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Techno-Economic Analysis of BESS Integration for the Revamping of a 3.0 MW Photovoltaic Plant

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Abstract:

The growing integration of photovoltaic (PV) generation and the decreasing production of the current solar power plants have increased the necessity to devise cost-efficient approaches in increasing energy output whilst keeping account of grid export limitations. This thesis examines the technical and economic viability of the project to upgrade an existing power plant with 3.0 MW of photovoltaic power generation and considers the use of battery energy storage systems (BESS) to optimize the profitability of the project. The work is based on 7 years of real production data of a solar power plant, which gives a solid empirical foundation to evaluate the performance of a plant and prevent uncertainties that come along with purely simulated generation models. Various revamping cases were investigated, with incremental growth in the installed PV capacity, taking into consideration technological improvements in the modern modules. Constant price of electricity sales and fixed grid interconnection limit were taken and long-term effects like degradation, operating cost, and system lifetime were considered. This was an initial economic screening, which was performed through the use of spreadsheet calculations to approximate revenues as a result of several PV-BESS configurations. The most interesting case was then modeled in detail with the System Advisor Model (SAM), which allowed detailed analysis of hourly operation, seasonal behavior, degradation, and financial performance with a 20-year horizon.

The findings indicate that PV revamping is a significant way of boosting the yearly energy generation and profitability of the project. In the cases investigated, the maximum economic benefit is gained at 20% increase in PV capacity. Though the setup with a small BESS would theoretically give the highest NPV, time-series analysis shows that the battery is practically idle since the grid export limit will never be hit. Therefore, the battery will not lead to extra energy-saving or income generation. The paper concludes that a 20 percent PV revamping without battery storage would be the most economically viable solution to the problems analyzed.

1. Introduction:

1.1 Global Renewable Energy and Solar PV in Decarbonization

The world has discovered solar photovoltaics (PV) to be one of the pillars of decarbonization of the energy sector. Countries all over the world are accelerating the transition of fossil fuels to bio-based energy systems to address climate change. Solar PV, in particular, has undergone radical price reductions and has turned into the most affordable alternative of new electricity production worldwide ((IEA-PVPS), 2023). According to the net-zero emissions roadmap published by the IEA, approximately 90 percent of global electricity in the year 2050 would be produced by renewables, and almost 70 percent of the renewable energy would be wind and solar PV. This massive growth is already underway: as of 2023, PV generation rose by 25% to about 1600 TWh (about 5.4 per cent of world electricity) - the fastest annual growth of any renewable energy. The fact that solar power is scalable and its cost has been reduced a lot makes it one of the pillars to achieving the climate targets.

As PV solar energy is installed in the grid, it needs the stabilization of energy fluctuations and the minimization of energy waste. Curtailment of solar power and sometimes negative electricity prices at times of maximum PV generation are already being seen in some locations, further proving the need to create increased flexibility in the systems. The proposed solutions are grid infrastructural developments and energy storage that are increasingly becoming critical to ensure that the overall potential of solar PV is exploited in a reliable manner. Many renewable deployment and grid modernization policies are being forced in Europe. (A, Emery, & Warta, 2013)In Italy, in particular, these policies help to grow solar PV capacity beyond 36 GW, the capacity on the end of 2024 to 80 GW by the year 2030. It is also targeting about 15GW of battery energy storage by 2030 in order to support these larger renewables fleet. These ambitious goals will include new installations and also to make sure that the current solar resources and storage get as much performance as possible to balance the grid.

1.2 Challenges of Aging PV Plants

The high-capacity PV power plants that were developed over a decade ago are old, and the performance is already beginning to suffer. PVs are also known to decrease their production with time by approximately 0.5 percent of the power output annually - meaning that the output of a 10–

15-year-old plant can be lost in a quarter of the power output as compared to the nominal output power. The lifespan of power electronics, such as inverters, is also limited; the frequency of failure is expected to grow exponentially after about 10 years of operating. Consequently, older PV plants can face increasing downtimes and more expenses on maintenance. (Agency I. E., 2023)

A study of PV installations in Europe found that the actual effective life of a lot of systems is a bit less than the 20-25 years that had originally been predicted, since significant failures begin to appear at an accelerating rate after about 15-20 years of operation. This aging affects profitability and the production of the solar power plant. To explain, a 3 MW-sized plant can be developed taking optimistic factors into account, but in ten years' time, it might be supplying approximately 90 percent of the initial output. This reduction in production directly reduces the income of power sales or feed-in tariffs.

Besides the aging of components, the old PV plants are known to have obsolete technology and ineffective design as per modern standards. The power and output of early generation solar panels are not the same as the latest generation of solar panels, hence the solar potential of the location is not used to the maximum. (Agency I. R., Renewable Power Generation Costs in 2022, 2023).The old generation power plants may be fixed-tilt array but new solar PV systems are tracked to track the sun to boost production. These are the factors that contribute to the growing gap in performance between the old PV plants and the state-of-the-art plants. The PV farms undergoing the process of aging are under the threat of technical and operational problems that can turn into extended outages and expenses. In conclusion, the global PV is at a point of maturity, and an urgent need has been felt in regenerating or enhancing the efficiency of the old solar farms, thus remaining a major contributor in the renewable energy quota.

1.3 Revamping Solar PV Plants: Concept and Policy Incentives

In order to counter the performance degradation and exploit the technology advancement, the project owners increasingly resort to revamping and repowering of the already existing solar PV systems. Revamping an existing facility involves upgrading it to enhance its performance or to recover its initial performance by replacing defective or outdated components (including inverters and PV modules) with new ones. (Agency I. R., Renewable Power Generation Costs in 2022, 2023) The total installed capacity is kept relatively the same in a revamp, but the production and reliability of the plant are increased by a higher quality of equipment. Conversely, repowering contains modifications of the PV modules, inverters, and electrical design in order to enhance the installed capacity and yearly output over the initial design.

Practically, revamping and repowering are often linked: By replacing the old equipment with more efficient ones, the margin of capacity or physical space can be freed to place more PV modules. The possible rewards can be seen in real life. An example of such reform is a fleet-wide revamping initiative in Italy, which is increasing the capacity of 35 solar plants by 43 percent without expanding land-use by fitting more efficient solar panels. Likewise, retrofitting modules that are 10 years old and worn out with newer, higher efficiency modules has translated to the stunning results of output - one refurbished plant increased the energy output by a factor of about 38 percent, and its performance ratio skyrocketed (even with its incentive contract unchanged). These examples show how prudent upgrades can not only restore the performance lost but also add to the production of the plants and contribute to their sufficient extension of the useful life of the PV assets. (Agency I. R., Renewable power generation costs in 2022, 2023)

The focal point of revamping decisions is in national incentive policies. Several European PV facilities were established in 2010-12, such as those in Italy, which have long-term feed-in tariff (FiT) programs that guarantee a fixed amount per unit of solar power generated. However, the projects depended initially on these FiT contracts (which are often 20-year contracts). Nevertheless, they also come with some conditions, which are that, should a plant be altered considerably in a manner that alters the characteristics, which also brought it to the FiT in the first place, the incentive can be withdrawn. In Italy, the government (via GSE) has come up with highly comprehensive guidelines to regulate the upgrades and differentiate between usual maintenance and major modifications. The recent regulations permit a limited upgrade of capacity, the maximum amount being 1 percent of original capacity on PV systems over 20kW, without losing the FiT and the tariff is compensated for to the new capacity. With a 3.0MW plant, this is at best an incremental 0.03MW, which is subject to the incentivized rate. Additional capacity above these limits is now expressly allowed, although additional capacity over the 1 percent limit will still not be under the original FiT. Rather, it is required that the additional power be sold in other arrangements (e.g. under market off-take contracts / PPAs), besides the production with FiT. Such provisions of the policies allow the owners to be able to modernize their PV, as well as be able to expand their PV plants to satisfy the current technology and climate targets, and still sustain the revenue stream of the existing FiT. In fact, the owners of these plants are using these opportunities - some Italian PV parks have already enhanced their productivity up to higher efficiency modules, and some new panels have been added to the free area, which are run on a merchant basis (selling electricity to the market beyond the FiT. These types of projects are points to emphasize how technical upgrades need to be exposed to the incentive framework in order to realize much more solar generation out of the old installations.

