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# TOWARDS A NEW APPROACH IN EVALUATING THE PRACTICAL ECONOMIC PERFORMANCE OF OFF-GRID STORAGE-LESS HYBRID ENERGY SYSTEM WITH INTEGRATED SOLAR FORECAST

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**ABSTRACT:** Photovoltaic (PV) energy plays an important role in the energy transition, especially for off-grid contexts, through a format of Hybrid Energy System (HES) with storage system. Yet, using a storage system comes with additional investment costs, extra environmental impact and maintenance issues, etc. For an off-grid PV/Diesel HES, a precisely designed Power Management System (PMS) with short-term solar forecast could be used to reduce or even avoid the use of energy storage system. Hence, this work aims to find out the feasibility of this concept, and introduce a new approach to evaluate the HES performance rather than using classic statistical metrics like Root Mean Square Error (RMSE) and MAE (Mean Absolute Error). Besides, several scenarios are tested to explore the influence of different elements on HES performance.

**Keywords:** Stand-alone PV Systems, Plant Control, Economic Analysis

## 1 CONTEXT & OBJECTIVE

In an off-grid context, the energy systems are mostly relied on fossil fuel energy [1]. During the energy transition, Photovoltaic (PV) energy is largely used through a format of Hybrid Energy System (HES) with storage system [2]. Yet, using a storage system comes with some extra adverse effects, such as high additional investment costs [1], extra environmental impacts [3] and maintenance issues, etc. A precisely designed Power Management System (PMS) with short-term solar forecast could be used as a transitory solution to reduce or even avoid the use of energy storage systems.

This work aims to find out the feasibility of this concept through evaluating the storage-less HES performance using PMS and solar forecast techniques. Yet, the classic metrics like Root Mean Square Error (RMSE) and MAE (Mean Absolute Error) could not always correctly describe the HES performance, especially when using different forecast methods [4]. For example, an over-estimated and under-estimated forecast with same level of RMSE could have quite different practical results. Hence, in this work, a new cost-based approach is introduced to properly evaluate the performance of stand-alone storage-less HES.

## 2 CASE STUDY & APPROACH

### 2.1 Case study

The case study of this work is an energy system for a mining site located in a tropical area in West Africa, with a rather 50 MW energy demand 24/7. This energy system is initially a diesel Genset-based energy system with 70MW capacity. Due to the more and more important environmental issues and the increase of the fossil fuel price, the PV energy is integrated into the energy system to reduce the environmental impacts and the Levelized Cost of Energy (LCOE) of electricity production.

When using PV energy, its intrinsic temporal variability has to be considered to ensure grid stability [5].

The common choice to tackle this issue is to use an energy storage system [6], [7], such as the pumped-hydroelectricity station, batteries, etc. However, while accomplishing this issue with the use of energy storage system, it also brings side effects like high investment costs, extra environmental impacts and maintenance issues, etc. Hence, the energy system of case study uses an innovative format of HES with PMS and short-term solar forecast rather than energy storage system.

### 2.2 Approach

The main idea of using a PMS with solar forecast is to predict the future residual demand, which is the difference between the total demand and the PV production, then committed by smartly dispatching the diesel generators.

To be able to simulate the behavior of HES using solar forecast, a python-based simulation platform using *oemof* is designed and implemented for the simulation [8], [9].

In this simulation work, probabilistic climatological and perfect forecast are used to define the full range of performance gain. The former forecast is used as a simple forecast method to provide the lower bound of economic gain, the latter forecast is the prognostic forecast which aims to provide the upper bound of possible economic gain. When using this probabilistic forecast information, the  $P_{50}$  quantile level is used to generate the Genset dispatch as the common choice [10], the uncertainty range derived from other inter-quantile levels like  $P_0 - P_{50}$  is used to size the spinning reserve, which is the energy buffer of the HES to mitigate the solar variability. This solution aims to cover almost all the over-estimated forecast cases since the over-estimated forecast could be dangerous if the spinning reserve is not correctly sized. Yet, the under-estimated forecast case could be dealt with PV curtailment, which is relatively easier to handle.

