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► **To cite this version:**

Fuqiang Zhuang, Rodrigo Amaro E Silva, Hadrien Verbois, Thomas Carriere, Benoît Gschwind, et al.. A PERFORMANCE COMPARISON BETWEEN THE ISOLATED HYBRID ENERGY SYSTEM WITH AND WITHOUT BATTERY ENERGY STORAGE SYSTEM. 22nd WIND & SOLAR Integration Workshop, Sep 2023, Copenhagen, Denmark. hal-04230764

HAL Id: hal-04230764

<https://minesparis-psl.hal.science/hal-04230764v1>

Submitted on 6 Oct 2023

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A PERFORMANCE COMPARISON BETWEEN THE ISOLATED HYBRID ENERGY SYSTEM WITH AND WITHOUT BATTERY ENERGY STORAGE SYSTEM

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Keywords: Hybrid Energy System (HES), BESS, Off-grid, Unit Commitment, Solar forecast, PMS/EMS

Abstract

This work explores the performance difference between the approach with and without Battery Energy Storage System (BESS) for an off-grid Hybrid Energy System (HES). For the storage-less case, the solar forecast is used to mitigate the system variability. The evaluation is achieved through a highly configurable Python-based simulation platform and a cost-based evaluation approach, where the simulation results are considered as the system performance indicator. In this work, two forecast methods and 6 different BESS sizes from 0 to 50MWh are tested. The results show that the use of BESS can enhance the system stability, increase the PV energy share in the final energy consumption, and reduce the final system cost, especially in a situation with uncertainty. In cases with a high PV penetration rate, a larger BESS provides greater advantages, however, the overall performance-to-cost ratio of an oversized BESS is lower compared to a properly sized BESS. For a high-value off-grid system, BESS proves to be a useful and efficient option. Alternatively, a reasonably accurate forecast is also a viable cost-effective choice.

1 Introduction

The integration of Photovoltaic (PV) in energy systems, especially in an off-grid context, needs to take into account the variability of this energy source [1], [2]. Using a battery energy storage system (BESS) is a common choice to address this issue[3], which has been largely evaluating its benefit in Hybrid Energy Systems (HES) in the literature. Besides, there are also works that explore storage-less concepts [4], [5], [6] based on the probabilistic forecast and Unit commitment control strategies, which is more challenging but could dismiss the use of BESS, as a cost-effective approach. This work performs a comparative evaluation of both approaches under the same conditions, focusing particularly on the economic and stability aspects of isolated HES. It shows the specificity of each approach and their associated applications.

2. Methodology

2.1 Simulation tool

This work uses an in-house highly configurable Python-based simulation framework, which is based on an open-source library oemof [7], with a core using Pyomo [8] as modeling language, and several post-added features. This platform is designed to allow users to customize their energy system configuration and the simulation parameters (such as PV penetration rate, BESS capacity, forecast methods, forecast

horizon, and genset dispatch update time), according to their requirements.

2.2 Case study

The composition of the energy system in our simulation is shown in Figure 1, involving 6 generators with different characteristics, providing a total nominal power of 60MW. The consumption corresponds to an industrial mining site, which has a rather stable energy demand in the order of 48MW, with a PV installation for 48MW (i.e., 100% PV penetration rate capacity-wise).

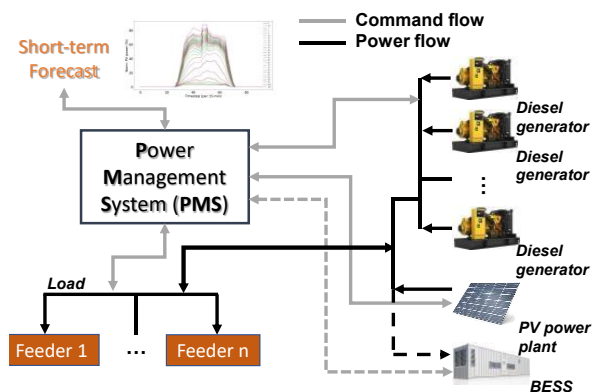


Fig. 1 Hybrid Energy System with 6 diesel generators of 60 MW nominal power, 48 MWp PV installation, its operation is driven by a short-term solar forecast to meet a rather stable 48 MW demand.

