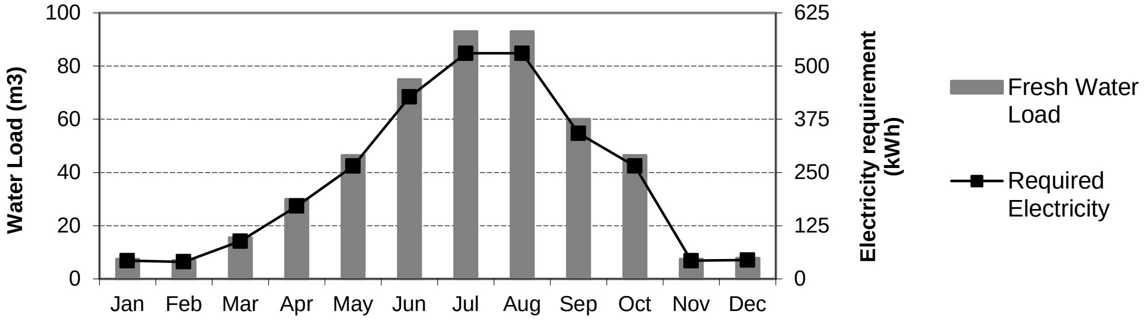

Figure 3. Fresh water consumption and required electricity to produce it.

2.3. Renewable Resources – Wind and Sun

Two sources of information were available on wind average speed. Through NASA's website on data information on surface meteorology and solar energy [13] it's possible to get a monthly profile according to the geographic coordinates of a certain location. To the location of Berlenga Island the database indicate a baseline annual average of 5,16 m/s. In addition to this information, wind potential on the island was evaluated through a monitoring campaign from December 2006 to September 2007 [14]. The campaign's reported an average wind speed of 6,74 m/s, significantly higher than NASA's baseline annual average. As so, it was used 6,74 m/s as a scaled annual average value on the simulation. The scaled data retains the shape and statistical characteristics of the baseline data, but may differ in magnitude.

Solar data information provided by HOMER database was used, according to the geographic coordinates of the island – 4,092 kWh/m2/day and 0,518 Clearness Index.

2.4. Equipments

To perform HOMER simulations, RES system equipments shown on Table 1 were considered.

Table 1. Capital and operation and maintenance costs of a RES system's equipment.

Equipment	Capital Cost	O&M Cost
6 kW Wind Turbine	29445 €/unit [15]	600 €/year [16]
15 kW Wind Turbine	76700 €/unit[15]	850 €/year [16]
Photovoltaic Array	5500 €/kW [17]	10 €/kW [18]
Battery 6CS – 7,6 kWh	850 €/unit [19]	10 €/year [19]
Battery 4KS – 6,94 kWh	770 €/unit [19]	10 €/year [19]
Inverter/Converter	550 €/kW [19]	-

3. HOMER simulation results

Solar and wind data, electric loads and equipments required to build a RES system were described on the previous sections. The project lifetime is 25 years.

3.1. Berlenga Project Configurations

The Berlenga Project originally proposed two alternative configurations for the required RES system: Configuration A – PV (34 kW)/Wind Turbine (36 kW); Configuration B – PV (80 kW). In order to meet Berlenga Project constrains, both configurations should attend the required domestic electric load and include batteries with capacity to bear three days of average consumption, i.e., 230 kWh [9-10]. After running the simulation with this storage capacity, the only feasible configuration resulted on a PV (80 kW)/WT (36 kW) system, mainly due to high electric demand on summer days. As so, it was necessary to extend the storage capacity to enable the simulation of both Configurations A and B – Table 2.

3.2. Additional electric load scenario

Configuration A and B were simulated to attend the domestic electric load monitored on the scope of the project as shown on Fig. 1. It was simulated a RES system configuration to attend additional street lighting and water desalination electric loads – Current Load Scenario – resulting on Configurations C and D, as shown on Table 2. Adding these two additional loads resulted in higher Initial Capital Cost (IC) and NPC, basically due to the requirement of extra storage capacity and respective O&M costs, however the cost of energy (COE) dropped. HOMER defines COE as the average cost per kWh of useful electrical energy produced by the system. The lower COE shows more efficient use of the electricity produced, as the same amount of electricity is produced and more energy is effectively used.

Table 2. RES systems configurations proposed by Berlenga Project.

