Degree Project in Sustainable Energy Engineering
Second cycle, 30 credits

Sizing and dispatch optimization for PV BESS systems in specific markets
Thesis Report

NATALIA TRIUNFO
Abstract

The consistent rise in electricity demand, coupled with the degradation of our planet’s resources, has driven the growth of renewable energy. Various strategies are being implemented to facilitate the transition to renewable sources, encompassing initiatives such as increasing transmission lines, developing energy storage technologies, or combining different renewable energies. Furthermore, the electric grid is transforming from a centralized structure to distributed generation.

This study primarily centres on the synergy between photovoltaic generation and battery energy storage systems used in micro-generation applications, one for an industry in Uruguay and the other for a rural community in Greece. Diverse combinations of photovoltaic and storage capacities are analysed, with the battery dispatch optimized according to the market price and the emissions of electricity generation separately. Subsequently, the objective is to verify whether the installation of energy storage systems yields tangible benefits compared to solely net-metering practices.

Sammanfattning

Det ökande behovet av elektricitet i kombination med en försämring av planetens resurser har propellerat en tillväxt av förnybara energi. En rad olika strategier används för att implementera en övergång till förnybara energiresurser, vilket innefattar initiativ som exempelvis utbyggnad av transmissionsnät, utveckling av energilagringsteknologier och kombinationer av olika förnybara energier. Dessutom sker ett skifte i elektricitetssystemet, från en centraliserad till en decentraliserad struktur.

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<tr>
<td>ADME</td>
<td>Administración del Mercado Eléctrico - Electricity Market Administration</td>
</tr>
<tr>
<td>BESS</td>
<td>Battery Energy Storage Systems</td>
</tr>
<tr>
<td>CAPEX</td>
<td>Capital Expenditure</td>
</tr>
<tr>
<td>CO₂eq</td>
<td>Carbon Dioxide Equivalent</td>
</tr>
<tr>
<td>CRES</td>
<td>Centre for Renewable Energy Sources and Saving</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>E</td>
<td>Electricity</td>
</tr>
<tr>
<td>ENTOSOE</td>
<td>European association for the cooperation of transmission system operators</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IRENA</td>
<td>International Renewable Energy Agency</td>
</tr>
<tr>
<td>ISO</td>
<td>Independent System Operator</td>
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<tr>
<td>KPI</td>
<td>Key Performance Indicators</td>
</tr>
<tr>
<td>kWp</td>
<td>Kilowatt peak</td>
</tr>
<tr>
<td>LCOE</td>
<td>Levelized Cost Of Energy</td>
</tr>
<tr>
<td>MED</td>
<td>Mediterranean</td>
</tr>
<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
</tr>
<tr>
<td>NDCs</td>
<td>Nationally Determined Contributions</td>
</tr>
<tr>
<td>NECP</td>
<td>National Energy and Climate Plan</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>OPEX</td>
<td>Operating Expenses</td>
</tr>
<tr>
<td>PEGASUS</td>
<td>Promoting Effective Generation and Sustainable USEs of electricity</td>
</tr>
<tr>
<td>Prod.</td>
<td>Production</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaics</td>
</tr>
<tr>
<td>SoC</td>
<td>State of Charge</td>
</tr>
<tr>
<td>SS</td>
<td>Self-Sufficiency</td>
</tr>
<tr>
<td>UN</td>
<td>United Nations</td>
</tr>
<tr>
<td>UTE</td>
<td>Administración Nacional de Usinas y Trasmisiones Eléctricas - National Administration of Electric Power Plants and Transmissions</td>
</tr>
<tr>
<td>VAT</td>
<td>Value-Added Tax</td>
</tr>
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</table>
1 Introduction

Sustainable Development Goal number seven, proposed by United Nations, seeks to guarantee universal and reliable access to affordable and clean energy by 2030 while substantially increasing the share of renewables in the global energy mix. Since the early 2000s, the renewable energy industry has grown significantly, aided by international protocols, government policies, and lower costs.

Across the world, there is a prevailing trend towards transitioning to renewable energy sources and decarbonizing various industries and services. Numerous companies have been working on developing diverse forms of renewable generation, striving for better performances, and cost reduction. Among these technologies, solar PV generation is the one that had experienced the most significant decrease in the LCOE over the past decade (UN, 2015; Hannah Ritchie, 2022; IRENA, 2021).

Global policies are actively promoting the transition to renewables. However, integrating renewables into the grid is challenging due to the instability and difficulty predicting natural resource behaviour. Various ways to contribute to an easier switch are in development, such as building more transmission lines to interconnect grids, combining various renewable sources, integrating, and improving energy storage, or inciting a more active demand side. The trend towards decentralized power generation is growing in Europe and other regions, involving all types of consumers, from industrial plants and companies to individual households (Palmer, 2022).

It is still uncertain which is the best solution to include renewable energies in the generation matrixes in large quantities. Moreover, there is no consensus on the optimal approach for integrating decentralized generation into traditional grids.

There is no silver bullet for this problem. Hence, this report aims to assess the extent which the location’s socio-political framework and the system load behaviour determine the proper integration of a PV-BESS distributed generation system into the country’s grid. In order to achieve it, the best approach for integrating two different PV distributed generation systems into the grid is determined. These distributed energy systems serve distinct types of consumers: one industrial and the other composed of several domestic units. For a more comprehensive study, the chosen locations are inside and outside the EU, each with a different energy matrix, electricity prices and political context for distributed generation using renewable sources.