As mentioned, the over-estimated and under-estimated forecast could bring different results in energy system performance. Thus, the classic metrics like RMSE and MAE could not always correctly describe the HES performance. For example, an over-estimated and under-

estimated forecast with same level of RMSE could have quite different practical results.

In this work, a new cost-based approach is therefore used to evaluate both system stability, economic and solar forecast performance. To explore the influence of different elements on HES performance, several scenarios are tested.

### 3 RESULTS & DISCUSSIONS

#### 3.1 Scenario with different PV penetration at clear day

In the first work, different PV penetration rates from 0% to 200%, with a step of 25% are tested. The two forecast methods mentioned before are used in the simulation. Different sky states like clear day and variable day are also tested to provide a relatively complete evaluation of different elements.

For a given clear day and given energy system setup,

the summary of energy system result is shown in Figure 1. When using perfect prognostic forecast, the optimal penetration rate is 175%, then the system cost increases due to the PV curtailment. When using the more basic climatological forecast, the optimal penetration rate is 50%, after that, the system cost increases for the same reason as PV curtailment. The system cost in blue square decreases significantly since gensets are stopped when PV energy is sufficient for all energy demand without energy excess, the associated fuel cost is hence avoided.

Unlike the perfect forecast has no uncertainty to consider, the climatological forecast has a conservative uncertainty, which means that to cover the uncertainty range between  $P_0 - P_{50}$  would need a huge Genset capacity for the spinning reserve sizing. Due to this reason, the energy system becomes unfeasible when the PV penetration rate becomes too important.

The detail of system costs using different forecast

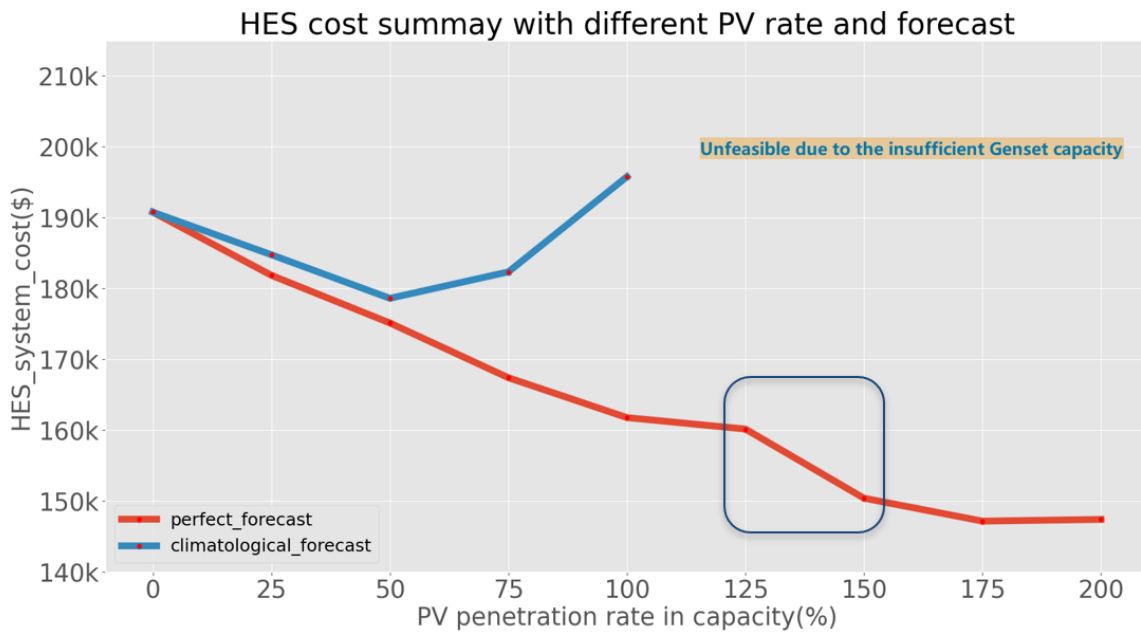


Figure 1: Summary of system performance with different PV penetration rates at clear day situation