1.4 Grid Constraints and the Role of Battery Energy Storage

One of the main limitations that may be encountered when upgrading a PV plant is the grid export limitation. Usually, PV plants are often restricted to a maximum power that they can add to the grid at any one particular moment, either through interconnection agreements or by size of the inverter (to provide grid stability). In 3.0 MW PV plant described in the research, the export constraint maintained by the grid operator is 2.8 MW, and hence, even assuming the solar array has 2.8 MW capacity in bright sunshine conditions, only 2.8 MW is exported - the rest is automatically clipped (curtailed). This limit is directly proportional to the potential generation and income because any amount of generation beyond 2.8 MW shall be lost. PV designers have long been known to over-size PV capacity (solar modules) relative to AC capacity (inverters/grid connection) to be able to guarantee that maximum power is collected under less-than-ideal conditions, with certain midday peaks being clipped off. (Baringo, 2016) Not to be as is common, since oversizing has become a normal practice due to decreased PV module prices, though it can result in massive wastage of the generated power if not done.

An effective solution to this curtailed energy is Battery Energy Storage Systems (BESS), which would allow turning this useful but curtailed energy into a resource with a profit potential. With the addition of BESS on the site, the PV plant will be in a position to store the surplus solar energy collected when the sun does produce more than 2.8 MW of solar energy requested and can be released at a later stage when the sun does not produce the 2.8 MW of solar energy requested or at the time of increased demand. Practically, the battery absorbs the energy that was being wasted and smooths out and extends the power flow of the plant. It was found that when the batteries are coupled to PV, a substantial reduction of the inverter clipping losses can be achieved: the additional PV power can be redirected to the battery until the battery is fully charged. (Bazilian, 2013)This implies that the system will be able to achieve a better overall utilization of its PV capacity - the

DC/AC ratio of PV plant can be driven very far above its conventional value of near 1.2, when it is equipped with a battery without energy wastage. In reality, a BESS large enough to accommodate our 3MW (DC) array would enable our array to behave more like a 3MW resource below the 2.8MW AC export limit by time shifting a portion of the generation off-peak.

Other than filling in the grid cap, a battery system enhances the economic value of the plant through energy time-shifting and as an ancillary service. In a liberalized market of energy, electricity price decreases in the daytime, and the price of electricity in the evening drops when the sun is not shining; therefore, the frequency of use of the gas-fired generators can increase. The available battery capacity allows the operator to charge on excess solar energy that is of low value and discharged in the evening at high prices due to the electricity price. (Bento, 2016) Such increases of revenues per kWh, in sunny areas with solar rate soaring such as southern Italy, where the threat of curtailment is on the increase, the PV+ BESS combination has the benefit of generating more revenue from idle energy production. There has been an awareness of these advantages, and Italian energy planners have now announced PV-plus-battery hybrids as a national priority. The new regulation and capacity auctions (such as the 2025 MACSE storage tender with Terna) are designed to bring big batteries online and actively encourage the projects capable of storing the solar excess that would otherwise be curtailed and offer it at a later more favorable time. Therefore, incorporation of a BESS is a significant measure in the updated 3.0 MW facility to break the export limit and gain as many benefits as possible of a PV capacity expansion and add to the provision of a more adaptable, resilient power grid.

1.5 Feasibility Study Objectives and Relevance to Energy Transition

With the various affecting factors mentioned above, a detailed feasibility study cannot be disregarded before revamping of the 3.0MW PV plant and integration of BESS can be pursued. The central issue the study will seek to consider is to get the optimal PV upgrade and battery system arrangement that provides the optimal technical performance and economic payoff under the specified constraints. (Blair, Dobos, Freeman, & Wagner, 2014) Certain crucial trade-offs will be studied: to the extent that it will result in less wasted energy by generating more, this increase in energy production could be more than the load. A smaller battery may imply that there will be unused useful energy and a big capacity battery might eliminate all the clipping but not utilized sufficiently during the solar production is low, which might not be cost effective. Thus, there needs to be an adequate techno economic analysis to pursue the compromise. Technically, it will include a simulation of the energy production in varying upgrade conditions of the plant) and a simulation of the battery operation to ensure that the 2.8 MW threshold of export will be adhered to at any moment. This will give the figure of additional energy that can be extracted and supplied per configuration annually. The economic part will focus on estimating the costs in capital and operations and the extra revenues that the upgraded plant can bring. Viability studies will involve the calculation of key performance indicators like; net present value (NPV), internal rate of return (IRR) and payback period of various configurations. By alternating the technical and financial analysis, the study objective is to arrive at the configuration which is technically and economically optimal. (Boardman, 2018)

More importantly, this thesis is driven not only by the requirements of a single project, but also by the bigger picture of the energy transition in Italy and Europe. It is best that countries in the EU in general increase the lifespan of PV plants and get more production of the available renewable assets to achieve national and EU-wide decarbonization goals. Each megawatt-hour of solar power recovered out of a PV plant by refurbishing, replaces one unit of generation fueled by fossil fuel and contributes to achieving renewable energy goals. The maximization of the production utilizing the currently preexisting PV installations as a method of introducing large volume of clean energy production is a cost effective and efficient way to work towards the elimination of much of the thermal generated capacity in Italy. Moreover, energy storage added to the PV plant will increase the flexibility of the grid. The experience gained during this feasibility study would be applicable on a larger scale than this single plant, and can serve as a guide on the way other old PV plants would be updated in order to keep the energy transition going. (Boardman, 2018) With Europe aiming to reach its 2030 and 2050 climate ambitions, new technologies like the redesigning and the integration of a solar plant with a battery will continue to play a more and more significant role. It is on this basis that the current research on the revision of a 3.0 MW PV plant with a carefully chosen BESS is quite pertinent. It reflects the bigger challenge of modernizing existing infrastructure by introducing the latest storage technology and harmonizing the technical upgrades with policy and market framework to provide sustainable, reliable and economically viable energy. The ability to fully examine the technical capabilities and the financial performance, the project envisions that a poorly performing PV plant gets a second, futuristic investment, and may feature significantly in Italy in terms of its future-renewable energy ambitions. (Brown, Spatial and temporal variation in the value of solar power across United States electricity markets, 2020)

2 Literature Review:

2.1 Global and European Trends in Solar PV Deployment and Aging of PV Assets

The growth of solar photovoltaic (PV)-based deployment in the world has become unprecedented over the last 10 years and has reached a cumulative installed capacity of more than 2.2 TW worldwide in 2024. In 2024, annual installations of PV hit a new high of about 554-602 GW. This is mainly because of the decreasing prices of PV panels and climate goals positioing solar to place it on a path to provide more than 10 percent of world electricity. China finds the most attractive market - with installation of between 300+ GW target in 2024 alone - with nearly two-thirds of new capacity installed, followed by European Union with a target of almost 63 GW by 2024. (ERPI, 2018)The United States and India have also been experiencing equally accelerating additions (47 GW and 32 GW in 2024 respectively). This has seen solar PV established firmly as a foundation of new power generation, with an estimated 75 percent of all new renewable capacity in the world in 2024.

