Techno-Economic Evaluation of Different Hybrid Power Generation Systems for a Partially Isolated Village in the Bajo Guadalquivir Region

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***Abstract*—Due to the sparse distribution of some sparsely inhabited villages in southern Spain and the poor electrical infrastructure that feeds them (often through a single line), blackouts are common in these villages, especially during adverse weather conditions. Turning the village into an isolated grid. This factor makes it necessary to use a diesel backup generation system, which increases the price of electricity due to the cost of fuel. This research will compare different Hybrid Renewable Energy Systems (HRES) to reduce production costs when villages operate as isolated grids. Different generation topologies will be developed, combining the small autonomous system with autonomous photovoltaic solar systems or with Battery Energy Storage Systems (BESS), as well as autonomous wind turbine power systems, with batteries or with flywheels.**

***Index Terms*—Hybrid Renewable Energy System (HRES), Photovoltaic System, Battery Energy Storage System (BESS), Isolated Grid, Generation Cost, Small Autonomous System, Wind Power System, Flywheel.**

I. INTRODUCTION

The Bajo Guadalquivir region and its surrounding areas are zones within the province of Seville, Spain, where there are around 50 villages with fewer than 1,500 inhabitants. Most of these inhabited villages are powered by a poor transmission system. When the winds are stronger than usual or a big storm is coming, the system fails, leaving hundreds of homes in an indefinite blackout. This research will focus on Marismilla, a small village dependent on the town hall of Las Cabezas de San Juan, also located in the province of Seville.

This village experiences multiple grid disconnections throughout the year. It relies on a diesel generator during these outages, significantly increasing the electricity generation cost. On the other hand, they have the advantage of having a large land extension with favorable conditions for both photovoltaic and wind generation, benefiting from good sunlight exposure and windy areas.

Through the diesel generator, the entire village population is covered. However, the prolonged increase in electricity costs is unsustainable for many families. Hence, this paper presents an optimal HRES design for an isolated grid, comparing several of the most popular technologies.

The process of creating an optimal design begins with an analysis of the current load profile and the capabilities of the existing generation system. Following this, an optimization procedure is carried out, focusing on minimizing generation costs and maximizing the number of customers served. The system is modeled as an isolated and autonomous setup throughout the year to clearly demonstrate the advantages of different technologies. This study uses HOMER (Hybrid Optimization of Multiple Energy Resources) to achieve optimization goals and validate the HRES design. [1]

The rest of this paper is structured as follows. Section II details the isolated system under study, Section III compares the technological viability of HRES, Section IV simulations and results, and Section V concludes the article.

II. STUDIED SYSTEM

The village of Marismilla is located in the municipality of Las Cabezas de San Juan, in the province of Seville, within the autonomous community of Andalusia, Spain. With just over 1,500 inhabitants and 335 houses, Marismilla is situated at coordinates 36º53'26.88" N and 06º19'17.35" W. The village covers an area of 12.2162 km2, mostly composed of farmland, and is located at an elevation of 8 meters above sea level. [2] Figure 1 shows the exact location.

Fig. 1. Location of the studied system [3]

When the Marismilla system becomes an isolated grid, it relies on a costly diesel generator. With the recent increase in fuel costs, this system is becoming less profitable, although it remains the only viable solution during blackouts.

Marismilla is powered by diesel generators with a generation capacity of 100 kW. Since exact information is not available, it has been modeled generically with a Fuel Curve Intercept of 3.66 L/hr and a Fuel Curve Slope of 0.236 L/hr/kW. The recommended minimum load ratio is 20% of the generator capacity; however, this recommendation cannot be applied due to the occurrence of low demand. The single-line diagram of Marismilla's power system when operating as an isolated grid is presented in Figure 2.

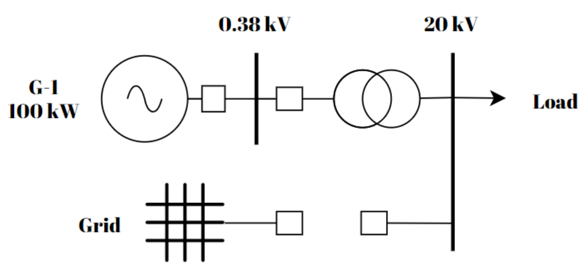

Fig. 2. Single-line diagram of Marismillas system.