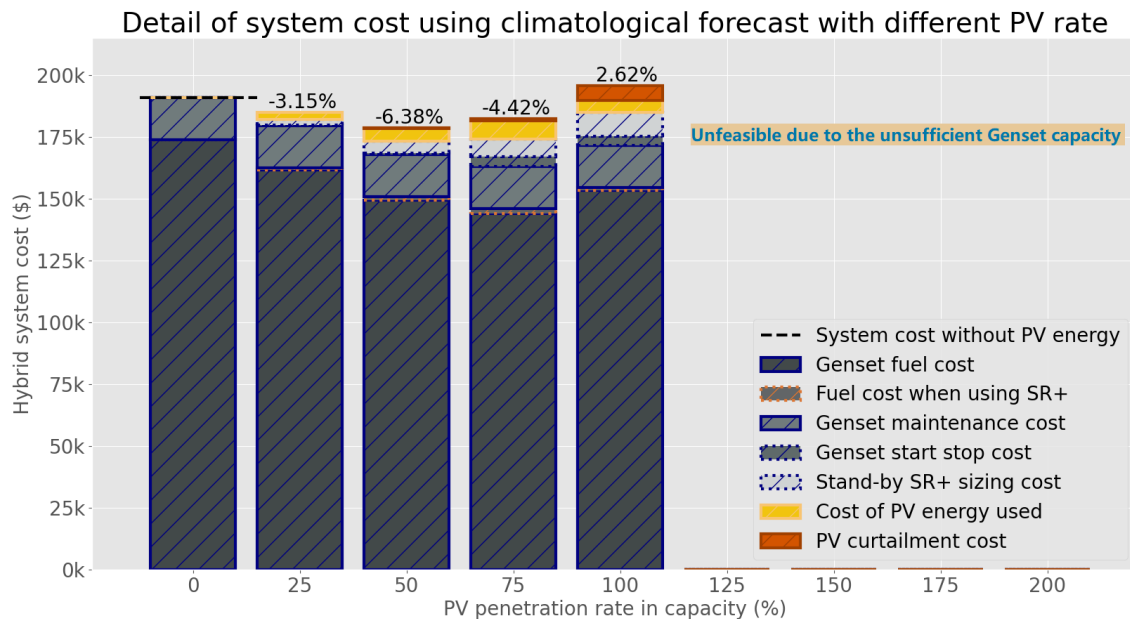
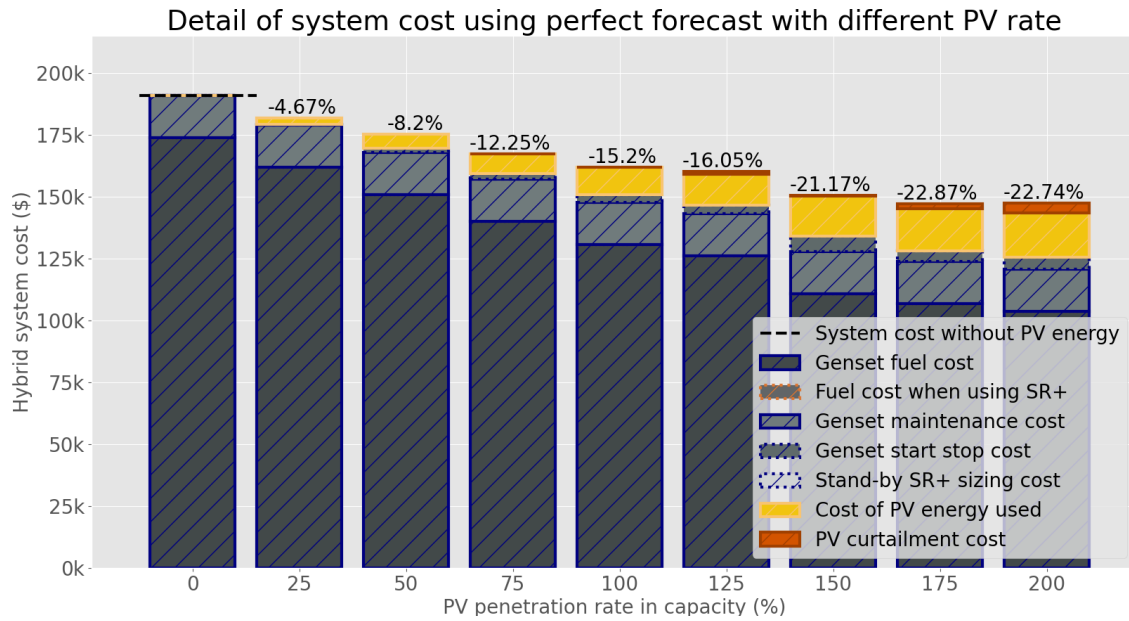