RES Config	PV (kW)	WT 6kW (unit)	6CS (unit)	4KS (unit)	Conv (kW)	IC (k€)	O&M ($/yr)	NPC (k€)	COE ($/kWh)
3 day storage	80	6		30	21	642	8789	764	1,415
A	34	6	35		19	390	5744	506	0,937
B	80			65	21	495	4168	579	1,073
C	34	6		40	19	398	6101	520	0,757
D	80			80	21	508	4874	606	0,882

3.3. Optimal configuration by HOMER

As an alternative solution to the originally proposed configurations, above referred as A and B, HOMER was used to shape an optimal RES system based on PV panels, wind turbines and a battery bank to store electricity in order to attend the same domestic electric load shown on Fig 1. It was included a 15 kW wind turbine on this simulation in addition to the 6kW wind turbine. The optimization results are shown on Table 3. Three different configurations result to be possible for the implementation of a RES system on the Berlenga Island: Configuration 1 – PV (25kW) + WT (3x6kW); Configuration 2 – PV (65 kW); Configuration 3 – WT (9x6kW). Configuration 1 represents the HOMER optimal configuration – lowest NPC. The RES system based on PV-only (Configuration 2) is significantly more expensive than mixing PV and WT. A third option (Configuration 3) is available using wind turbines only. This one has a lower IC than configuration 2, but the higher O&M costs results on a higher NPC.

Table 3. HOMER optimal configuration when attending the domestic, water desalination and street lighting loads.

RES Config	PV (kW)	WT 6kW (unit)	WT 15kW (unit)	4KS (unit)	Conv (kW)	IC (k€)	O&M ($/yr)	NPC (k€)	COE ($/kWh)
1	25	3		85	22	298	6374	426	0,620
2	65			95	21	438	5430	548	0,796
3		9		100	19	350	10387	559	0,813

Comparing Berlenga Project's original configurations C (PV/WT) and D (PV-only) with configurations 1 (PV/WT) and 2 (PV-only) resulting from HOMER optimization, it is clear that the last ones present better financial indicators, especially the PV/WT configuration.

3.4. Sensitivity Analysis by HOMER

3.4.1. Electric Load

The effect of higher electricity requirement on HOMER optimal configuration was assessed through a sensitivity analysis, by creating two additional electric load scenarios: 10% Increase Scenario – 10 % increase on domestic and water desalination electric load; 20% Increase Scenario – 20 % increase on domestic and water desalination electric load. Street lighting remained unchanged on both scenarios. A PV/WT system resulted to be the optimal configuration for both scenarios. The NPC increases linearly with the electric load – Fig. 3. Comparing configuration C (34 kW PV/36 kW WT) with HOMER optimal configuration for each electric load scenario, it can be stated that the greater the electric load the closer is the economic performance of both configurations even though the optimal configuration proposed by HOMER is always cheaper – Fig. 4.

With 10% load increase scenario the three possible configurations for the RES system showed on Table 3 are feasible. As the electric load increase 20%, PV-only solution becomes unfeasible.

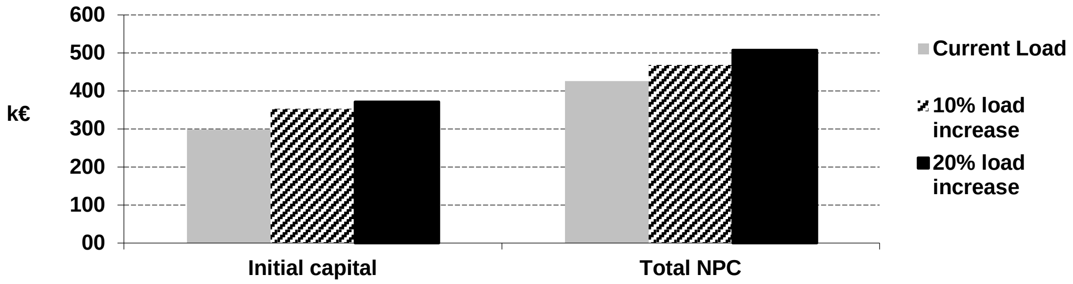

Figure 4. Effect of increasing electric load on RES system costs.

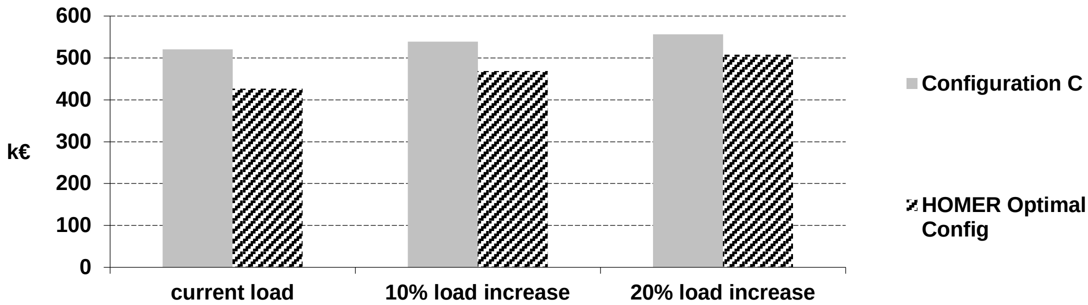

Figure 5. NPC comparison between Configuration C and Configuration 1.