In pursuit of the objective, the report studies different PV system capacities using energy storage as grid firming for each case, and the optimal configurations are chosen based on a set of technical and economic KPIs, along with CO₂ emissions. Lastly, the optimal results for each case are compared to the current alternative proposed by the respective government without BESS.
2 Background

2.1 Renewables integration to the grid

Climate change, fuel diversity, energy security, and other factors have propelled the rapid development of renewable energies. Nowadays, many countries are committed to increasing the shares of renewables in their energy mixes as part of their NDCs. Different policies have been created to support the development of renewable electricity generation. As these technologies mature, with continued financial subsidies and decreasing costs, they are becoming more competitive in the market and are expected to have a progressively dominant presence in the world electricity generation matrix. See Figure 1.

![Figure 1 Global weighted average LCOE for newly commissioned utility-scale solar PV, onshore and offshore wind, 2010-2021 (IRENA, 2021)](image)

The increasing penetration of these energies and their potential impact on the stability and operation of current grids is a cause for concern, limiting their adoption. The main challenge of these technologies is the intermittency of natural resources, which can be diurnal or short duration, especially for wind and solar.

Regarding solar power, a short-duration intermittency could be when a cloud passes over solar collectors, decreasing the power production from the affected system. This intermittency may appear brief; nevertheless, the time it takes for a passing cloud to shade a whole PV system depends on its speed and height, as well as the size of the PV system. It may take minutes rather than seconds for a 100 MW PV system.

Diurnal intermittency is more predictable than short duration, mostly occasioned by the variation in insolation during the day as the sun rises in the morning and sets in the evening. Over the day, as the equipment’s temperature increases, some solar cells’ efficiency may decline, resulting in less PV production.
These intermittencies lead to variable outputs from the generation system that may result in possible issues with the electric grid's reliability and stability, including frequency and voltage regulation, load profile following and broader power balancing. Accurate day-ahead and hourly forecasts are essential for the reliable operation of the power grid and the scheduling of complementary generation resources.

When system outputs are low, generation backup might be required to fulfil customer demand. Renewable firming is needed to reduce irregular production and handle the concerns of load profile following and power balancing. It can be achieved in different ways, by introducing some other generation type, purchasing from the intraday market or with energy storage. Capacity firming balances the necessity to energy procurement or build more dispatchable capacity. As a result, as renewable energy penetration increases, energy storage is becoming more relevant and cost-efficient.

Most research from the 2010s suggests that traditional planning and operational practices are only adequate for up to 15% renewable penetration levels. Although the lower presence of renewable energy on the grid can be successfully integrated, admitting more than 30% of generation from these intermittent sources would require new design methods for power systems and operation. Several years have passed since then when renewable energy has matured rapidly, but in any case, storage is still developing as a method to minimise load-following resources and enhance renewables integration. Moreover, energy storage for capacity firming can also help reduce renewable generating curtailment by maximising energy scavenging. (Sioshansi & Fereidoon, 2011; California ISO, 2010; MIT Energy Initiative, 2011)

### 2.2 Energy Storage and batteries development

Energy storage systems and battery development have become essential to transitioning towards sustainable energy production and enabling better integration of renewable distributed generation. The benefit of these systems is the ability to store excess energy generated during high production periods for later utilization during peak consumption hours. This approach effectively minimizes energy curtailment and contributes to the balance between grid generation and demand. (IEA, 2022)

However, there are many critical factors to consider when finding the optimal battery system design for a particular application. Various technologies exist at the moment, each with distinct costs, different behaviours and diverse degradation periods depending on the number of charging/discharging cycles and the depth of discharge. The impact of the use can be improved when combined with accurate demand forecasting for the short or medium term, allowing for optimal utilization of the energy storage capacity and enhancing the whole system's flexibility. (Alsaidan, Khodaei, & Gao, 2018)

Nevertheless, it is important to acknowledge that the successful integration of energy storage systems into a grid is highly influenced by various factors, including the energy market dynamics and legal framework of the corresponding country, along with any economic or infrastructure limitations. (IEA, 2022)
2.3 Current electric grid structures

As mentioned above, the world is moving to a cleaner, decarbonized energy generation; solar and wind resources have become more affordable, and electricity is predicted to become the primary energy carrier. Many countries seeking to accelerate the decarbonization process develop different policies that support and encourage the installation of renewable generation systems for self-consumption in industries, companies, and households.

Prosumers are all entities actively participating in the energy system, whether they consume and produce or solely produce heat or power, provide energy services, are members of an energy community, or own and operate grid infrastructure.

To date countries have not been motivated to track distributed energy systems, and the definition of prosumer considers a variety of sets of technology and ownership arrangements. The overall number of active participants in the EU energy system is unknown. However, for specific technologies or individual Member States of the EU, some figures are accessible.

In the Netherlands, the number of PV prosumers has gone from less than 500,000 in 2015 to over 1 million in 2020, while in Portugal, the number of PV prosumers has climbed from 3,000 to over 30,000 in 2019. Prosumers in Poland increased from 51,000 in 2018 to 847,000 in 2021, with an installed capacity of about 6 GW. The number of prosumers is advancing rapidly, and the energy market is transitioning, trying efficiently to integrate diverse distributed generation systems across the grid. (European Environment Agency, 2022)

Net-metering was developed as an instrument to facilitate the integration of these renewable distributed generation systems. Allowing self-consumers to supply the excess electricity they generate back to the grid and receive a compensation, usually in the form of a credit on their electricity bill.

There are mainly two variations of net-metering. "Classic" net-metering provides remuneration at the same rate as the retail price, resulting in the meters running backward when self-consumers feed electricity into the grid. Whereas, with net-billing, the electricity fed into the grid is valued at a lower rate than the retail price, while the electricity drawn from the central grid is charged at the retail price. Which encourages self-consumers to use the electricity they generate.