Figure 2: Detail of system cost with different PV penetration rates using climatological forecast at clear day situation



**Figure 3:** Detail of system cost with different PV penetration rates using perfect forecast at clear day situation

methods are shown in Figure 2 and Figure 3, with the increase in PV penetration rate, the general system cost and fuel consumption continue to decrease till its saturation moment, which means that Integrating PV energy in HES can indeed reduce the system cost before its saturation.

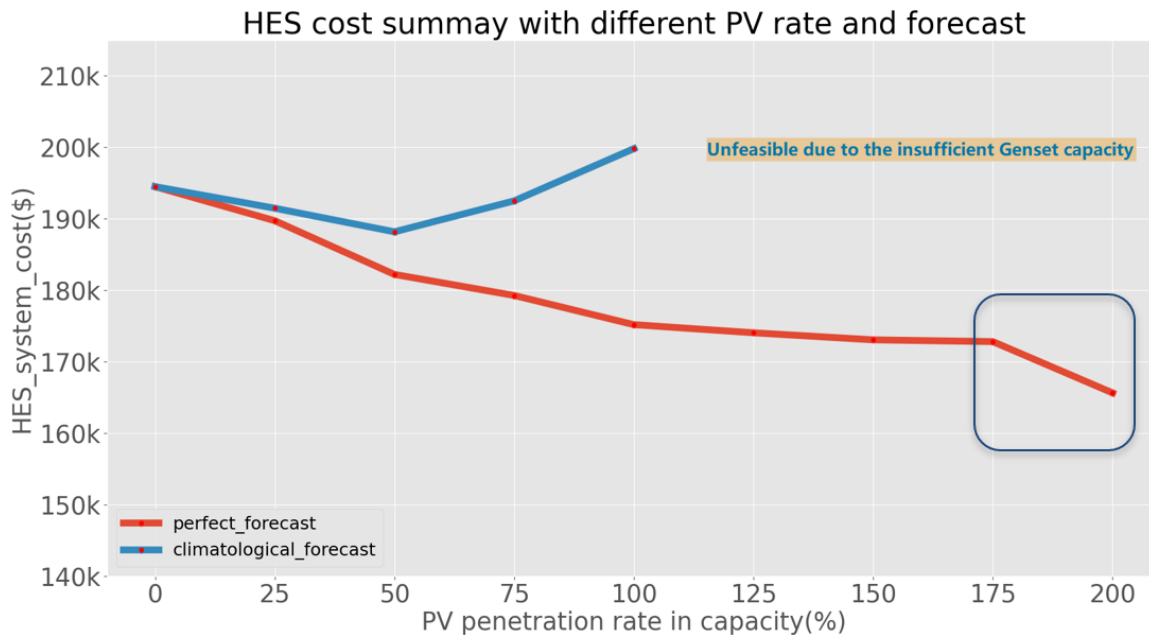
### 3.2 Scenario with different PV penetration at variable day

For a given variable day with the same configuration at clear day, the summary of energy system result is shown as in Figure 3. When using perfect forecast, the system cost continues to decrease with higher PV penetration rate, even at 200%. The situation in blue square like at clear day is postponed at variable day. In fact, both of them are due to the lower solar resource in variable day, the saturation of PV energy integration is therefore later.