The fuel price for this system is 1.48 €/L [4], which can result in electricity generation costs as high as 0.7748 €/kWh. Although the main activity in this region is agriculture, such electricity costs can be untenable for small businesses such as restaurants or workshops.

The daily average electricity consumption of the area is 593 kWh, with a theoretical peak load based on community models at 89.2 kW (though such a peak is highly unlikely). The load profile of the Marismilla system is presented in Figure 3. As mentioned, this profile follows the typical shape of a community load. [5]

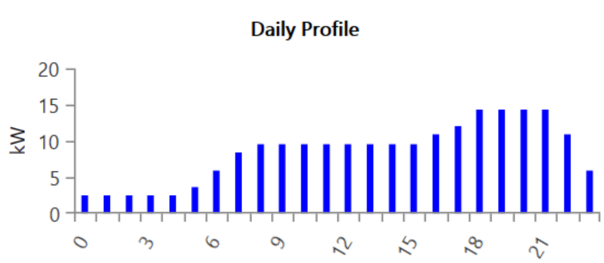

Fig. 3. Load profile of Marismillas system.

III. Technological Viability of Hybrid Renewable Energy Systems (HRES)

A. Solar Irradiance Data

The solar irradiance data for Marismilla is obtained from the NASA Prediction of Worldwide Energy Resources (POWER) database. It provides hourly global horizontal irradiance (GHI) data for the selected location over 22 years (1983-2005). Daily radiation varies between 7.79 kWh/m² in July and 2.51 kWh/m² in January, with a clearness index of around 0.55. These data are represented in Figure 4. [6]

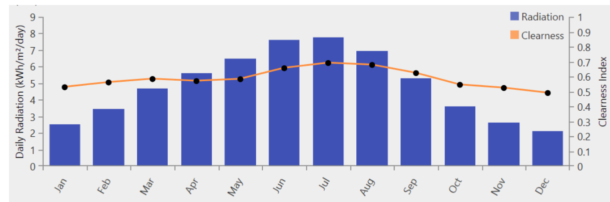

Fig. 4. The average daily solar data for each month.

B. Wind Resource

The wind resource data for Marismilla is obtained from the NASA Prediction of Worldwide Energy Resources (POWER) database. It provides the monthly average wind speed at 50 m above the earth's surface for the selected location over 30 years (1983-2013). Average wind speed varies between 6.21 m/s in December and 4.52 m/s in September. These data are represented in Figure 5. [6]

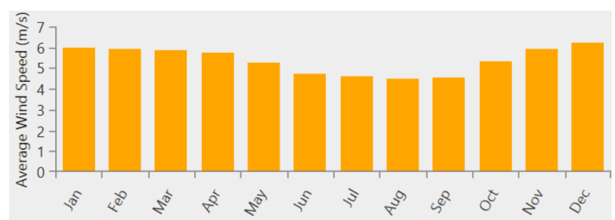

Fig. 5. The average wind speed data for each month.

C. Converters, batteries, and flywheels

Nowadays, these are not major issues due to the commercial accessibility of all these devices. Having sufficient space for their proper installation and fulfilling their ongoing maintenance requirements ensures their effective operation.

IV. Simulations and Results

The objective of the HRES design in the Marismilla system is to achieve the lowest possible generation cost. Hence, we have optimized all the alternatives as much as possible, leaving almost all the parameters to the discretion of the HOMER software and using standard models. Only the power of the existing diesel generator was fixed.

A. Solar Photovoltaic

After running a simulation with the sizing parameters for the photovoltaic solar installation and converter set to free, the architecture optimized for the lowest possible cost provided by HOMER is as follows:

- Diesel Generator: 100 kW
- Photovoltaic

Quantity	Value	Units
Rated Capacity	27.3	kW
Mean Output	4.9	kW
Mean Output	118	kWh/d
Capacity Factor	18.0	%
Total Production	49,925	kWh/yr
Minimum Output	0	kW
Maximum Output	25.2	kW
PV Penetration	19.6	%
Hours of Operation	4,383	hrs/yr

TABLE I
PV PARAMETERS

As shown in Figure 6, the maximum solar energy production is achieved at midday. The main disadvantage is that during the months of peak demand, the production window becomes somewhat narrower.