Net-metering also drives the development of smart meter technologies, which give users real-time information about their electricity production, consumption, and pricing. (Iliopoulos, Fermeglia, & Vanheusden, 2020)

Another point is that the current grid operates based on demand, adjusting the production to meet the changes of the former. However, the future electricity system will work based on supply. As mentioned above, solar and wind-based power production depends on factors such as the time of day, season, and weather conditions, causing production to fluctuate. Therefore, it will be necessary to match demand with the generation rather than adjusting supply to meet demand.

The future mix of centralised and decentralised energy generation is still unclear, given that technology is constantly evolving and new approaches to future issues are being developed, such as strengthening the power grid, improving transmission systems, and including long and short-term energy storage. (European Environment Agency, 2022)
3 Methodology and KPIs

For a proper analysis, it is necessary to collect basic generation and demand data for the systems studied, along with historical emission and price curves for electricity, detailed below in the Systems characterization section. For data processing and simulations of different system configurations, the System Advisor Model (SAM) is used for PV generation profiles, as well as a Python model that simulates different sizes of solar capacity, the BESS dispatch, based on generation availability, price curves and emission, as well as demand behaviour patterns. While simultaneously trying to achieve a slower system degradation, minimizing energy curtailment, and covering demand on peak hours.

3.1 Key Performance Indicators

As mentioned above, given the intermittency of solar energy and the inclusion of storage in the power generation system, it is essential to establish a balance between solar installation capacity and battery size. These two parameters are the ones that characterize the different simulated systems.

For assessing the various PV-BESS arrangements, the following KPIs were selected, that consider the impact of the two parameters, directly or indirectly, allowing to compare the alternatives in a qualitative way.

3.1.1 Levelized Cost of Energy (LCOE)

The levelized cost of energy represents the net average current cost of generating one unit of energy over the lifetime of a project, considering the capital cost, annual operating cost, discount rate, and annual output.

The formula to calculate it is defined as follows.

\[
LCOE = \frac{CAPEX + f(x = OPEX, i, n)}{f(x = E_{net}, i, n)}
\]

With:

\[
f = \sum_{t=0}^{n} \frac{x}{(1+i)^t}
\]

CAPEX as capital costs

OPEX as annual operation and maintenance costs

\(E_{net}\) as annual production

f as a function to get the annualized discount rate values

i as discount rate

n as years along the lifetime
3.1.2 Self-sufficiency

Self-sufficiency represents the proportion of the total load covered by the combined PV and BESS systems, and in this case, is defined by the following equation:

\[ SS = \frac{E_{PV \text{ to load}} + E_{BEss \text{ to load}}}{E_{Total \text{ load}}} \]  \[3\]

3.1.3 Avoided Carbon Emissions

The avoided carbon emissions are calculated for each hour using the average carbon intensity of the electricity production of each country, calculated with equation number 4:

\[ CO_2 \text{ avoided} = \sum_{h=1}^{8760} CO_2 \text{ intensity}_{avg \text{ electricity production}} \bigg|_h (E_{PV \text{ to load}} \big|_h + E_{BEss \text{ to load}} \big|_h) \]  \[4\]

3.1.4 Savings

The savings are calculated as the avoided cost due to self-generation, calculated hourly using the corresponding price curve with the formula below:

\[ Savings = \sum_{h=1}^{8760} \text{Electricity price} \bigg|_h (E_{PV \text{ to load}} \big|_h + E_{BEss \text{ to load}} \big|_h) \]  \[5\]

Lastly, to be able to compare the optimal PV-BESS system to the net-metering alternative also in a qualitative way, the Avoided Carbon Emission indicator defined in subsection 3.1.3 is used, along with the following KPIs:

3.1.5 Net Present Value (NPV)

The NPV is used to determine the financial viability of a project, calculating the present value of all future cash flows expected with the project. If the NPV is greater than zero, the project is profitable. Equation 5 is used to calculate it:

\[ NPV = \sum_{t=0}^{n} \frac{Cash \text{ flow}_t}{(1 + r)^t} \]  \[6\]

With:

- \( n \) as years along the period
- \( r \) as discount rate

3.1.6 PV curtailed

In a system with self-generation, when the electricity generated surpasses the demand, the production output is deliberated reduced in order to keep the balance between the load and the supply. This reduction is the energy curtailed.
3.2 Model

The model used to find the optimal configuration of the PV-BESS system in each case is shown schematically in Figure 2.

![Figure 2 Schematic representation of the dispatcher optimizer](image)

As inputs, the model requires the demand profile, the generation profile, and the capacity for the current installation. The price curve and the emission intensity of electricity generation are also necessary. All the sets are hourly over a year.

Different PV capacities, power rates and capacities for the BESS are specified. And the model simulates all the possible combinations between the mentioned parameters, optimizing the dispatch of the battery based on price and then again based on equivalent CO\textsubscript{2} emissions. The first outputs of the models are the hourly PV production over a year, detailing how much is used to charge the battery, curtailed and feed directly to the load, as well as the electricity purchased from the grid and the battery SoC. For each run, there are two annual sets detailed per hour created per combination, one with the dispatch optimization based on the electricity price curve, and the other based on CO\textsubscript{2} emissions.