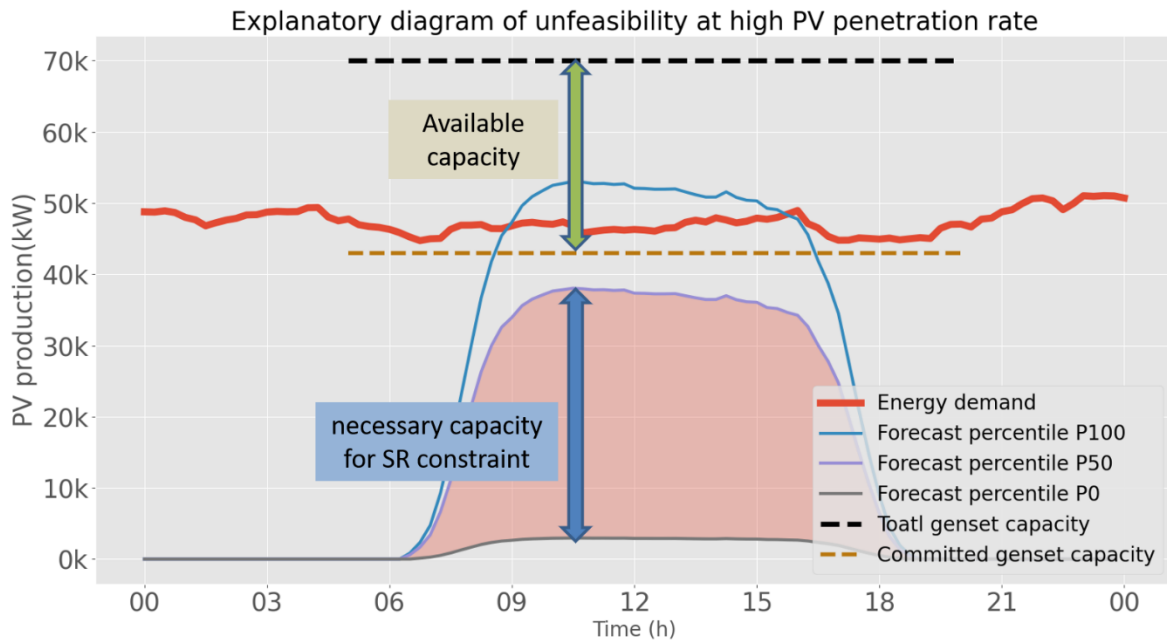
When using climatological forecast, the optimal

penetration rate is still at 50%, then the system cost increases due to the PV curtailment. When the PV penetration rate becomes too high, the energy system is unfeasible.

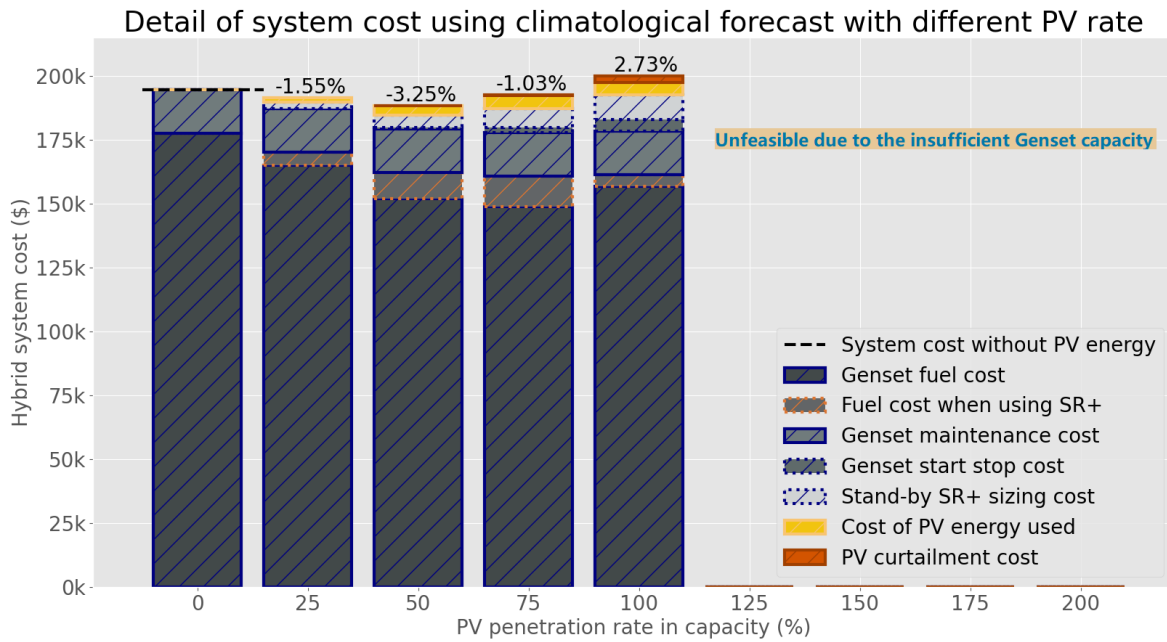
Both in variable and clear sky states, the energy system becomes unfeasible when the PV penetration rate becomes too important. A higher PV penetration rate with same level of uncertainty range asks for a bigger Genset capacity for spinning reserve sizing. As shown in Figure 5, the available capacity is the difference between the total Genset capacity and the committed Genset capacity. When the need for Genset capacity for spinning reserve is larger than the available capacity, the energy system is unfeasible. The maximum PV penetration rate is hence limited by the forecast uncertainty and available genset capacity. In other words, less uncertain models allow higher PV capacity integration.