3.4.2. Wind speed

As occurred with the electric load sensitivity analysis, a PV/WT system resulted to be the HOMER optimal configuration when assessing wind speed influence. The economic impact of the average wind speed on the optimal RES system can be assessed on Fig. 5. Using NASA's database value for annual average wind speed, NPC increased around 11% on all three electric load scenarios.

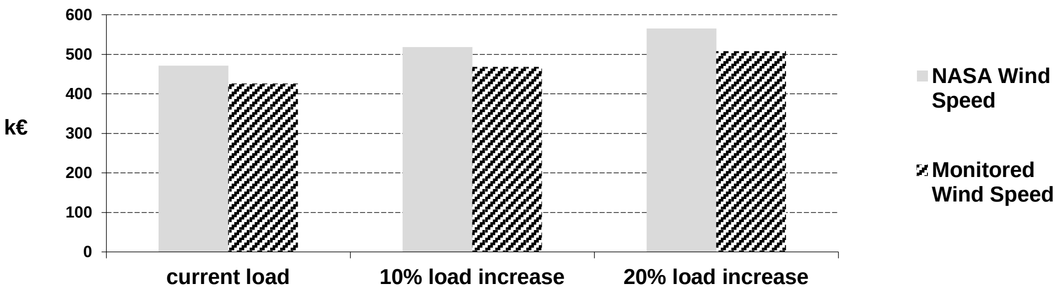

Figure 6. Effect of the average wind speed on system's NPC for each of the electric load increase.

For the current load scenario, the feasibility of the three possible configuration systems is not affected despite the WT-only system results to be almost 80% more expensive than the PV/WT optimal configuration. As the load increase 10% the WT configuration becomes no longer feasible and with 20% electric load increase PV/WT is the only feasible configuration.

4. Conclusions

One of the assumptions made by Berlenga Project's authors was to use a three day storage capacity (230 kWh). HOMER's system simulation showed that this storage capacity not enough for the proposed RES system configurations (A and B) mainly because of the high demand on summer months.

Information on system's cost issued by the Berlenga Project is not completely obvious. A cost of 600 k€ for configuration A (PV/WT) and 750 k€ for configuration B (PV-only system) was assumed, but it is not clear if those are IC or NPC [9]. Assuming those values as NPC and that the aim is to attend the domestic electric load monitored under the Berlenga Project, the costs resulting from HOMER simulation for both system configurations are lower than those proposed by the Berlenga Project: 506 k€ for configuration A and 579 k€ for configuration B. When attending additional street lighting and the water desalination loads (configurations C and D) the costs rose, due to higher storage capacity needed, but they still were far from the costs advanced by the Berlenga Project. This cost gap can be explained, at some extent, by the fact that the costs advanced by the Berlenga Project were from 2007, three years ago. When performing the "free" optimization to attend domestic, water desalination and street lighting loads (Current Load Scenario), the optimal configuration (configuration 1) includes 25 kW photovoltaic panels and three 6 kW wind turbines. Both PV/WT and PV-only optimized configurations resulted to be cheaper than the ones proposed by the Berlenga Project.

Two sensitivity analyses were performed to assess the impact of electric load deviation and average wind speed on the RES system cost and configuration attending domestic, street lighting and water desalination loads. As the electric load rises, the closer is the economic performance of both Berlenga Project (configuration C) and HOMER optimal configurations, even though the latter is always cheaper. This means that the configuration proposed by the Berlenga Project was oversized for the present electric load requirement. This may be an assumed choice, having in mind the future load growth, when new electric loads were included in the grid, the only equipments to add on the RES system should be batteries to store electricity. Despite using NASA's data to profile the average monthly wind speed, a scaled value for the wind speed based on the monitoring campaign made on the Berlenga Island was used to compute the simulation, for a better representation of local conditions. Higher average wind speed means more available wind resource and less costs to generate the same amount of electricity. The higher wind speed value results on a 10% lower NPC for the optimal PV/WT configuration. This is true both for current load and for load increase scenarios. This analysis stresses the importance of use valid reliable data, namely renewable resources availability data, when performing a technical and/or economical assessment of a RES system.

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