Cumulative capacity of PV in Europe has been growing at a rapid pace in the past 15 years, and a significant percentage of installations are currently in their mid-life. Numerous of the earlier utility-scale PV farms in Europe date back to 2005-2012 when there were generous feed-in tariff (FiT) policies. As an example, in Germany, the end of a 20-year FiT support of plants (over 1GW/year) is being reached in 2028-2033 following a 2008-2013 solar boom. Certain early facilities are already above the 20-year mark - by 2021, a number of GW of German wind and solar capacity will be out of their life span. Italy also received a similar relief in a rush by its programs of Conto Energia FiT (2005-2013) and thus the initial generation of Italian PV plants (2008-2009) are 15 years old. The depreciation of these assets also casts doubt on performance and optimum lifetime energy extraction, thus opens a door for revamping or upgrading of old PV systems. (European Commission, 2018)

It is necessary to mention at the same time that a great part of global PV capacity is relatively new. The International Energy Agency (IEA) reports that we have about 70 percent of PV systems that were installed since 2019. Additionally, the PV technology has also been refined so that newer panels have an increasing lifespan, up to approximately 20 years (when first installed, panels installed around 2007) to up to 25-35 years (when first installed, panels in the mid-2020s). (Eyer, 2010) This implies that majority of the PV systems are at the start of their operational stage. However, the effects of aging are now being realized in older PV plants (10-15 + years old) in Europe, the U.S., and other early-adopter markets, such as deteriorating performance ratios and component malfunctions. On the one hand, this aging can be a problem and upgrading or rather modernizing such systems can significantly boost production and make these systems much more effective, thus extending the lifespan of these assets. There are also emerging issues of curtailment in high PV penetration areas to clarify that even with solutions like storage and grid upgrade, more versions of older (and recent) PV installations were still not able to give their full potential output. The PV sector in the world and Europe in particular is characterized by a dramatic increase in the number of new installations and a growing interest in the management and optimization of the old first-generation PV plants. (Feldman D. B., 2020)

2.2 PV systems degradation:

In a lifetime of operation, all PV modules are degraded by environmental stresses and wear-out processes associated with the modules. Power output typically declines by small fractions per annum, and long-term projections have indicated average degradation rates of the order of 0.5-1% per annum for crystalline silicon modules. This implies that in normal circumstances, a standard crystalline PV panel can produce approximately 90 percent of the nominal power after the first 10 years of use. (Feldman D. B., 2021)As an example, NREL claims that modules tend to degrade their performance by less than 1 percent per year, so the loss in the amount of output is frequently not noticeable within the initial few years unless extremely accurate measures are taken. Manufacturers normally assure the power rating of modules to be within a 25-year remaining power of approximately 80.

Nevertheless, the degradation rates of the PV systems will probably have a greater degradation than previously expected, due to real-world conditions. A global study on PV degradation in 2025 found an average degradation rate of 1.00%/year, which is higher than what was mentioned in the old studies. The following is a detailed review that bases the data sent within the last five years, the rates of degradation depend on the technology of the module and the climate: (Finance) Thin film modules (Gen 2) tend to be easily degraded compared to crystalline silicon (Gen 1), and the temperature under the sun (as well as other climates) is more likely to cause faster deterioration of the performance. Indicatively, in tropical or desert regions, above-average annual degradation of PV systems can be expected due to such factors as UV-induced discoloration, thermal cycling, humidity and soiling. On the contrary, the lower irradiance and cooler climates (e.g. Northern Europe) do have a slightly lower level of degradation on average. There is no significant trend involving the degradation rate with the year of installation - i.e. more recent modules are not conclusively slower or faster to degrade than older modules so far, although modern type technologies of module have not yet collected decades of field experience. (Helman, 2020)

PV modules are susceptible to common corrosion of the glass, wear of anti-reflective coating, encapsulants discoloration, fatigue of the interconnections between the cells, solder bond failures, potential-induced degradation (PID), and cell micro-cracking. They result in reduced current or voltage output as time goes by. In a fully silicon based module it is a normal occurrence that even by the year 10 not less than half to half of the original power output is lost - once more depending on quality and site conditions. An earlier experiment by Jordan and Kurtz (2013) reported a median of 0.5%/year for the silicon modules, but other polycrystalline systems in warm (hot) climates lost 1%/year or more. Field data of the old plants are being used to validate the results of numerous PV arrays with 10% or higher cumulative power loss due to degradation by natural processes after 10 years of service. Unchecked, this loss is a direct translation to loss of generation of energy and profit by the owners of the plants.

Other applicable performance degradation in the performance of other BOS (Balance of System) components, like inverters, can also be used, although with a relatively shorter life cycle (compared to modules) of approximately 10-15 years. It has also been pointed out that in the past 8-10 years of operation, PV inverters begin to fail at a higher rate, and in the majority of cases, the cause of failure is the degradation of the fragile power. The inverters could fail or perform poorly at a time, which further reduces the energy output of the PV plant as time goes by. Thus, the issue of ageing of both modules and inverters promotes the general degradation of PV systems. In order to quantify the situation under deterioration in the performance and determine the causes, frequent monitoring and diagnostics (e.g. IV-curve tracing, thermography, degradation analysis tools) are used. (Hirth, 2015)These trends emphasize the importance of upgrading (substitution of traditional components) after a duration of about 10-15 years: changing old modules and inverters to new components with a higher efficiency, one can restore the initial or even an improved work of a plant. Proper degradation is also important in lifetime energy yield predictions and economic project analysis of PV projects in order to take into account project extensions or retrofits.

2.3 Future concepts and practices of PV Plant Revamping and Repowering.

PVs that have already aged have also been revamped and repowered as part of the efforts to make them more efficient. The two terms are used interchangeably, but in industry practice, the two words have different meanings. Revamping is also employed to refer to the replacement or reorganization of a few of the components of a PV plant, as a way to repair or re-establish it to its original capacity. (Hirth L. Z., 2015) Repowering, on the other hand, is a process that occurs with the intention of supplying more capacity or energy generation, which is over and above what the plant was designed to produce, and which gets superimposed on the already existing asset. In simpler terms, revamping tries to restore an old plant into its original state, and repowering tries to surpass the initial operation and extend life.

Typical revamping remedies include new modules (in order to accommodate a high rate of degradation or defect rate), new inverters (more recent, more efficient, and more reliable), and revamping of BOS issues such as wear on cabling, combiner box, or mounting structure. By replacing inefficient old PV modules with other, more efficient modules, the operators can regain lost capacity; by replacing old modules with the same overall DC rating with new ones with the same overall DC rating, they can reclaim the portion of the lost energy yield to degradation. The upgrade to the newer inverters, an almost 10-year-old plant, can significantly improve uptime and reduce the cost of maintenance, as new inverters will have new warranties, as well as come with improved performance. (Hirth L. Z., Optimal deployment of storage in European power systems., 2015). The revamping process focuses on either one-to-one replacement of the components or a series of minor additions that do not impact the nominal capacity of the plant or its connection to the grid.

Repowering may also include adding more PV modules, implementation of tracking systems rather than fixed-tilt racking, or other drastic changes to the design to boost energy output. E.g. a repowering project may alternative a array of 150W panels of 2010 with half the new 450W bifacial panels, and re-arrange the fixed racks into single-axis trackers. The total DC capacity can also be increased, or remain unchanged, but the energy corresponding to one year can increase by very large factors due to a rise in the module efficiency, in the tracking benefits. An experiment in Italy established that rather than cutting the nameplate of an established plant by preserving the original DC size and grid connection but changing all other equipment, the yearly production of the old was increased more than four times that of the old, yet the nameplate rated the same or, in other words, a much smaller area is needed to support this level of capacity. In practice, this will either provide additional room in an already laid-down plant to increase the quantity of panels (a sort of expansion section that will not be subsidized) or even enable the installation of the co-located batteries, which, accordingly, will become added value to the location.

Technical and economic reasons motivate the idea of revamping PV plants. Technically, many PV plants built before 2010 used emerging technology at the time. This has led to serious malfunctions in these first-generation utility PV systems, such as failures of some modules (e.g., from manufacturers now out of business), excessive degradation, or cracking of the backsheet (as well as inverter failures). An upgrade would improve system performance and address the low reliability, especially when spare parts for old equipment are hard to find. Economically, older plants- particularly in Europe- are working at high feed-in tariffs negotiated for a 20-year period. Thus, any additional or recaptured kWhs generate revenue. The payback period for replacing damaged modules or inverters in high-FiT plants can be very short. For example, a 100 MWp PV plant in Italy was reconfigured, and replacing about 12 MWp of failed modules from manufacturers with high failure rates yielded a higher internal rate of return due to high subsidies on the saved energy. The concept of revamping is gaining momentum among plant owners who want to maximize site assets as they mature and continue generating revenue.