With this sets, the annual production for each configuration is obtained, with its LCOE, self-sufficiency and associated emissions. In this study the LCOE is calculated for two time periods, one corresponding to the lifetime of the battery, and the other one to the lifetime of the whole project. With these results and combining the different optimizations, it is possible to iterate with different system parameters in search of better KPIs.
4 Locations

4.1 Greece

More than half of the electricity generation in the Hellenic Republic comes from fossil fuels and derivates. However, it is switching to a more renewable energy mix, increasing the number of solar energy installations. The irradiation levels in Greece are favourable for profitable PV installations. Last year the country connected 1.36 GW of new PV capacity to the grid. Of this, 341.5 MW was connected to the transmission grid and about 1020 MW was connected to distribution grids. According to its NECP, the local PV share is expected to reach 14.1 GW by 2030 and 34.5 GW by 2050. Greece also aims for battery energy storage capacity of 5.6 GW and 23.3 GW for 2030 and 2050, respectively. (IEA, 2022; Tsagas, 2023; Greek Government, 2023)

Net-metering, introduced during 2013 and 2014, aimed to promote the advance of solar setups in the country. Nevertheless, it was poorly conceived, resulting in a sudden surge of investments that were too costly and non-viable in the medium term. Since 2019, net-metering opened for all renewable sources. The country implements a classical net-metering regime that pledges significant benefits to those who join to accelerate distributed generation. (Iliopoulos, Fermeglia, & Vanheusden, 2020)

In addition, since April 2023, Greek households and farmers can apply for a public fund to pay for the purchase and installation of small PV and ESS. The new program could cover between 20% and 65% of the cost of the PV system, depending on considerations such as the installations capacity and the applicant incomes. For the ESS, it can cover from 90% up to 100% of the cost of purchase and installation of the batteries. The installations eligible are up to 10.8 kW capacity for PV and 10.8 kWh for battery storage. (Tsagas, 2023)

Considering this framework, it is of interest to compare the potential outcomes of implementing a BESS against net-metering. That is why one of the elected sites is a microgrid in Farsala, Greece. The Mega Evydrio community is part of the PEGASUS Interreg MED project, which consists of commercial, private, and public buildings with prosumers and electricity producers. All the electricity generated is from PV that, including two proposed projects, adds up to a total capacity of 723 kWp. The system is connected to the public grid but also can operates in island conditions. (Interreg Mediterranean Pegasus & CRES, 2019)
4.2 Uruguay

Moving away from the European Union, one of the leading countries in the transition to renewable energy in Latin America is Uruguay. Where in 2020, 94% of the electricity generated came from renewables. The interconnections with Argentina and Brazil of 2000 and 570 MW, respectively, along with the hydroelectric plants located in the different rivers of the territory, allowed the fast incorporation of large amounts of renewables. However, since the generation source with the highest installed capacity in the country is still hydraulic (31.2%), the ability to meet the demand is severely affected when rainfall and water availability decrease, resorting to electrical energy import from Brazil or Argentina. (IEA, 2022; Dosil, 2020; ADME, n.d.)

Around 4% of the electricity generated in 2020 came from solar energy. Although its share in Uruguay energy matrix is low, the installation of solar energy in the country has been promoted since 2018, through the exemption from VAT on the sale of PV solar panels and promoting the national manufacture of components for solar energy systems, this can reduce a project initial investment up to 50%. The accumulated micro solar generation power has been growing exponentially since 2014 and investment in new solar farm projects are expected in the coming years. (Government of Uruguay, 2021; Energía Solar, n.d.)

Decree 173/2010 enabled users connected to the low-voltage electricity grid to generate their electricity from renewable sources and defined the net-metering system for the country. This system allows prosumers to inject their surpluses, compensated at the same price as the kWh consumed according to the defined tariff. However, the energy injected into the network cannot exceed the amount consumed by the prosumer within a year. (Government of Uruguay, 2010)
5 Systems characterization

5.1 Data collection and assumptions

For currency conversion, the annual averages of the year 2022 were used as exchange rates:

\[
\begin{align*}
1\text{EUR} & \quad - \quad 1.05 \text{ USD} \\
1\text{EUR} & \quad - \quad 43.43 \text{ UYU}
\end{align*}
\]

(Exchange-Rates.org, 2023)

To ensure the credibility of the modeling, historical data from both locations were used as the base. Table 1 summarizes the main characteristics considered and sources for both cases, while Table 2 outlines key demand parameters. The sections below describe both systems in more detail.

Table 1 Data collection summary

<table>
<thead>
<tr>
<th>Source</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greece</td>
<td>Consumers - 295 houses - 16 shops - 4 public buildings - 471 streetlights - 3 pumping stations for water [1]</td>
</tr>
<tr>
<td></td>
<td>Producers &amp; Prosumers - 214 kWp PV installed on 80 houses (around 2.7 kWp each) - 9 kWp PV installed on public building - 500 kWp total PV parks [1]</td>
</tr>
<tr>
<td></td>
<td>Emissions Carbon intensity data collected from 2022 [2]</td>
</tr>
<tr>
<td></td>
<td>Electricity prices Data collected from 2020, 2021 and 2022, given the fluctuation due to the energy crisis in the EU. [3]</td>
</tr>
<tr>
<td>Uruguay</td>
<td>Consumers One production line that works three times per day from Monday to Saturday [4]</td>
</tr>
<tr>
<td></td>
<td>Producers 805 PV modules 217 kWp total [4]</td>
</tr>
<tr>
<td></td>
<td>Emissions Carbon intensity data collected from 2022 [5]</td>
</tr>
<tr>
<td></td>
<td>Electricity prices Data collected from 2022 [6]</td>
</tr>
</tbody>
</table>


Table 2 Electricity consumption and generation

<table>
<thead>
<tr>
<th>Greece</th>
<th>Uruguay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual energy [MW]</td>
<td>788</td>
</tr>
<tr>
<td>Max power [MWh]</td>
<td>0.3</td>
</tr>
<tr>
<td>Average power [MWh]</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Numbers obtained using sources [1] and [4] from Table 1.