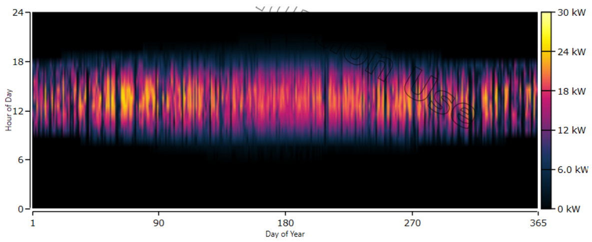

Fig. 6. PV Power Output.

- Converter
  The converter sizing to support both the photovoltaic installation and the batteries is 16.8 kW, with a clear predominance of the inverter over the rectifier.

Economic Results

The NPC (Net Present Cost) of the system is 3.37 million euros, representing the total cost of the system over its entire lifespan, discounted to the present. The LCOE (Levelized Cost of Energy) is 0.717 €/kWh, indicating the average cost per kWh of energy generated, considering both investment and operational costs. The system has a renewable fraction (Ren Frac) of 6%. The simple payback period is 10 years. [7]

B. Solar Photovoltaic + BESS

After running a simulation with the sizing parameters for the photovoltaic solar installation, batteries, and converter set to free, the architecture optimized for the lowest possible cost provided by HOMER is as follows:

- Diesel Generator: 100 kW
- Photovoltaic

Quantity	Value	Units
Rated Capacity	196	kW
Mean Output	35.1	kW
Mean Output	843	kWh/d
Capacity Factor	18.0	%
Total Production	307,835	kWh/yr
Minimum Output	0	kW
Maximum Output	180	kW
PV Penetration	141	%
Hours of Operation	4,383	hrs/yr

TABLE II
PV PARAMETERS

As expected, the maximum power output of the photovoltaic generation plant occurs around midday (Figure 7), when irradiance records reach their peak. At this point, it is possible to entirely stop depending on the generator and even use the excess to charge the batteries.

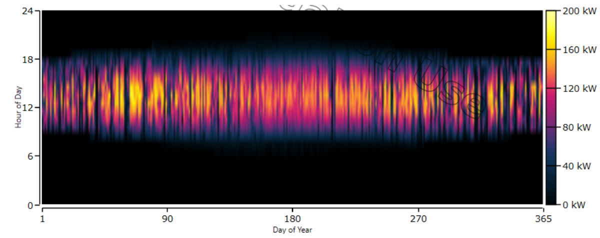

Fig. 7. PV Power Output.

- 1kWh Li-Ion

Quantity	Value	Units
Batteries	510	qty.
String Size	30.0	batteries
Strings in Parallel	17.0	strings
Bus Voltage	180	V
Autonomy	16.3	hr
Storage Wear Cost	0.193	€/kWh
Nominal Capacity	510	kWh
Usable Nominal Capacity	408	kWh
Expected Life	15.0	yr

TABLE III
BATTERY PARAMETERS

The continuous evolution of the battery's state of charge can be observed through simulations over the course of an average year. In Figure 8, it is shown that the battery reaches its maximum SOC around 14:00, after several hours of photovoltaic generation, and reaches its minimum SOC around 06:00, after several hours of discharge due to the lack of solar generation, reaching its lowest point.

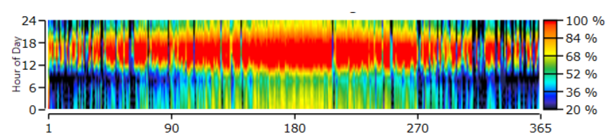

Fig. 8. State of Charge.

- Converter
  The converter sizing to support both the photovoltaic installation and the batteries is 70.4 kW, with a clear predominance of the inverter over the rectifier.

Economic Results

The NPC (Net Present Cost) of the system is 1.57 million euros, representing the total cost of the system over its entire lifespan, discounted to the present. The LCOE (Levelized Cost of Energy) is 0.348 €/kWh, indicating the average cost per kWh of energy generated, considering both investment and operational costs. The system has a renewable fraction (Ren Frac) of 87.0%, which means that 87% of the energy generated comes from renewable sources. Finally, the simple repayment period is 6 years. [7]- [8]

C. Wind Turbines

In this case, as in the previous one, the HOMER simulation is run, leaving the size of the number of generic 100 kW wind turbines unrestricted. The architecture provided by HOMER for lowest-cost optimization is as follows:

- Diesel generator: 100 kW.
- Wind Turbine:

Quantity	Value	Units
Total Rated Capacity	400	kW
Mean Output	95.9	kW
Capacity Factor	24.0	%
Total Production	839,781	kWh/yr
Minimum Output	0	kW
Maximum Output	400	kW
Wind Penetration	383	%
Hours of Operation	7,009	hrs/yr
Levelized Cost	0.00434	€/kW

TABLE IV
WIND TURBINES PARAMETERS

You can observe (Figure 9) that, unlike photovoltaic systems, energy production is distributed throughout the entire time frame. However, it must be noted that the production is generally less consistent, with periods of low or even zero output.

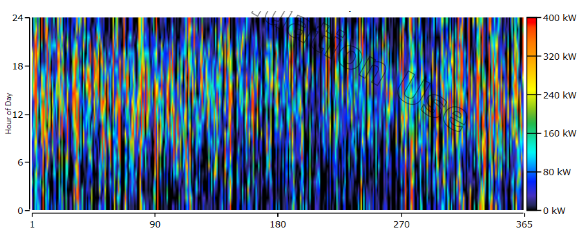

Fig. 9. Wind Turbine Power Output.

Economic Results

The NPC (Net Present Cost) of the system is 2.19 million euros, representing the total cost of the system over its entire lifespan, discounted to the present. The LCOE (Levelized Cost of Energy) is 0.485 €/kWh, indicating the average cost per kWh of energy generated, considering both investment and operational costs. The system has a renewable fraction (Ren Frac) of 55.4%, which means that 55.4% of the energy generated comes from renewable sources. Finally, the simple repayment period is 6.7 years. [7]

D. Wind Turbines + Flywheel

This case is similar to the previous one, but it includes an energy storage system based on a flywheel. For such systems, HOMER does not allow for optimization of their sizing, requiring the number of flywheels to be fixed. Given their cost and the expected volume of wind generation, we will simply install a generic 100 kW flywheel.

- Diesel generator: 100 kW
- Wind Turbine:

Quantity	Value	Units
Total Rated Capacity	300	kW
Mean Output	71.9	kW
Capacity Factor	24.0	%
Total Production	629,836	kWh/yr
Minimum Output	0	kW
Maximum Output	300	kW
Wind Penetration	288	%
Hours of Operation	7,009	hrs/yr
Levelized Cost	0.00434	€/kW

TABLE V
WIND TURBINES PARAMETERS

The distribution of wind turbine power output is quite similar to the previous one, with the difference in scale due to the fact that there are now only three wind generators.

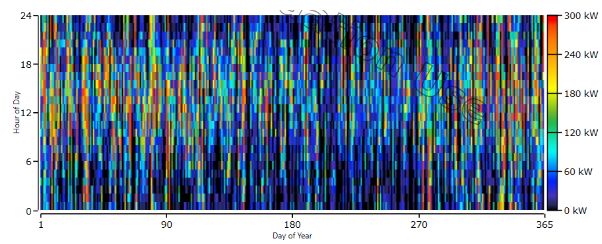

Fig. 10. Wind Turbine Power Output.

- Flywheel

Quantity	Value	Units
Batteries	1	qty.
String Size	1	batteries
Strings in Parallel	1	strings
Bus Voltage	825	V
Autonomy	1	hr
Storage Wear Cost	0	€/kWh
Nominal Capacity	25	kWh
Usable Nominal Capacity	25	kWh
Expected Life	20	yr

TABLE VI
FLYWHEEL PARAMETERS

It is observed (Figure 11) that the flywheel-based system is impractical, as the SOC is at 100% most of the time. Additionally, its autonomy of only one hour is not favorable. This type of system is more focused on improving grid stability rather than storage, hence it does not fit well within the studied system.

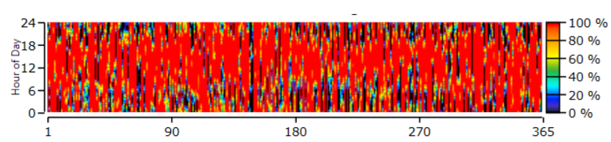

Fig. 11. State of Charge.

- Converter The converter sizing to support both the wind turbine installation and the flywheel is 11.2 kW, with a balance between the inverter and the rectifier.