Regulatory constraints should be carefully taken into account while revamping and repowering the project. Accurate limitation of the change that can be effected on a plant is often imposed under grid connection agreements, FiT contracts and permits. To illustrate, in Italy, GSE (Gestore Servizi Energetici) built specific requirements in 2016 (not the latest yet) in order to allow the PV renovation without losing the original FiT incentive. By regulation, the overall DC capacity should not be more than a moderate tolerance, and the system should have the same export to the grid; otherwise, that can be considered to be a new installation, which will not be under the older tariff. Italian developers operating within these limits have been able to upgrade plants by adding tracker systems and high-power output panels, so that the extra energy could be counted before the program as the FiT allowance and make a significant profit boost. In other markets, some of the policies allow a certain percentage of capacity increment when repowering, while others take into account any capacity increment as new. In such a manner, the revamp strategies would be conditional on both the technical condition of the plant and the policy environment. A revamp properly executed can enhance productivity up to 20 percent, with more economical components, add 10-20 years to its financial immortality, and even lessen land-use density up to 40 percent, without undermining the economic viability of the project. (Hoppmann, 2014)

2.4 The Clipping and Inverter Sizing Effect in PV Systems.

Another design parameter that is sensitive and affects the production of energy is inverter power, or rather, the ratio of DC power in the PV array to the inverter C power. Largely grid-tied PV systems are designed with a DC/AC ratio (Inverter Loading Ratio, ILR) of more than 1.0, i.e. the PV arrays' problem capacity exceeds the inverter source capability of producing AC current. Since the size of the PV array can be implicitly matched to the size of the inverter, it is possible to gather more energy during less-than-optimal conditions (morning, evening, winter) and fail to gather some of the peaks on very sunny days. The specified practice has turned into a personal tradition in utility-scale plants: average ILRs in most markets are approximately 1.1 to 1.3, and the values are even greater in some instances. (IEA, 2023) As an illustration, in the United States during the year 2016, the capacity-weighted average ILR was about 1.25. The definition of design to ILR at a range of 1.2-1.4 has been said to be a definition of a balanced design- increasing the yield of the yearly product by a significant percentage (having a loss of about 5 percent of the energy in the form of clipping).

DC will oversize and generate a greater amount of energy under low irradiance conditions, enabling the inverter to remain longer under optimal energy production. As the nameplate power of PV modules could barely reach under ideal circumstances at midday, the production of 1.2-1.3 ILR will provide maximum full loading of the inverter more often, resulting in higher kilowatt-hours of output. (Jordan, Photovoltaic degradation rates—An analytical review. Progress in Photovoltaics: Research and Applications) The drawback is that during the daytime under the sunshine, though the sun is brightest, the array could be capable of producing a power excess that cannot be converted and is thereby wasted (clipped). In the moderate oversizing, unfortunately, this loss of clipping is nothing in comparison with the gain. A real-life example used in the literature provides an example of a plant with DC/AC = 1.3, which generated a thinner portion of energy yearly of approximately 12 percent by clipping approximately 2 percent of the total energy. Clipping losses tend to be small. Even running to 1.4 clips is likely to be a good concession in the majority of cases. Finally, very large ratios (e.g. 1.7-2.0), however, have a decreasing marginal pinch with clipping rates of an extremely high level (possibly more than 10-20 percent annual production). Thus, an optimal range between which the LCOE is minimized - models and the competitors in the industry tend to keep this to a 1.2-1.3 range with the common locations. (Jordan & Kurtz, 2013)

The issue of long-term performance and the revamp decision also depends on the size of inverters. The PV plants of the early generation (2000s) would sometimes be built at a point of 1.0 ILR, and this was partly due to a better price of modules, and also because they did not want to waste any energy. The latter plants started consuming more ILRs since the module cost reduced. To basically enhance the ILR, a refurbished older plant may be interested in adding a bit more DC capacity (assuming that it is not prohibited) to guarantee that more power will be harvested. As an illustration, as the percentage deterioration of the modules in 10 years is 10+, the effective ILR would actually be diminished by a degradation effect, something that would have a clipping effect between 0.00 and 0.05. (Kaldellis, 2012) It can be redesigned under the limitations of FiT to permit as many DC panels as possible to be added, and then the inverter can be clipped off, and the point where it can be clipped can be used as fully as possible when the peak is low.

It is also worth mentioning that the environmental conditions influence the optimum ILR decisions: Cloudy conditions at high latitudes result in better ILR, as the lack of sun rays by the PV array and inverter is the only limiting factor in the uncommon sunny summer days. Aggressive oversizing would, on the other hand, lead to the appearance of more clipping events; and thus, ILRs at the lower end can be utilized to avoid excessive losses during midday. Thermal limiting, as well as lifetime should also be considered - the larger the over-capacitance at any given time, the more load inverters will suffer, when they become hot, although most inverters do have some overload capability, and can be operated often at very high temperatures Even the plant controls and the current design of inverters will now be able to dynamically adjust to control loading. Generally speaking, DC oversizing has proven to be a highly effective cost-cutting technique and allows the improvement of energy output; it is once more directly related to the fact of PV plant upgrading. Here, inverter scaling takes a different form where storage (below) is factored in because a battery can charge via any additional PV that would otherwise be clipped; literally clipped energy is recaptured in the case of a DC-coupled configuration.

2.5 Battery Energy Storage Systems (BESS): Technologies, Applications and Cost Trends.

The next facilitative technology that emerged to have a significant impact on the integration of renewable energy with ease to provide power to it is BESS. There are many types of battery technologies, but in the past decade, lithium-ion batteries have been the player of the utility-scale and behind-the-meter energy storage market as they can be combined with high round-trip efficiency long cycle life and energy density and with rapidly decreasing Li-ion has hence a sizable number of the new BESS scales deployments within the last several years beginning with small 10 kWh residential scale batteries up to huge grid scale systems of 100 MWh plus. (Kittner, 2017) Within the Li-ion, a tremendous shift occurred as part of the large-scale adoption of LFP chemistry - from around 48 per cent in 2021 to around 85 per cent of LFP in utility-scale battery projects. LFP batteries are thermally safer and more stable (both in temperature), as well as having reduced lifetime and lower cost per kW at a trade-off. (Laboratory, 2023)

Flow batteries (e.g. vanadium redox flow), lead-acid (life cycle); fully outdated except for small or legacy scale, sodium-sulfur (used in a few grid-scale projects in Japan), and more recent batteries include sodium-ion, or advanced metal-air, battery types. These flow batteries have a potential of extremely lengthy cycle life, on-demand energy/power scaling, and this could make them interesting in long-term storage when prices are lowered. However, they have not been extensively used yet compared to Li-ion. By far the biggest type of energy store in the world is the large-scale pumped hydro storage, but BESS is the fastest-growing type of energy store in new applications.

BESS is also broadly applicable in the energy sector and has both front-of-meter and behind-the-meter applications. Applications in front-of-meter applications also include frequency regulation and ancillary services, energy shifting, capacity firming, peaking capacity, and deferment of a This often involves the hoarding of midday sun production and discharge of the same in the evening peak - a conception which is already becoming handy as the amount of the sun grows. optimization of self-consumption (reserving surplus generated PV to later be consumed in the home or the business), control of demand charges (to smooth out a customer load to prevent maxes), battery related to energy backup, and network participation are all achieved with behind-the-meter batteries. The capability to operate batteries in various modes is not a common value; an energy source has the ability to time-shift energy and can provide rapid frequency response and back-up power, as is the case with battery control. (Louwen A. v., 2016)

The trends in the cost BESS have been rather favorable in the last 10-15 years that have led to its further adoption. According to the statistics given by IRENA, the cost per utility-scale battery storage project in 2010 would reduce to about 93 percent in 2024 by about 2571$/kW and 192$/kW, respectively. This amount includes all the costs of balance-of-plant, a battery pack is one such expenditure, which was estimated at factors like Bloomberg NEF in 2010 to only 130/kWh per unit on average in 2023. It is interesting to note that although the period between 2023 and 2024 is even, the cost of a 4-hour length system was minimized, and in 2024, the cost of the system installed was low by another 32 percent compared to the cost in 2023. Cost reduction has been caused by the existence of economies of scale related to the gigafactory scale of production, enhanced energy density and design of batteries, and a move to more prolific chemistries. It has shattered the myth that 24-hour renewable energy is expensive, and in most markets, PV+ storage is a viable or cheaper option than traditional generating power during its periods of most need. There is further rapid growth in installations in response to the falling costs: the cumulative battery storage across the world is set to increase rapidly by 2030. It is anticipated that lithium-ion will stay the leader within the coming years, yet longer storage periods, in turn, obviate further interest in innovative options and separate usage of the batteries of EVs as a second life. (Louwen A. v., 2019).