**Figure 4:** Summary of system performance with different PV penetration rates at variable day situation



**Figure 5:** Explanation diagram of system unfeasibility cases



**Figure 6:** Detail of system cost with different PV penetration rates at variable day situation

The detail of system costs using different forecast methods at variable day are shown in Figure 6 and Figure 7. Due to the lower solar resource, the PV production is naturally lower, the fuel consumption is hence higher in variable day. The gain of using PV energy with a same level of capacity is therefore lower than clear day situation.

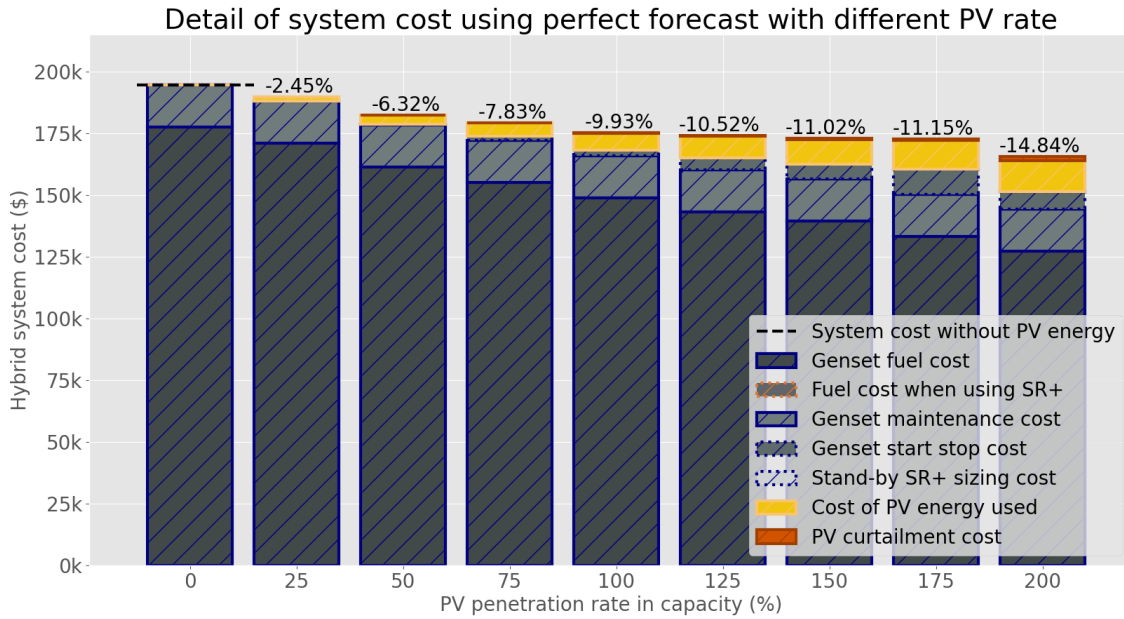
By comparing Figure 2 and Figure 6, an interesting phenomenon is noticeable. For climatological, no matter at clear day or variable day, the uncertainty range for a given period remains the same. Hence, the cost of preparing a steady spinning reserve is the same. Yet, the solar variability at clear day is much less than at clear day, which results in high spinning reserve preparation cost and low use rate of spinning reserve at clear day. Hence, for basic forecast model like climatological forecast, the strategy of sizing

spinning reserve should be adapted to the sky state.