Economic Results

The NPC (Net Present Cost) of the system is 2.8 million euros, representing the total cost of the system over its entire lifespan, discounted to the present. The LCOE (Levelized Cost of Energy) is 0.62 €/kWh, indicating the average cost per kWh of energy generated, considering both investment and operational costs. The system has a renewable fraction (Ren Frac) of 66.5%, which means that 66.5% of the energy generated comes from renewable sources. Finally, the simple repayment period is 12 years. [7]- [8]

V. Conclusion

In light of the obtained results, it is evident that the **photovoltaic generation system with lithium-ion storage is by far the most advantageous alternative, providing a quicker return on investment.**

Now, as we can observe in Figure 12, where the baseline case (diesel generator) is compared with the studied case (generator + PV + BESS), the return on investment occurs from the 6th year onwards. In other words, for a standard lifespan of these installations, 25 years, the average period Marismilla would need to operate as an independent system is 2 months per year for the system to be profitable.

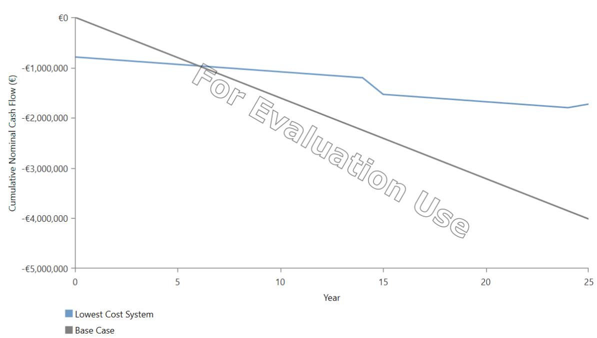

Fig. 12. Comparison Between Different Cases.

From that point on, the PV + BESS option will only lead to greater savings compared to any other alternative. Therefore, we can affirm that it is the most advantageous option and will reduce costs within our system.

One final consideration is that if we take into account the periods when the system is also connected to the grid, our already installed support system will further reduce the electricity price by generating energy that feeds into the grid. Although it is not the main focus of this study, a quick analysis of this alternative will be conducted to calculate the return on investment in this case (average electricity purchase and sale values in Spain 2024 have been chosen). Purchase: € 0.16422/kWh. Sale: €0.1125/kWh. [5]

The simulation shows that the average cost per kWh with this implementation will be €0.156/kWh, almost 10 cents below the market purchase price. For our system's average consumption, this means nearly €2,000 less in monthly expenses. This adds to the significant savings when the system operates as an isolated system, making it an even more viable alternative.

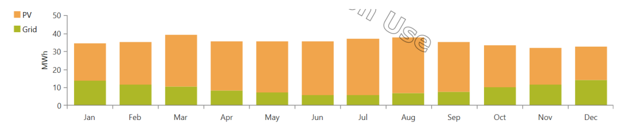

Fig. 13. Monthly Electric Production

References

[1] Jufri FH, Sudiarto B, Garniwa I. Optimal Hybrid Renewable Energy System Design for Generation Cost Reduction and Increased Electrification in Isolated Grid in Indonesia. In: 2021 IEEE 4th International Conference on Power and Energy Applications (ICPEA). IEEE; 2021. p. 147–52. DOI: 10.1109/ICPEA52760.2021.9639295.

[2] Marismillas Town Hall: Ayuntamiento de Marismillas. Database of the Marismillas Town Hall. Marismillas: development of autonomy and local management since 1995 [Internet]. Las Cabezas de San Juan: Marismillas Town Hall; [cited 2024 Oct 13]. Available from: https://marismillas.es/es/

[3] Google Earth: Google. Google Earth [Internet]. Available from: https://earth.google.com/web/

[4] Diesel or Gasoline: Diesel or Gasoline. Diesel or Gasoline [Internet]. Available from: https://www.dieselogasolina.com/

[5] Red Eléctrica de España: Red Eléctrica de España. Red Eléctrica de España [Internet]. Available from: https://www.ree.es/es

[6] NASA, "NASA Prediction of Woeldwide Energy Resource (POWER)." https://power.larc.nasa.gov/.

[7] IRENA (2020), *Renewable Power Generation Costs in 2019*, Abu Dhabi, 2020. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf.

[8] IRENA, Electricity storage and renewables: Costs and markets to 2030, no. October. 2017.