Considering the current legal framework in both countries, for simulated systems in Uruguay 30% discount will be applied to the CAPEX of the solar installation. While for the systems in Greece, assuming a consistent 0.2 MW PV installed in domestic residences, a fixed discount of 43% will be applied to the CAPEX of said domestic installations and 95% discount to the first purchase of the associated battery capacity determined by the corresponding solar proportion.
5.2 Generation and Demand

5.2.1 Greece

Considering the consumers named in Table 1, the biggest demand in Greece is mainly from households and pumping stations. Figure 3 and Figure 4 depict the annual load profile per week and day. The behaviour remains consistent throughout the week, with a consumption peak occurring during the night between 7 and 11 pm when power generation using PV is not available. Additionally, the load uniformly increases around the first 9th and last 4th weeks, corresponding to the winter season when solar energy production is lower. Another peak in weeks 28 and 29 can be attributed to heat waves in July.

*Figure 3 Weekly load profile for the Mega Evydrio community*
The generation system in Greece currently has an installed capacity of 223 kW of the total 723 kW projected. As can be seen in Figure 5, with the current installation, energy production can surpass the demand during the daytime, especially in a summer week. However, it is not by much. On the contrary, winter production can be close to zero, and during the peak consumption time during the year, the energy required is more than two times the maximum production.
5.2.2 Uruguay

In Uruguay, the chosen system is a beverage manufacturing plant located in Montevideo city centre. It operates from Monday to Saturday in three shifts, halts operations every Sunday and shuts down for maintenance for at least two weeks per year.

The load of the plant is linked to beverage production, which fluctuates throughout the year, with higher intensity observed during the summer, from December to March on the southern hemisphere. Figure 6 illustrates the daily variation in demand over a year, the profile is not as recognizable as in Greece, but the start-up curve of the production line is distinguishable.

When the weekly load is analysed, a clear consumption pattern can be observed in Figure 7, with significantly lower energy usage on Sundays.
The company did not design the PV system to cover the totality of the electricity demand but to alleviate grid consumption. It has an installed capacity of 279 kW. Consequently, every day while the plant is in operation, the load greatly exceeds the generation. Although, there is a significant surplus on Sundays, which could be used on other working days, as can be seen in Figure 8.

Figure 7 Weekly load profile for the production line in Uruguay

Figure 8 Load vs production on the maximum and minimum generation weeks in Uruguay
5.3 Carbon intensity

To analyse the emissions, it is necessary to collect historical data on the carbon intensity of electricity generation for each country, obtained through electricity maps. As can be observed in Figure 9, Greece reaches up to 661.2 g CO$_2$/kWh, consistent with its electricity generation matrix, of which 60% relies on fossil fuels and derivates. (IEA, 2022)

![Figure 9 CO$_2$ intensity of electricity generated in Greece](image)

In contrast, Uruguay has a relatively low carbon intensity. However, considering what was mentioned above about electricity generation in this country, where 94% comes from renewables, there is no full correspondence with the values of Figure 10. This inconsistency can be explained by the fact that the country’s generation is not enough to supply the national demand, so electricity is imported from Argentina and Brazil, where the proportion of renewable energy generation is not as high as in Uruguay. (IEA, 2022; ADME, n.d.)

![Figure 10 CO$_2$ intensity of electricity generated in Uruguay](image)
5.4 Electricity prices

Lastly, for a comprehensive analysis, it is necessary to have detailed pricing information. In this case, each country has vastly different situations.

The Hellenic Republic, along with the rest of Europe, have been strongly affected by the war in Ukraine and the energy crisis that continues to strike in the entire region. In Figure 11 it can be observed, that in 2020 the prices are concentrated mainly in a range of zero to a hundred euros and are repeated frequently. In the following years the price ranges extend considerably, with a decrease in the number of repetitions. This depicts the substantial price escalation and instability witnessed in recent years. The count of records decreases with each passing year, additionally the average of cost registered in 2020 was 45€/MWh, whereas in 2022 it escalated to 279€/MWh.

![Figure 11 Greek electricity price curve comparison for 2020, 2021 and 2022](image)

Further from Europe and its energy crisis, Uruguay has an electric power monopoly, regulated by the state entity UTE, which determines prices by time slot plus a fixed monthly charge. For this analysis, the regulations for year 2022 were used, which determined a fixed charge of 198 € and the following rates for users with a maximum contracted power equal to or greater than 200 kW:

- From 00:00 to 07:00: 49.5 €/MWh
- From 18:00 to 22:00: 251.1 €/MWh
- The remaining hours: 89.4 €/MWh

(UTE Uruguay, 2022)
5.5 Additional Parameters

Other parameters necessary for the simulations are detailed in Table 3 with their respective sources.

<table>
<thead>
<tr>
<th></th>
<th>Greece</th>
<th>Uruguay</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Price [€/kW]</td>
<td>690</td>
<td>809</td>
</tr>
<tr>
<td>BESS Price [€/kWh]</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>PV O&amp;M [€/kWh]</td>
<td>19.6</td>
<td>19.6</td>
</tr>
<tr>
<td>BESS O&amp;M [€/kWyear]</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Lifetime project [years]</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Lifetime BESS [years]</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Discount rate [%]</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>


6 Limitations

The limitations of the analysis are mainly two:

Firstly, incomplete data sets for demand or generation profiles due to failures in the electrical system, meters, or power outages. The hours with missing values were completed with the average between the previous and following value or based on values from a day with a similar behaviour.

Secondly, the PV generation profiles. The base case production was directly provided for the current installation in Greece, and the plant in Uruguay provided the necessary details of their PV installation to calculate the generation with SAM. However, when running the model to test various capacities of solar installations, instead of simulating each one, the generation profiles are obtained by scaling the base case, which is not completely accurate but is a good approximation.

Additionally, it is acknowledged that the prices of batteries, and the energy price per hour, given the energy situation in Europe, are highly fluctuating economic variables. Throughout the analysis, efforts will be made to mitigate the effects of these variations by conducting the necessary sensitivity analyses.
7 Modelling

Below are the values for the initial sets of simulations for the model. In Results analysis, more simulations are presented, with variations within a smaller range around the point of interest.