2.6 The hybridization of PV and BESS: Technical Advantages, Control Policy and Energy Shifting.

A hybrid of a PV plant and battery storage expose various possibilities to technical benefits and application possibilities. One of them is the ability to time-shift the energy: excess energy taken in during the day can be amassed and taken at a later time when the prices are greatest in the evening or other periods in the absence of the sun. The solar energy arbitrage is an addition to the proper utilization of PV generation, reduction of curtailment and allows the plant to supply the electricity to more profitable periods. (Luthander R. W., 2015)A PV+BESS system is capable of a larger solar output curve to furnish firm power that is predictable and can even be used as firm capacity to substitute fossil peakers. Net loads are also smoother, and ramp reductions are also diminished, which assists the grid operators in surmounting the rocky evening/morning ramp peaks that a high level of solar penetration is likely to bring about. A co-located battery can also play a part in rapid-response ancillary services - e.g. smoothing PV short-term variations, frequency regulation to stabilize the grid. This will augment the general grid incorporation of the solar plant, providing greater reliability and power quality. (Luthander R. W., 2015)

To couple with PV, there are two primary options of batteries, which are DC-coupling and AC-coupling. An AC-coupled system provides an AC connection at both ends of the PV array. The PV has inverters of its own as opposed to those of the battery, which has a power conversion structure or bidirectional inverter of its own. AC coupling also finds application in retrofitting storage into an existing PV plant, since the addition of a battery system in parallel without affecting the PV array or inverter is also possible. Flexibility and modularity have been a benefit of AC-coupled systems: batteries and inverters can be considered independently, and multiple battery units can be added to increase capacity, and even the battery may be charged by the grid should there be a need to do this. This means that, as an example, an AC-coupled BESS is possible; it can serve in the grid services at night and be charged from the off-peak grid power and released to the peak grid power in case it should be allowed to do so. It is also resilient in cases where the AC-coupled systems have no shared inverters between the PV and battery, and therefore, the system is not necessarily offline due to failure. The drawback of AC coupling is somewhat lower round-trip efficiency during charging of PV (Mitscher, Energy Policy). Conversion back and forth between steps of an inverter is an energy waste, and AC-coupled PV-BESS can be converted twice, and the loss will be a few percent of the energy, relative to DC-coupled designs. Nevertheless, AC coupling still competes effectively in the utility scale projects - in practice, on a large-scale project or retrofits, it may be the utility as a matter of the ease of integration and the possibility to mix and match hardware. Solar farms with storage. Several existing solar farms and battery containers have storage, built on the basis of battery containers, AC-coupled, attached to the medium-voltage AC collection system of the plant. (Moser D. D., 2018)

In a DC-coupled system, the battery is added to the DC side of the PV plant itself as part of the PV array, which can be connected to the PV array via a DC-DC converter or a hybrid PV inverter with a DC battery input. In DC coupling PV and battery, there is a shared inverter to be attached to the grid. This performance drawback is also present: PV power can be stored in the battery without converting it to AC, and hence, there is no conversion step that gets in the way. This has provided DC-coupled systems with great efficiency of retrieving solar energy into the battery (one inversion at a time when the battery later gives the energy back to the AC). DC coupling also enables the PV inverter to charge the battery when the PV inverter is at its peak capacity operational, in effect stealing the energy that would have otherwise been clipped because of its operation. As an example, a DC-coupled BESS can pull off the excess DC power if the PV array is producing more power than the threshold on the inverter (and is generating, e.g., on a sunny noon day with a high ILR system) than will otherwise be lost as heat at the inverter. With an AC-coupled system, any further PV will simply be turned away as the battery cannot accept any power other than by the AC connection, except when the PV inverter self-cuts to provide output to the battery, which present inverters cannot do without a DC connection. Therefore, DC coupling has a special property of clippy recapture: in effect, an experimental DC-coupled battery was found to have a capacity factor M and enhancement of PV cells by a small percentage (e.g. in an NREL model a DC-coupled battery was found to have raised its annual capacity factor of AC by a factor of 0.2 per cent); this is large enough to saturate the battery. Moreover, DC-coupled systems are cheap, being frequently only a DC/AC inverter, which will imply less required equipment. Such understatement would reduce both CAPEX and the complexity of O&M. (Moser D. D., 2018)

DC coupling, however, has its disadvantages and challenges. Nor is it as flexible in retrofits - a PV inverter that facilitates DC coupling, or one that would require conversion of the current inverters to hybrids, which is an enormously large change. A DC-coupled system is large and has one point of failure (Inverter) (Once this fails, both the PV and battery become useless). There are restrictions also to the applications of a DC-coupled battery as well, because it cannot be charged on the grid, whereas the PV might be. DC-coupled systems must be designed with special attention to the sizing requirements, and control: DC converter of the battery and the inverter should synchronize and align with each other to achieve maximum capture of the PV energy and not to fall short of the requirement of dispatching to the grid. (NREL, 2021) The problem of AC vs. DC coupling is that it is a tradeoff between efficiency/cost (DC-coupled is better) and retrofit ability/operational autonomy (AC-coupled is better). A 3 MW PV revamp example is to use when the purpose of the PV plant is to add a BESS, in which an AC-coupled containerized solution can be most convenient, and a DC-coupled can have the benefit of reclaiming clipping, meaning that it can be contemplated. (Perez, 1990)

In relation to control strategy, the analysis between acting with a combined PV+BESS system and using the system will involve an Energy Management System (EMS) or plant controller that will provide maximum discharge and charge of batteries. The strategies for the objectives are numerous:

- Maximize self-consumption (behind-the-meter): charge the battery with all the onsite solar load, discharge on a plug when the sun is less or a high tariff period.
- Time-of-use (merchant plants or otherwise varying in price across the day): charged at the cheap rate at times when electricity is cheap (or where PV would be curtailed) and charged at the expensive rate when it is expensive to charge the price so high, in maximizing revenue.
- Firm dispatch / Peak shaving: obtain a profile output of the plant. As an example, make sure a certain output at 5-9 pm peak, by means of retaining the midday energy. Or restrict ramp rate and maximum PV output to the grid code requirement or a PPA requirement.
- Grid services: provide some battery capacity to provide frequency control or contingency beds. This can also have a different signal (automatic generation control) and can be the EMS controlling state of charge, so that it can respond whenever it is needed.

Combined strategies (stacking): operators are trying to enlarge several streams of value into each other. A case in point is a battery that can perform daily energy shifting, as well as remove fast frequency response whenever it is not full or empty. Deep forecast-oriented predictive control may be applied to such multi-service processes on the grounds of AI. (Pfenninger, 2017)

The efficiency of control should also be in a position to manage the health of the battery, e.g. unnecessary cycling, maintaining a high state-of-charge, as a measure of providing a long battery life. PV +BESS might also test predictive algorithms, which would slightly charge less on a particular day, forecasting some grid incident of interest that would benefit them as having a small dose of spare capacity, etc. Forecasting could be used by the new PV+BESS facilities to dynamically adjust charging responses to make their operations more profitable and minimize degradation.

In summary, a BESS and a PV plant will boost an intermittent resource to an incremental and more dispatch-friendly resource. Technical benefits include more total sun utilization, the ability to cover evening peaks, as well as providing solid capacity and greater grid stability due to rapid response. The concept of control and coupling can be tailored: AC-coupled is easy and versatile, DC-coupled is efficient, and can collect every photon. As battery prices fell and some level of adaptability is required, PV+BESS hybrid systems cannot be found in the niche category any longer - they are now regarded as firm capacity sources, and some of them can even replace traditional peaking power plants in some applications.

2.7 PV + BESS Systems Economic Feasibility Modeling.

The techno-economic modelling that is required of the BESS to a PV plant has a number of economic requirements. The cost of capital and cost of operation of the battery system, the economic value of the influenced energy or services, the cost of battery degradation and replacement of battery, incentives or policy motives are the essential factors. Common economic data utilized are Net Present Value (NPV), internal rate of return (IRR), (Photovoltaic self-consumption in buildings: A review) Levelized Cost of Energy/Storage and payback period. Unlike a stand-alone PV system, a PV+ Battery system has numerous streams of revenue and operations to be modelled. Therefore, feasibility studies will often make use of special software or models to optimize the dispatch of a battery, like profit-maximization of the dispatch, subject to the limitations available.