In terms of BESS, capacity values from 0 to 50MWh (in 10MWh steps) were tested, assuming an expected lifetime of 15 years. For the storage-less case, the solar forecast is used as an input for our dedicated designed Power Management System (PMS), which drives an optimal dispatching order for diesel generators to meet the demand. For each genset dispatch update time, the PMS will consider both the solar forecast and the latest genset system state to drive a new dispatch order, and hence ensure an optimal system performance. For BESS-including cases, the BESS capacity is considered for energy management and spinning reserve (SR) sizing, where SR is the genset reserved capacity to mitigate the deviation between the power demand and generation, defined as the difference between the nominal power and the actual power output.

2.3 Solar forecasts

In this work, two forecast methods are used as references. The first one is Perfect Prognosis (PP) forecast, where the future PV production is known beforehand in a deterministic manner up to a certain horizon and can be considered as the upper bound reference of forecast performance. The Complete History – Persistence Ensemble (CH-PeEn) [9] is the second model used, which builds a probabilistic typical profile by grouping historical data according to the time of day. This model is a simple data-driven baseline, which can be considered as a plausible lower bound of forecast performance.

For extracting the most value of the probabilistic CH-PeEn model, a single percentile is used to drive the deterministic dispatch optimization and the uncertainty layer of the forecast is used to size the SR of diesel generators. In our work, we use the forecast uncertainty to size a pre-defined SR, which is smaller than the original SR. And we keep the real SR as a second-layer security buffer.

2.4 Performance evaluation

To evaluate the performance between the approach with and without BESS, their performance is evaluated through a cost-based approach which is used to drive the dispatch optimization.

It is based on the Unit Commitment problem, which aims to find out the best combination of power generation sources with minimum production cost. We implement all the system constraints such as genset startup time and forecast uncertainty into the model. And we use the state and power output of genset and BESS, as decision variables.

Firstly, the simulation generates orders for the genset and BESS according to the system state and forecast input, designated as planned order. Secondly, as time goes on, the initially implemented planned order is compared to real-time actual data [10], and regulation mechanisms are put in place to correct the power deviation. In case of power

overproduction, we reduce the genset output first (the genset slows down), then we charge the BESS with the rest PV energy excess, and PV curtailment is carried if still necessary. For the underproduction situation, we discharge the BESS to meet the lack, then increase the load of genset by using the spinning reserve of genset (genset speed up), if still needed, the load shedding action would be considered. All these regulation actions would generate a cost in the simulation, and the final effective system cost is used as system performance indicator.

2.5 Simulation setup

To explore the main research question of this work, as shown in Table 1, with the already described hybrid energy system, we evaluate system performance considering two different forecasting methods and for each assume 6 different BESS sizes, from 0 to 50MWh, in 10MWh steps.

Table 1 Key elements of scenarios

| Forecast method | BESS size |
|-------------------|-----------|
| Perfect Prognosis | 0 MWh |
| | 10 MWh |
| | 20 MWh |
| CH-PeEn | 30 MWh |
| | 40 MWh |
| | 50 MWh |
| | 50 MWh |

Each simulation considers an 11-month real data, including PV and demand measurements. The fuel cost and the BESS cells cost are gathered from the real-world project, which is coherent with a recent study [11]. The final system cost is hence the focus point of our work. For the CH-PeEn model, we also account for the failure of pre-defined SR, the failure in load shedding, and the help in stability when increasing the BESS size.

In our work, the forecasts provide an uncertainty range, as shown in Figure 2, we use one of the percentiles to drive the optimization (hereinafter called Px, with x being the probability level) and the uncertainty range below that same percentile is used to size the SR.