7.1 Greece

In the case of the Mega Eviydrio, considering that they plan to install a total of 723 kWp, this value, considered the minimum PV capacity to simulate, was included in the initial set of parameters for the simulations along with solar capacities ranging from 1 to 5 MW with a 1MW step. After obtaining the results, it was decided to continue with the second set detailed in Table 4. Subsequently, the remaining sets were selected using the same procedure.

The dispatcher uses the historical data to prepare for the demand, knowing the expected behaviour for 24 hrs ahead, since the daily profile is quite defined. On the other hand, given the great variation in electricity prices in the last three years in this country, it is decided to carry out the model for the three years: 2020, 2021 and 2022.

Table 4 Sets of parameters for the initial Greek model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Set 1</th>
<th>Set 2</th>
<th>Set 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV size [MW]</td>
<td>0.7; 1:1:4</td>
<td>1.0; 0.25:1.75</td>
<td>1:1:3</td>
</tr>
<tr>
<td>BESS power [MW]</td>
<td>0.5; 0.75</td>
<td>0.5:0.25:1.0</td>
<td>1.0; 1.5</td>
</tr>
<tr>
<td>BESS capacity [hrs]</td>
<td>0:1:16</td>
<td>0:1:16</td>
<td>0:1:16</td>
</tr>
<tr>
<td>BESS size [MWh]</td>
<td>0-12</td>
<td>0-16</td>
<td>0-24</td>
</tr>
</tbody>
</table>

Note: The notation "X1:X2:X3" signifies the set of values starting from X1 and incrementing by X2 until reaching X3. "Y1-Y2" is employed when the steps between values are not uniform. For multiple individual values or ranges ";" are used as separators. BESS size is the product between BESS power and BESS capacity.

Once finished the simulations, it was possible to observe that both levelized cost of energy and self-sufficiency had insignificant variations for the different price curves. This was expected since both KPIs at this point are based on annual values. The graph showing LCOE as a function of the self-sufficiency for the year 2022 is shown in Figure 12.

Figure 12 LCOE as a function of self-sufficiency based on prices from 2022.
On the other hand, for each case, the hourly values of the SoC of the battery and the amount of energy provided directly from the panels vary substantially from 2020 to 2022, and with it, the amount of energy saved by being independent of the grid. This can be observed in Figure 13, which depicts the savings as a function of self-sufficiency. It is worth mentioning that the slope becomes more pronounced as market prices increase each year.

![Figure 13 LCOE as a function of self-sufficiency for prices from 2020 to 2022.](image)

After analysing the first results, it was decided to proceed into simulations on systems with a BESS capacity range between 2 to 5 hours, and 0.5, 0.75, and 1 MW power, while switching the PV capacity of the system from 700 kW to 3MW with a 50kW pace. The Results Analysis section includes these simulations along with the previous ones.

### 7.2 Uruguay

Considering that the annual load of Uruguay is approximately twice that of Greece, the simulations will start with a range of 1 to 2 MW of PV with a step of 0.25 MW. Once again, the following sets are defined once the results of the previous ones have been obtained.

Table 5 Sets of parameters for the initial Uruguayan model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Set 1</th>
<th>Set 2</th>
<th>Set 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV size [MW]</td>
<td>1.0:0.25:2</td>
<td>3; 4</td>
<td>2.5:1:4.5; 2.75:1:4.75:5</td>
</tr>
<tr>
<td>BESS power [MW]</td>
<td>0.75; 1; 1.5</td>
<td>0.75; 1; 1.5</td>
<td>1; 1.5; 2</td>
</tr>
<tr>
<td>BESS capacity [hrs]</td>
<td>0:1:16</td>
<td>0:1:16</td>
<td>0:1:16</td>
</tr>
<tr>
<td>BESS size [MWh]</td>
<td>0-24</td>
<td>0-24</td>
<td>0-32</td>
</tr>
</tbody>
</table>

Note: The notation "X1:X2:X3" signifies the set of values starting from X1 and incrementing by X2 until reaching X3. "Y1-Y2" is employed when the steps between values are not uniform. For multiple individual values or ranges "," are used as separators. BESS size is the product between BESS power and BESS capacity.

In this case, the three sets are simulated with the same price distribution but different battery forecasts. First for 24 hours and then for 48 hours. Figure 14 shows all the points obtained from the various configurations with ESS, optimizing the dispatch based on the price of electricity per hour. This time, for calculating the KPIs a period of one year is considered.
The difference between the curves is negligible, although it increases for lower self-sufficiency and higher LCOE, associated with lower PV capacity and larger ESS installations, respectively. It would be convenient to keep the analysis of results differentiated for each forecast if the systems to be studied were more considerable in size. However, for this case the study will continue using the values resulting only from the analysis with 48 hours forecast.

![Figure 14 LCOE as a function of self-sufficiency, for 24 and 48 hrs forecast.](image)

For this case, the attention centres around ESS with 2 to 6 hours capacity and a power of 1, 1.5 and 2 MW. The simulations couple all the possible ESS configurations with PV systems with a capacity range between 2.5 to 5 MW and a 100 kW pace.

### 8 Results Analysis

The configurations to be studied in more detail are those that constitute the pareto front of LCOE as a function of self-sufficiency. This entails ensuring a lower LCOE for each obtained self-sufficiency value. For both countries, an upper limit is established for the LCOE. In the case of Greece, considering the average electricity price was 279 €/MWh, a maximum of 300 €/MWh is adopted as the limit. Similarly, using the same criteria, the maximum allowable LCOE for Uruguay is set at 250 €/MWh. This was done integrating both dispatch optimization performed by the model, based on the price of electricity and based on emissions.