The economic value in the case of a utility-scale PV+BESS under market conditions is received in a variety of sources:

- Energy Arbitrage: The market for selling electricity at a better price simply by storing it at a lower price now of the day when the price is low and then releasing it to the market at an opportune time when the price at the middle of the day is high. The amount of revenue has a direct correlation with the difference between the day-night/off-peak price and the peak price.
- Capacity Value: the system may be paid capacity, or get resource adequacy credit, when it can do the following when it reaches peak demands. This is increasingly coming to be considered with storage being given a ride in capacity markets.

- Ancillary Services include fast frequency control, spinning reserve, and voltage service - these services will be monetized in most markets. The fast-reacting batteries are rather competitive in terms of frequency control, and in this respect, the battery may improve the economy of the project on numerous occasions in the case such a market is present.
- Delaying benefits: There are cases when the addition of storage can delay the need for the transmission or distribution upgrade.
- Incentives/Subsidies: government incentives have a long way to go. Exemplification: A tax credit can be in the form of storage investment tax credits, grants or need-favorable financing to facilitate feasibility. Europe has potential programs that facilitate storage addition or the provision of flexibility. (Programme, Trends in photovoltaic applications, 2023)

A powerful economic model will be employed in order to approximate these streams of values by simulating the functioning of the battery in the course of a year. It must also take into account such a scenario as battery degradation: each charge-discharge cycle will cause a small decrease in battery capacity, which means that intensive use will lead to increased revenue and low life. In many models, the degradation may take the form of, e.g. limiting the depth of discharge, or cycling through full equivalence and modeling when the battery needs to be augmented or replaced to go on. (Sapkota, 2019)This involves a cost to the cash flow analysis. The optimal dispatch can also provide a balance between revenue maximizing and life maximization to maximize profits - revenue stacking is mandatory to enable the battery investment to be self-employed. This suggests a combination of sources of revenue, so revenue stacking is the property required of asset stacking and a more general property recommended by industry analysts. One such example is that a battery could also obtain middle energy to the extent of arbitrage revenue, but the same would not be able to obtain the ROI target. When it can also obtain frequency response revenue when unused, the two revenue types together can tip the scales towards positive NPV.

The economics of the project are quite delicate with the cost assumptions. Battery prices are also dropping, and a project that was once viewed as a non-economic project some years back can be practiced currently. As stated above, the BESS installed will be approximately 200/kWh (and the price of the battery pack will be 100/kWh), in 2024. Given a 3 MW aka 2-hour battery capital cost of the 3 MW battery at the order of 200-300/kWh of the equipment (3), then a capital cost of say

1-1.5 million/MW would be derived as the capital cost. Such an expense would be offset by estimated incremental revenue: e.g. capturing clipped energy (PV curtailed or limited by an inverter), shifting a MW or two to the evening spike and even any savings on a demand charge or grid support payment. The cash flow model would involve current PV revenues and other revenues from batteries. The pertinent case scenario in the setting involving Italy, thus, is that in the event the PV is fixed on a constant FiT, a battery addition does not render the FiT more lucrative, favoring the production of kWh in the making of which kWh have been made earn, regardless of the time at which the production takes place. In fact, with FiT high and guaranteed, a battery would not at all be lucrative in case the plant had to be curtailed at any rate due to grid capacity. Instead, the battery would come in handy regarding the provision of grid services or even help expand the size of the solar plant. As such, co-locations in legacy FiTs, there may be a practical disadvantage to the economic viability of co-location of a battery, and changes in policy might be necessary to permit the battery to be economic. Conversely, a post-FiT or merchant generation might include a battery to boost the revenue aspect considerably during other times of high prices. (Luthander R. W., 2015)

The economics are enhanced in the face of the studies, and pilot projects have proved that proper due right sizing of the battery and multi-use work. On the example of an Italian asset manager, the IRRs to replace the simple PV module in a FiT plant were more than 10 percent, and a battery added to a plant may result in additional earnings (say by participating in the capacity market in Italy or providing fast frequency response, already paid by Terna). The UK market (or others like Germany) is now interested in retrofitting older existing solar farms with batteries, in order to create new revenue streams now that the original subsidies are wearing out - in other words, transforming an older FiT-subsidised plant into a merchant-hybrid plant. The other important economic consideration is that when the FiT expires in 20 years, the income of the PV plant may drop to the rates of the wholesale market; introduction of the storage would also contribute to the shift of the time and enable obtaining superior prices or other ancillaries and continue to support the profitability of the asset in the second life. (Schmidt & Hawks, The future cost of electrical energy storage based on experience rates., 2017).

On the whole, PV+ BESS would have its economic feasibility model:

- Determine all streams of values: energy, capacity, ancillary, etc., across project life (typically 10-20 years battery) according to their PV lifetime.
- There are a few costs to bear in mind: battery capital, battery replacement/augmentation costs, additional O&M costs (including augmentation and possibly inverter maintenance), as well as an augmented project overhead.
- Self-optimal dispatch: This is a common optimization problem. It shall be a linear optimization, but is collinear by battery physics and market definitions, and optimizes the net revenue.
- Sensitivity analysis: the analysis of how sensitive the results are to the cost of the battery, the dispersion of the energy prices, the scope of its life cycle, discount rates, etc. This demonstrates what the business case is potentially susceptible to the most. (Schmidt, Hawks, & Gambhir, The future cost of electrical energy storage based on experience rates., 2010)

The general agreement in the majority of the literature is that policy and market design contribute significantly towards economic viability. PV +Storage projects have begun where incentives or remuneration for storage can be identified. In their absence, profitability may be contingent on profitably large peak/off-peak price differentials or evasion of curtailment losses. Accordingly, the second part is the consideration of the policy considerations with a focus on feed-in tariffs and the rearrangement of the regulations in Italy and Europe.

2.8 Policy and Feed-in Tariffs for PV Revamping in Italy and Europe

Incentive schemes and policy structures have a greater impact on the choice to transform PV plants and add storage. Feed-in Tariffs (FiTs) were important in the initial implementation of solar in Europe, in which they ensured higher than market rates to solar generation, which was usually 20 years in duration, upon commissioning. There was a FiTs rush in countries such as Germany, Italy, Spain, to mention a few, in the 2000s-2010s. Today, when said plants get old, the conditions that come along with FiTs can either be used to ease upgrades or become obstacles. One of the issues of policy is that the revamping or repowering of an old plant should not compromise the conditions of its subsidy or grid connection. (Short & Packey, . A manual for the economic evaluation of energy efficiency and renewable energy technologies, 2013)

The example provided of Italy is very good concerning its respective regulations on revamping. In 2016, guidelines were formulated that described the concept of revamping and repowering of plants facilitated by FiT through the government of Italy, and this was further streamlined in 2020. Under the provisions of these regulations, the owners of the plants can alter and even upgrade functionality, subject to certain specifications. Other significant limitations include not operating above the approved maximum capacity of the plant, nor shifting the point of connection to the grid or the area of the land underneath. Nonetheless, as long as the operator does not cross any such limits without informing GSE, the first FiT will be applied to the plant generation. (Short W. P., A manual for the economic evaluation of energy efficiency and renewable energy technologies, 1995) The policy has been instrumental in the revamping boom of Italy: any potential investors are eager to upgrade old plants that received very high FiTs, as any additional kWh generated with better technology would also receive the same high payout. Even in 2020, Italy eased the planning permission to speed up the process to modernize PV assets. Such favorable policies could make Italy a fairly good market as far as the restructuring of investments is concerned. The process of revamping old-first-generation plants, high FiT payment and the lack of complexities have made companies keen on revamp projects - according to WiseEnergy and other companies, dozens of revamps have been happening since 2020 in Italy.