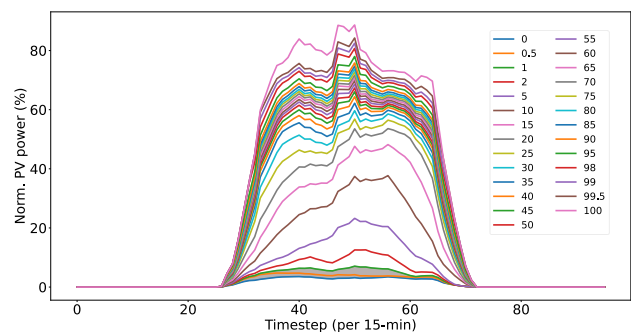


Fig. 2 Scheme of CH-PeEn probabilistic forecast with an uncertainty of 27 percentile levels

Notice that when considering a baseline model like the CH-PeEn that can lead to broad (i.e., underconfident) uncertainty intervals. In turn, due to the considerable amount of PV capacity here evaluated, this can lead to a requested SR which is larger than what the diesel genset could provide. Thus, for the storage-less or even small battery cases, the upper percentile - which drives the optimization and impacts the requested SR – had to be reduced to ensure a feasible simulation.

In terms of the characteristics of the 6 diesel generators, the detail is shown in Table 2, including their nominal power, operating range, etc. They are all gathered from the real-world project data, to be coherent with the PV and demand measurement.

Table 2 Diesel generators characteristics

| Name | Nominal power | Operating range | Fuel type | Startup time | Minimum uptime |
|------|---------------|-----------------|-----------|--------------|----------------|
| DG1 | 2 MW | 40-100% | Diesel | 1-min | 15-min |
| DG2 | 6 MW | 40-100% | Diesel | 5-min | 15-min |
| DG3 | 8 MW | 40-100% | Diesel | 5-min | 15-min |
| DG4 | 11MW | 50-100% | HFO* | 15-min | 60-min |
| DG5 | 15 MW | 50-100% | HFO* | 15-min | 60-min |
| DG6 | 19 MW | 60-100% | HFO* | 15-min | 60-min |

HFO*: Heavy Fuel Oil

3 Results

3.1 Result of using CH-PeEn forecast

The presence of battery in a context of uncertainty impacts the system operation and cost in several ways: the additional cost, the additional flexibility (as SR) the storage implies, as well as the ability to shift surplus PV generation in time and being able to further reduce diesel consumption.

While using the CH-PeEn model, we use the P50 to drive the optimization, and the uncertainty range P50-P0 to size the SR since we aim to cover all the overestimated forecast cases.

However, as mentioned before, while the percentile level is too high, it may ask for a too important power capacity for the SR and result in an infeasible situation. The result of the first stage shows that the highest percentile for the storage-less case and 10 MWh BESS is P5 and P40, respectively.

The result of using the CH-PeEn model is shown in Figure 3, when increasing the BESS capacity, the system cost is significantly reduced by 8.5% from 0 to 10 MWh, since it reduces fuel consumption the most. Then the system cost is reduced by 11.9% with 20MWh, where the gain and investment cost become smaller. And for the cases with even larger BESS size, system cost is reduced by around 12.5%. When BESS is larger than 30 MWh, the gain in the economic aspect is limited in this setup.

With the increase of the BESS, the PV curtailment rate keeps decreasing, which proves that BESS can help in improving the PV self-consumption rate, which is defined as the ratio between the power effectively being consumed and the power generated. This information is indirectly obtained from the reduction of the PV curtailment.

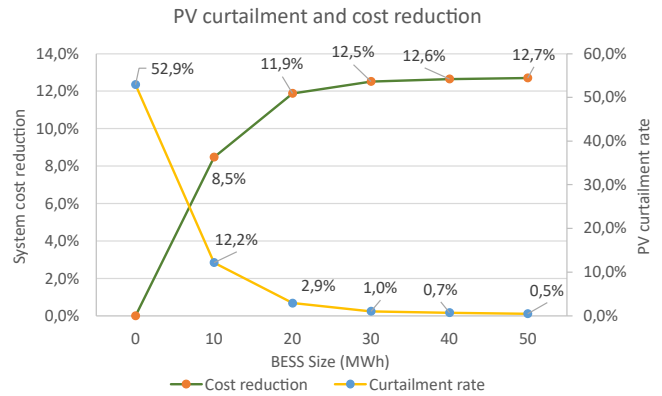


Fig. 3 Simulation result of system cost reduction and PV curtailment rate while using CH-PeEn forecast with different BESS sizes.