The configurations obtained from the pareto fronts are compared using the KPIs defined in section Methodology and KPIs. This comparison is conducted both during the useful life of the BESS (8 years) and after the entire project duration (25 years), incorporating the applicable discounts for each country. The discounts are applied solely to the initial purchase cost, under the assumption that tax benefits are not retained for the full 8 years.

Figures displaying the LCOE, self-sufficiency values, savings, and avoided CO₂ achieved for each configuration are presented below. Additionally, a chart shows whether the configurations were obtained through dispatch optimization based on price, emissions, or both.
8.1 Greece

8.1.1 BESS and project analysis Pareto optimal points

![Figure 15 Pareto optimal points for BESS and project lifetime analysis](image1)

8.1.2 BESS configurations

![Figure 16 Self-sufficiency and LCOE for the optimal configurations during the BESS lifetime](image2)

![Figure 17 Monetary savings and avoided emissions for the optimal configurations during the BESS lifetime](image3)
8.1.3 Project configurations

Figure 18 Distinction between price and emission optimization (BESS analysis)

Figure 19 Self-sufficiency and LCOE for the optimal configurations during the project lifetime

Figure 20 Monetary savings and avoided emissions for the optimal configurations during the project lifetime
8.1.4 Final PV-BESS Selection

In Figure 15 two distinct trends can be seen, the one with lower self-sufficiency values is associated to the 700kW PV capacity and all its respective configurations. Whereas the curve with the highest self-sufficiency values is composed by different PV capacities, ranging from 2 to 4 MW, with BESS of mostly 3 hours duration.

From the figures above, when conducting the study solely over the initial eight years, the configurations in the interval from 2.4 to 2.9 MW capacity stand out, with high self-sufficiency and low LCOE. On this spectrum, there is no tradeoff between these two KPIs, as neither is for savings nor avoided CO$_2$. It is worth mentioning that these specific points were not included in the analysis during the total 25 years due to their associated high LCOE. This cost disparity is attributed to the high expenses associated with BESS replacement in years 8, 16, and 24 across the project's lifespan. When applying the discount rate in vigor for battery acquisition in year 8, the configurations LCOE decrease as shown in Figure 22, featuring configurations associated with LCOE below €300/MWh.
Considering the location of the Mega Evydro community and the space available for PV installations, the 4 MW configuration with a BESS of 0.75 MW power and 2.25 MWh capacity is selected. Additionally, taking into account that a PV installation with a total capacity of approximately 700 kW is already planned, a configuration with said capacity and a 2.25 MWh BESS will also be studied.

Configurations ranging from 2.4 to 2.9 MW were discarded, because there is no guarantee that the domestic BESS discounts will be maintained in the future.

8.1.5 Comparison considering Net-metering

In this section, both systems previously selected are compared to their alternative without BESS, with the same solar generation capacity. This evaluation examines the influence of solely net metering in contrast to the flexibility of choosing when to utilize the grid. In Table 6 the selected configurations economical KPIs are evaluated for 2022 and 2020 prices. For the former, the additional KPIs, avoided CO$_2$eq and PV curtailed are presented in Table 7.

Table 6 NPV and Annual Savings for PV systems alternatives with and without BESS with 2020 and 2022 prices

<table>
<thead>
<tr>
<th></th>
<th>2022</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7 MW (+ 2.3 MWh)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV + BESS</td>
<td>262</td>
<td>1.0</td>
</tr>
<tr>
<td>PV</td>
<td>240</td>
<td>2.5</td>
</tr>
<tr>
<td>4 MW (+ 2.3 MWh)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV + BESS</td>
<td>1372</td>
<td>12.5</td>
</tr>
<tr>
<td>PV</td>
<td>1374</td>
<td>14.3</td>
</tr>
</tbody>
</table>
At first glance, the strong dependence of the system's profitability on market prices is noticeable. As mentioned earlier, the average electricity cost in 2020 is approximately six times lower than in 2022; this enables yearly savings to offset investments in panels and batteries throughout the 25-year project lifespan.

The annual savings for the same system with or without a battery are similar, equally in 2020 and 2022. Furthermore, the difference decreases as the installed solar capacity increases. This can be attributed to the fact that the annual savings come mainly from the sale of excess electricity generated rather than from what is saved by not consuming energy from the grid during peak hours. The optimization of the battery dispatch based on the price, is so that the demand consumes from the BESS instead of the grid, not to achieve greater profits with the sale of electricity through net metering.

Focusing now solely on the 2022 values obtained, alternatives with and without BESS are both profitable, the second one has a higher NPV, but the difference is not that significant. However, the other indicators do have a considerable difference in favour of the PV-BESS system. In particular, the avoided equivalent CO$_2$ emissions are around three times lower when using energy storage. However, it is relevant to mention that the production of the PV modules and batteries have associated emissions of around 7.4 kg CO$_2$eq / kW$_{DC}$ and 161 kg CO$_2$eq / kWh respectively. When considering a life cycle assessment, the real difference between both alternatives will decrease due to the emissions associated to the battery elaboration. In Table 8 an approximation is made to assess the gap, but when studying a 25-year period, with a small battery capacity the difference in emissions is still in favour of the PV-BESS system. (Parlikar, Truong, Jossen, & Hesse, 2021)

<table>
<thead>
<tr>
<th>Avoided CO$_2$ eq [ton]</th>
<th>Annual PV curtailed [M€]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PV + BESS</strong></td>
<td>251</td>
</tr>
<tr>
<td><strong>PV</strong></td>
<td>82</td>
</tr>
<tr>
<td><strong>PV + BESS</strong></td>
<td>300</td>
</tr>
<tr>
<td><strong>PV</strong></td>
<td>95</td>
</tr>
</tbody>
</table>