This question of the way to solve the situation when FiTs will run low in 20 years is now being discussed by numerous countries in the broader European context. Germany has FiT, which was initially legislated in 2000, and its initial solar FiTs lapse took place in 202. Small systems were initially used, though, by 2021, increasing numbers are off FiT every year. Germany has determined that even though FiT payments no longer take place after 20 years, the installations will still maintain the juridical nature of possessing the meaning of a renewable generating facility, with the priority to be accommodated in the grid. The owners could sell the power at market rate or with new tenders/ PPAs. (Sioshansi R. D., Estimating the value of electricity storage in PJM., 2009) The interim option of small systems receiving a small amount of payment in a couple of years was also offered by the government, yet the operators will, on the whole, have to consider another type of revenue. This can be described as a policy environment where repowering can provide impetus: e.g. in 2023, repowering a solar farm built in 2003 may be to add more panels to boost output and enter into a 15-year PPA as FiT is no longer there. Augmented capacity or storage has also been evaluated by their owners in Spain, where several of the pioneer solar plants in Spain have had their subsidies either terminated or cut in the 2010s to enable them to operate at wholesale rates in the market. The Renewable Energy Directive (RED II) of the EU encourages the repowering of the renewable plants as it requests stream permitting because repowering has the possibility of significantly increasing the output with little environmental cost (use of the already existing facilities). However, it also states that the problem in question is that the repowering may also have an effect on the subsidy accreditation and grid connection, which should be addressed by the regulators. (Sisternes, Jenkins, & Botterud, 2016)

European laws are evolving, exactly under storage integration. Originally, on most FiT schemes, co-located storage has not been an option and not every scheme was able to do so (such as by ensuring that none of the brown electricity in the building is being sold as an FiT-subsidised green energy). However, the operation of a battery may be metered so that in Italy, a FiT plant may include a battery, but only the electricity generated may receive the FiT. It is not possible to have the battery go and buy cheap night power and emit to get the solar FiT (which will be cheating the incentive program through arbitrage). Technical regulations might compel a certain sort of setup in such a way that it prohibits importing to the FiT meter or bills it accordingly. Policy lags behind, and many countries are now offering incentives even in the act of storage itself (e.g. rebates or entry into a capacity mechanism) that can be sold to complement the profits of an older PV plant.

In perspective, the biggest theme is post-FiT Repowering. The EU has a target of 2030 renewable targets (42.5 percent RE in final energy by 2030), and repowering old plants has been considered another form of quick capacity addition. Repowering in the case of PV may mean the use of the already available grid connections to supply additional PV and batteries. On the expiry of the old agreement, a developer may repower an old 3 MW PV plant to 5 MW with a battery set, provided that the regulations permit, on the land or connection capacity it has. Several European countries are in the present state of repowering auction or repowered plants in order to make new bids. Another consideration should be to give priority to grid access and repowered plants - the aspect that old installations still have grid access privileges in Germany is a good illustration. (Trancik, Energy technology innovation: Learning from historical cost reductions, 2015)

The conclusion is that policy is highly crucial when deciding on the process of PV revamping:

- Italian GSE has a wave of upgrades in the offing and can be revamped at the expense of FiT.

- In the rest of Europe, emphasis lies on end-of-life management of FiT-supported plants. Many of them will still be in service in new regimes of operation, which are market-based, or they will be repowered.
- Policymakers are also considering co-location of storage - an example of this is that the UK and France have amended their policies to allow batteries to be added to existing renewable locations, provided they are properly metered, and there are no threats to support contracts associated with this.
- Repower EU plan and RED II directive point to the fact that administrative barriers to repowering must be removed because it can bring a huge production rate of renewable in a limited time. This entails lean upgrading and a grid connection license.

Finally, as a reality, energy storage might require financial support or market subject. Absence of effective mechanisms of revenue collection can stall battery adoption. Some countries have been putting in place capacity markets or flex markets where the batteries may earn revenue, hence encouraging retrofits to the solar plants to provide this.

The policy environment to be refurbished in case of a 3MW PV plant in Italy is very positive: once the upgrade is in the definition of revamping applied by GSE, the plant will obtain the opportunity to retain the incentive as well as gain more production. A BESS added here would be a further new twist, but one which would need to be highly sensitive to the metering regulations in order to serve the incentive of only true solar generation. With the age of the PV plants all over Europe, the flock of filter machines will begin to reveal an increasing number of case studies and projects of successful revamping and storage connectivity, with the help of the cordial policy frameworks.

The FiT for the PV plant under study was set to be 0.484€/kWh at the time of commissioning. This rate was set when the PV plant was commissioned. However, in the case of revamping, it is necessary to adjust the fit, taking into consideration the increase in nominal power. In case of revamping, the following equation is used to calculate the FiT:

$$\mathrm{FiT}_{\mathrm{new}} = \frac{\mathrm{FiT}_{2011}}{1 + \Delta P}$$

where ΔP is the increase in nominal power due to revamping, in case of 20 percent revamping ΔP will be 0.2.

2.9 Case Studies/Past work on PV Revamping and storage integration

Literature and practical programs are actively on upgrades and conversion of old PV plants and storage installation of already available solar gardens. Such case studies provide as practical insight as the benefits and challenges of such upgrades.

One may refer to the WiseEnergy revamping plan in Italy as stated above. One of the published case studies involved the sale of PV plants by specific revamping of a portfolio of 100 MWp of PV plants (average age of PV plants is 9-10 years). An analysis of the portfolios has found that 35 percent of the portfolio panels are no longer in business and that they had a very high rate of failures and depreciation. Replacement of 12 MWp of the most problematic modules that produced an IRR greater than 11 made the revamp investment portfolio significant and increased the output and reliability of this investment portfolio. (Tsanakas J. A., 2017). After 2021, the further development of the revamp was more radical: trackers were added to the buildings; fixed-tilt buildings were replaced with bifacial ones with a higher power output, and the core inverter was replaced by a distributed one. To enhance the annual energy output of operating plants by over 25 percent, as mentioned, these projects were referred to as deep repowering projects without loss of the FiT revenue on the incremental energy. The case studies emphasized that, despite the existing plant and its performance according to expectations, there is always room for value added, especially when incentive policies are effective.

A different example of a case study is in America: Convergent Energy + Power custom-made 2 MW/2 MWh of battery systems and retrofitted two 1 MW solar farms in Massachusetts and is one of the first solar-plus-storage retrofits of its kind in that market. This was directed towards battery use to perform capacity charge regulation (reducing the load during peak events yearly), and participate in the frequency market, respectively, outperforming those with the existing solar incomes. Retrofit was in form of AC-coupling battery containers on each installation and integration of a control system that could predict peak events and could therefore dump the battery as well as bid in the ISO-NE regulation market Preliminary results showed that the hybrid system had worked in peak-demand charges to the off taker and incurring additional revenue on the market which is more economical in the economics of the project. Among the most important was the necessity of having a sophisticated dispatch algorithm to keep the battery state-of-charge between peak-shaving and frequency response, essentially a feasible form of revenue stacking to a retrofitted PV+ storage system. (Wang, Luo, & Dooner, 2015)

With regard to research studies, there are various papers that have conducted techno-economic analyses of batteries in addition to utility PV plants. In one such example, an NREL report (2020) applied the hypothetical retrofit of a large solar farm with various battery sizes in scenarios of varying prices at the market sun-connect.org. It was discovered that the battery was barely cost-effective at 2020 prices when it could attain high price differentials and attain additional revenues. (Zakeri & Syri, Electrical energy storage systems: A comparative life cycle cost analysis., 2015) It however, indicated that retrofit of PV+ storage would possibly become widespread by mid-2020s as these expenses continue to fall and price volatility would probably increase. Other studies have examined the question of optimal size: a small battery can be adequate to help reduce ramp rate and partial peak shifting, while a larger battery with a 4-hour capacity can enable full firm capacity delivery during the evening at a higher cost. The situation of usage and tariff arrangement would decide what is the best alternative.

Europe also has projects where there is PV + storage coupling. In the UK, however, in a few of the large-scale solar farms, batteries have been deployed to provide grid provision, including frequency response, with auction regimes distributed by the National Grid. A case in point is a 64 MW solar park in Wiltshire, where a 50 MWh battery on site swiveled into the grid as a contributor in the ancillary service markets of the grid, as well as to time-shift the output of the sun at evening spikes. The decision helped the project become profitable because the UK is undergoing rapid development of the frequency response market, underscoring the need for such integrations. Similarly, in Germany, repowering the post-EEG plants with storage is discussed, and developers experimented with a 6 MW solar farm built in 2006 by adding a 1 MW/1 MWh battery to determine how much of the curtailed or excess energy of the day could be stored and sold back later. The initial estimates were that it would take a fraction of total output to be held in store so as to affect virtual total rubbish against the new generation, and that a battery of small size can greatly enhance the useful output of a plant, provided that the constraint of export to the grid was a consideration.