The detail of the system cost composition with different BESS sizes is shown in Figure 4. As shown, while the BESS is used, from 0 to 10MWh, it reduces the genset cost through the fuel consumption and increasing the PV energy used. After that, the gain of enlarging the BESS becomes smaller since the PV penetration rate is relatively limited for a much larger BESS.

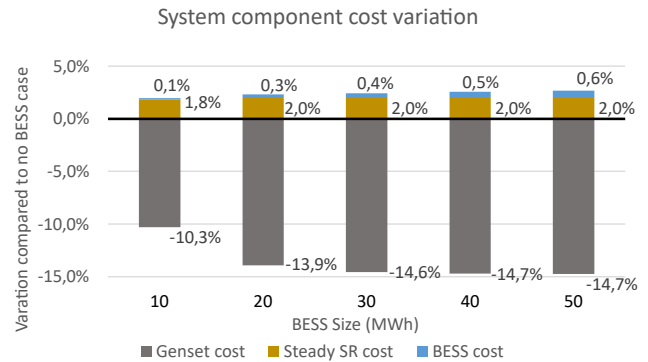


Fig. 4 Variation of different parts of the general system cost when using the CH-PeEn forecast with different BESS sizes.

3.2 Result of using Perfect forecast

While using the perfect prognosis forecast, it has no deviation regarding the initial planned order to be handled. Hence, the result of this scenario could give guiding information for the case with very high quality and accurate forecast.

While using perfect prognosis with 100% PV penetration, the system cost reduction is quite small. Compared to a no BESS case, using a 1h BESS of 20% demand (10MWh) for the

industrial profile, the annual final system cost could be reduced by 0.45%. While increasing the BESS to double or even triple its capacity, the system's economic gain stays at a similar level. The system cost is composed of genset cost, BESS cost, PV cost, and steady SR cost. For this perfect forecast case, PV cost and steady SR cost remain the same.

In fact, with a larger BESS, the genset cost keeps decreasing but the BESS cost is also getting higher. Finally, the cost reduction through fuel consumption is compensated by the increase of BESS cost, the general system cost doesn't change much. The first reason is that the PV energy share is relatively small compared to the daily demand, and the advantage of using BESS is hence limited. Besides, with a perfect forecast, the BESS could not show its advantage in mitigating the system variability.

To explore the influence of BESS with a higher PV penetration rate, we also achieved the same test with 200% PV penetration rate. The results of cost variation for both 100% and 200% PV penetration are shown in Figure 5. Compared to the no BESS case, the general system's economic gain is more important than the 100% PV penetration rate cases. Using a 1h BESS of 20% demand (10MWh) for the case with a higher PV penetration rate, the final system cost could be reduced by 1.5%, where the general system cost gets a higher reduction thanks to the higher genset fuel consumption saving.

While increasing the BESS to double or even triple its capacity, the cost of BESS investment is getting higher but slightly lower than a linear increase thanks to a huge amount of purchases. However, with the increase of BESS, the gain/cost ratio keeps raising become less and less high, at 2.3%, 3.0%, 3.6%, and 4.2%, for each 10MWh step, respectively.

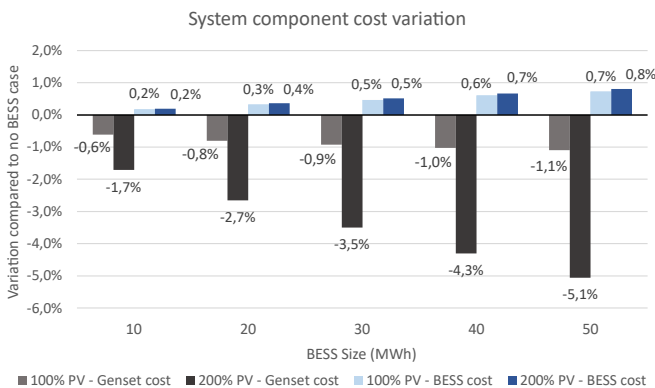


Fig. 5 Cost variation of different parts of the general system cost when using perfect forecast with different BESS sizes