### 3.4 Scenario with different forecast horizons

In the second scenario, two forecast horizons (60-min and 120-min) are tested to evaluate the influence of forecast horizons on system performance. The forecast methods used are still probabilistic climatological and perfect prognostic forecast. The PV penetration rate used here is 50%, which is the actual penetration rate of the case study. The reference case used is the case without PV energy.

The result is shown in Figure 8, which shows that a relatively longer forecast horizon could help in reducing the system cost.



**Figure 7:** Detail of system cost with different PV penetration rates at variable day situation

When using perfect forecast, 120-min forecast horizon could reduce more than 10% system cost compared to a no PV case, and 2% better than the case with 60-min horizon. When using climatological, the gain of 120-min is around 7.6% lower than the no PV case, and around 1% better than the case of 60-min forecast horizon. It means that a longer forecast horizon has a more positive influence for high-quality forecast methods. For a basic model like persistence, the impact is relatively smaller.

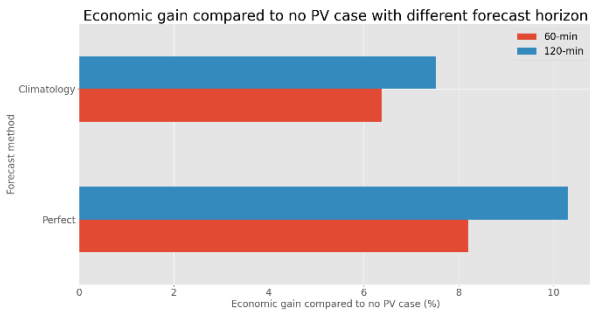
Yet, this result has its limit due to several elements, such as the dataset, the forecast methods used, the strategy of using forecast uncertainty to size the spinning reserve, the forecast horizon used and the Genset order update frequency. To have a more complete evaluation, a further study with above parameters would be achieved.

#### 4.3 Limit of storage-less design

Due to the storage-less design, the ability to integrate PV energy is limited. Hence, when the PV penetration rate is too high and the strategy of spinning reserve sizing is conservative, the maximum PV penetration would not be higher than 100% in PV installation capacity over energy demand. To be able to accommodate more PV energy, a less uncertain forecast model, a less conservative spinning reserve sizing strategy, or installing an energy storage system are the possible solution to consider. The former two solutions aim to reduce the need for available Genset capacity and the latter solution is to add the possibility of storing energy.

#### 4.4 Perspective

This work shows the feasibility of this concept, as a transitory solution towards 100% renewable energy, the first result seems interesting when building a storage-less Diesel-PV HES. Yet, there is no study about the complete evaluation of environmental impact and economic gain from a life-cycle perspective, for the comparison between the classic PV-storage system and this storage-less Diesel-PV system. A further associated study should be therefore carried out.



**Figure 8:** Influence of forecast horizon in economic gain

## 4 CONCLUSION & PERSPECTIVE

### 4.1 Feasibility of Diesel-PV concept

The concept of using PMS with solar forecast for a storage-less HES is shown to be feasible. In this concept, the main enablers of this concept are either an automated dispatch or a strict manual operation of Gensets, cooperated with the smart PMS and accurate solar forecasts.

### 4.2 Gain of using PMS with solar forecast

The gain of using solar forecast depends on many elements, such as the weather condition, PV penetration rate, forecast model, the Genset characteristic, etc. For the given data, the simulation results show a range up to 22.9% of decrease in daily system costs with perfect forecast and 6.4% with climatological forecast.

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