Table 7 Avoided CO2 and PV Curtailed for PV systems alternatives with and without BESS

<table>
<thead>
<tr>
<th>Avoided CO$_2$ eq [ton]</th>
<th>Without PV+BESS prod.</th>
<th>With PV+BESS prod.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PV + BESS</strong></td>
<td>6275</td>
<td>6276</td>
</tr>
<tr>
<td><strong>PV</strong></td>
<td>2050</td>
<td>2050</td>
</tr>
<tr>
<td><strong>PV + BESS</strong></td>
<td>7500</td>
<td>7502</td>
</tr>
<tr>
<td><strong>PV</strong></td>
<td>2375</td>
<td>2375</td>
</tr>
</tbody>
</table>

Table 8 Avoided CO2 for 25-year period considering main components production
8.2 Uruguay

8.2.1 BESS and project analysis Pareto optimal points

![Figure 23 Pareto optimal points for BESS and project lifetime analysis]

8.2.2 BESS configurations

![Figure 24 Self-sufficiency and LCOE for the optimal configurations during the BESS lifetime]

![Figure 25 Monetary savings and avoided emissions for the optimal configurations during the BESS lifetime]
8.2.3 Project configurations

Figure 26 Distinction between price and emission optimization (BESS analysis)

Figure 27 Self-sufficiency and LCOE for the optimal configurations during the project lifetime

Figure 28 Monetary savings and avoided emissions for the optimal configurations during the project lifetime
8.2.4 Final PV-BESS Selection

Comparing the two analyses for Uruguay, given that the current tax benefit in the country applies only to the acquisition of PV, the optimal configurations with LCOE lower than 250 €/MWh do not vary much by changing the analysis time from 8 to 25 years.

As it can be observed in Figure 23, unlike in the case of Greece, there seems to be a trade-off between high self-sufficiency and low LCOE, that can be attributed to lower tax benefits for system installation and lower solar irradiance compared to Greece. On the other hand, it is worth mentioning that the higher the installed PV capacity, the greater the difference in the configurations obtained by the dispatcher optimization, depending on the price and the emissions.

As previously mentioned, the plant is located in the heart of the Uruguayan capital, so the number of panels that can be installed is limited by the available rooftop space on the premises. Hence, it was decided to continue studying the configuration of 1 MW of PV, with a BESS of 1 MW power and 2 hours of capacity. This arrangement has the lowest LCOE across both analysis periods and is optimal in terms of both emissions and prices.

8.2.5 Comparison considering Net-metering

The system composed of 1 MW of PV and 2 MWh BESS is compared now to the alternative without BESS, with the same solar generation capacity. For a qualitative comparison NPV is used and the following values are obtained.

Table 9 KPIs evaluation for 1MW PV system with and without BESS

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PV + BESS</td>
<td>109</td>
<td>-1.7</td>
<td>37</td>
<td>70</td>
</tr>
<tr>
<td>PV</td>
<td>309</td>
<td>3.2</td>
<td>30</td>
<td>189</td>
</tr>
</tbody>
</table>
For Uruguay, the PV+BESS configuration is not profitable. Furthermore, there is a significant difference in annual savings. Once again, a greater part of the savings comes from surplus production sales and not from avoiding consumption on the grid during peak hours. Additionally, the tariff schedule in Uruguay, very different from the electricity market in Greece, has defined hours for each price range that remain stable throughout the year. Achieving a positive NPV for a PV+BESS system could be feasible by configuring the battery dispatch to sell electricity to the grid during peak hours, generating higher profits to solvent the investment in the storage system.

9 Conclusions

After carrying out the study, it is concluded that the optimal approach for integrating distributed generation into the grid is not universal. The integration of these systems is strongly affected by the local electricity market dynamics, available tax incentives to support micro generation and renewable investments, and the national electricity generation matrix. Furthermore, in regions characterized by high solar irradiance, such as Greece and Uruguay, there are no significant compromises between high self-sufficiency and low LCOE. Another interesting point is that for most analyses produced, configurations optimized for price align closely with those optimized for emissions.

In more unstable electricity markets, such as the present-day European market, achieving independence from the grid using batteries is a profitable option. In addition, due to the current legal framework in Greece to encourage micro-generation, initial investments are significantly reduced, fostering a favorable environment for the profitability of such projects. Conversely, in Uruguay, where benefits for battery acquisition remain undefined, initial investments are notably higher. In addition, with a relatively stable current electricity market and a clearly defined tariff structure, optimizing the battery dispatch based on the electricity market to sell to the grid during peak-cost hours could yield a more lucrative outcome.

In addition, in electricity generation matrices that still strongly rely on generation using fossil fuels and derivatives, the use of distributed renewable generation, together with battery systems, is beneficial both for the consumer and the environment. As can be seen in Figure 17 and Figure 20, these systems can avoid more than 300 tons of CO$_2$ annually. Nevertheless, locations with more decarbonized national generation, such as Uruguay, do not benefit as much, avoiding only around 60 tons of CO$_2$ emissions. However, as stated in section 8.1.5, in those figures the elaboration of the different PV-BESS systems components have emissions associated are not considered. Battery production is very carbon intensive, that’s why a complete LCA is recommended to calculate the real amount of avoided CO$_2$, especially in systems with large storage capacities.

Finally, in these two specific scenarios, for the current situation in Greece, the most economically viable and environmentally friendly option is the installation of PV together with BESS. Given that the demand originates from a rural community with potential for population growth, investing in 4 MW of solar energy is a convenient option. In contrast, for Uruguay, characterized by an already decarbonized electricity mix, stable electricity prices and no battery purchase incentives, the best option is to install only the panels. It would be interesting to revisit the simulations, this time optimizing battery dispatch to maximize gains through net metering.
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