Besides, we notice that the cost reduction and PV energy share keep increasing as well, while increasing the BESS capacity. By taking a closer look at the PV self-consumption rate and the system cost reduction as shown in Figure 6, we found that the gain of BESS with 100% PV is limited even

using a larger BESS, due to the limit of PV installation. As shown, while using perfect prognosis, the PV self-consumption is already in a very high level. When the PV penetration rate is increased to 200%, there is more PV production to be integrated, the use of BESS hence helps more in increasing the PV self-consumption rate, by better organizing the use of PV energy, like time shifting, which means to stock the surplus of PV production during the daytime and use the stocked energy at night-time.

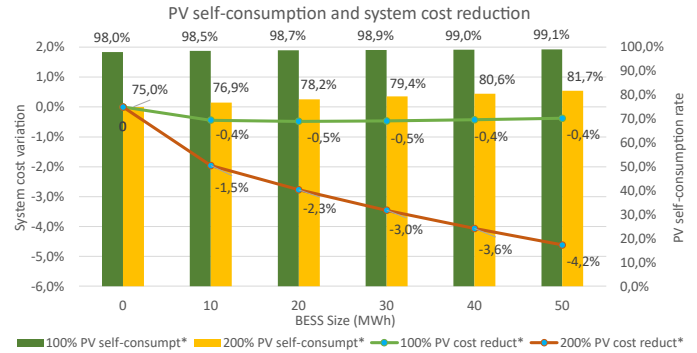


Fig. 6 PV self-consumption rate and cost reduction while using perfect forecast and different BESS sizes

It proves that using BESS could help improve the PV energy share and reduce the system cost. However, the eventually increase of economic benefit and PV penetration becomes smaller after a certain level of BESS size since the increase of BESS cost is faster than the fuel saving increase.

4 Conclusion

This work explores the performance difference between using or not a BESS for isolated HES, the evaluation is achieved through a cost-based performance evaluation approach and a Python-based simulation tool.

We tested 12 combinations, which are built with the perfect and the CH-PeEn forecast, as well as 6 different BESS sizes, from 0 to 50 MWh. The simulation result is considered the system performance indicator, where the case without BESS is used as a reference.

The results show that the use of BESS provides more flexibility in energy management and improves the integration of PV energy into the network. Using a suitable size of BESS can enhance system stability and reduce fuel consumption. While a larger BESS helps even more in enabling the PV energy penetration, but its performance/cost ratio becomes smaller, like the marginal effect. The performance difference between the perfect and CH-PeEn case tells that the use of BESS has a larger advantage for situations with higher uncertainty.

For basic forecast methods like the CH-PeEn model, either we can use a low percentile of the probabilistic forecast to

drive the genset production, by forcing PV curtailment to ensure the system stability, similar to the PV overbuilding concept [12]; or we can use BESS, which can greatly mitigate the system variability, by providing power in case of underproduction, and absorbing energy excess in case of overproduction. Besides, BESS could be used to consider a higher percentile level of the probabilistic forecast for genset dispatching. While considering a large uncertainty, BESS capacity could also be considered in static reserve power sizing, also called pseudo “spinning reserve”.

Nevertheless, for an accurate forecast like the perfect prognosis, the gain of using BESS is relatively limited. The low uncertainty of the forecast reduces the need for storage. The small power deviation could even be accommodated by the genset. Notice that the cost of developing a relatively accurate forecasting method, its development cost is around 50-100 times lower than a 10MWh BESS investment cost.

In general, the use of BESS is an efficient tool to mitigate solar variability of off-grid HES, particularly for cases with high PV penetration rates, and high requests for network stability. While considering the investment cost of the two approaches, using solar forecast with BESS is a viable cost-effective solution.

The results obtained are only based on the PP forecast and the CH-PeEn model, which are all data-driven methods. It would be interesting to test some more advanced methods, to see the influence of BESS in those cases.

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