Finally, academic literature has also begun to outline best practices for undertaking PV revamping and repowering. Mandelli et al. (2023) provided a review serving as a process guide, with the first part of the process being to carefully diagnose the performance issues, and then a feasibility study in terms of the cost of revamping the balanced versus increasing the output of energy and additional revenue is presented. It also underlines the consideration of the whole lifecycle, like disposal or resales of the replaced equipment. According to recent reports, it is important to consider the cost of battery augmentation (adding new battery modules after, say, 10 years as battery degradation occurs) in the economic analysis, and ensure that there are plans to recycle or use up the second life of batteries once the first life on the solar farm is over. New safety and grid-connectedness standards are also being developed for retrofitting storage, and the electrical code and any grid code for energy storage are mandatory.

It is to be noted that the current literature and the case studies demonstrate that further improvement of the work of a PV plant, by replacing the outdated parts of the system, and, perhaps, introducing the battery storage can make a considerable contribution to the improvement of the performance of the project and can extend the life of its design, and the corresponding economics can be attractive in numerous instances when old incentives or income sources are applied. The main challenges proven to be adherence to regulatory needs, technical integration, and making the economic pencil due to its costs and market conditions. The literature review will form the foundation for the thesis work, and that foundation will establish the feasibility of redesigning an existing 3.0 MW PV plant and selecting the best BESS for the given PV plant. On the basis of the above-presented trends, data, and practices, the following analysis will modify these findings to the case under consideration considering the actual state of the plant, the potential scope of the revamp, the correct battery settings, and the regulatory environment of Italy in a manner that will allow defining the most expedient strategy to pursue with the case of the revamp and storage integration.

The possibility of repowering and redesigning the already obsolete PVs and battery storage is an interesting opportunity to be more renewable and flexible in the near future. The PV fleet is expanding rapidly worldwide, and in Europe, a first generation of installations is approaching maturity. The performance degradation in PV systems typically ranges between 0.5-1 percent per annum and leads to a progressive decrease in energy production, which makes an intervention to restore the capacity. Both literature and industry experience show that limited revamping, i.e., replacement of damaged modules and inverters, can regain lost performance, and also that more radical revamping can be of significant benefit, i.e., repowering within the footprints of existing plants. The ratio of inverters deployed matters in their gains and through which storage can be made to store otherwise clipped energy. In addition to this, the cost of solar battery storage has dropped to approximately 90 percent over the last few years, which is why PV+ Battery hybrids are becoming popular. (Sapkota, 2019)

The technical benefits of PV-paired battery include energy time-shifting, intermittent output smoothing and ancillary services- all of which make solar more valuable in the grid. The control methods must be designed in such a way that they maximize the gain of such advantages, whether it is because of the AC-coupled or DC-coupled system architectures, which have advantages and disadvantages that have been reported in commercial materials and research materials. The role of capturing different streams of value with the aim of justifying the investment in storage is emphasized in economic modeling. These achievements of revamping projects in Italy, and further in retrofitting of single PV stations with storage, indicate, under the correct circumstances, that is, with high existing tariffs or a market to be flexible, as it appears to be mentioned, such projects may result in a high financial payoff.

A policy framework is one effective success factor: in Italy, there is a clear prospectus to refurbish under FiTs, and elsewhere in Europe, policymakers are gradually recalibrating the rules, in an endeavor to assist in repowering a renewable facility, as well as in the introduction of storage. Since the majority of early PV plants are approaching the expiry of their support terms, any policy granting a grace period and providing a temptation to repower will be of the utmost importance if they are unable to generate renewable energy. As the literature review suggests, the full potential of revamping and storage integration is perceived to lie in integrating policy and market mechanisms to enable these techniques to achieve their potential.

In general, the transformation of a 3 MW PV plant into one based on a BESS will depend on the use of the following issues that have been addressed in this paper: the current condition and the degradation history of the existing plant, the effectiveness of the new technologies in improving the performance, the optimum battery size and connection mode to meet the desired mode of the operation, the economic rationale of the new option under the current cost and tariff scheme, and the legalization of the practice in Italy. The obtained insights, both on the global trends in PV and case studies, will be expounded in the given thesis research to develop particular feasibility research. That way, it will give a good roadmap of modernizing the medium-sized PV installations into becoming modernized and storage-added resources that could continue to remain efficient and profitable decades later and generate clean energy.

3 Problem Statement:

The recent increased focus in sustainable energy development has positioned photovoltaic (PV) power to the center of the move toward electricity systems with low carbon emissions. Most older PV systems are now being operated far beyond their initial performance life, as more are installed as early incentive programmes come to an end - the "Conto Energia" scheme, introduced in Italy. (Brown, Spatial and temporal variation in the value of solar power across United States electricity markets., 2020) These assets still operational are often vulnerable to becoming less efficient resulting in diminished capacity to deliver maximum utility to the organization. This has particularly been observed in old PV plants that were installed with less advanced technological designs and limitations on designs based on grid conditions at that time. (Buerhop-Lutz C. P., 2017)

The case being considered is 3.0 MW PV plant that is almost 14 years old and operational. Despite its nominal installed capacity, the plant is constrained by a grid export of 2.8 MW which constrained the amount of generated electricity that could be exported into the grid. It is a technical limitation that leads to excessive clipping of energy during the times of the day when the solar production is maximum. As time passes, as the PV modules degrade and the ratio of the performance of the system diminishes, the gap between the installed and output increases. The plant is therefore not performing well economically, both on the energy yield and the income generated.

To make the economic picture even more difficult, the plant receives revenue income on both ends the fixed price per kilowatt-hour (kWh) of sold power and a feed-in tariff (FiT) that might be offered to enter the market when the plant was commissioned. Although these incentives were initially the most effective way of making undertaking an undertaking viable, there are some requirements on the part of the regulatory environment with regard to revamping efforts. Specifically, when the plant undergoes a capacity upgrade, then the feed-in tariff needs to be recalculated using other formula which drops the FiT rate in accordance with new peak power capacity. (Buerhop-Lutz, et al., 2017)This presents a fairly fine trade off which, in the event that the plant can be expanded to be bigger, in the event that the generation is also larger, the revenue potential is also more, but the FiT will most likely be reduced accordingly and this will make overall profitability calculation quite tricky.

The system of integrating a Battery Energy Storage System (BESS) comes out as a potentially applicable solution in this context. A BESS allows the plant to regulate production to periods when the solar plant would produce a lower amount of energy and essentially flattens the production curve to allow extra revenues to be generated without necessarily increasing the nominal capacity of the PV. Nonetheless, battery systems come at significant capital costs, put in operation and size complications. It is thus quite significant that the appropriate mix between the PV revamping and the BESS capacity is identified to establish technical optimization and profitability.

The central question addressed in this thesis is to comprehend whether the revamping of the 3.0 MW PV facility also integrating the BESS system can bring production and profitability to the maximum beyond current limitations in the regulatory environment as well as technical factors. This involves using various scenarios of such addition to PV capacity and different sizes of BESS to assess the layout, which provides optimal net financial payoff. The solution will consider energy generation, energy storage behavior, regulator adjustments in the form of feed-in tariffs and investment expenses. (Buerhop-Lutz, et al., 2017)

3.1 Objectives:

The purpose of the thesis will be to determine the technical and financial viability of the retrofit of an existing photovoltaic (PV) plant of 3.0 MW equipped with a battery energy storage system (BESS) by offering a feasible combination of a new PV capacity with a battery energy storage system (BESS). This research paper will seek to prove the validity of such an intervention in order to realize its higher energy generation and optimal revenue, which will translate to better profitability and performance of the plant, considering the current regulatory and operational limitations.

In particular, the current PV plant is fixed to a grid export rate of 2.8 MW, implying that on sunny days, there is curtailment of energy at peak sunset hours when there is excess energy production over the required amount of energy to be sold. Also, the individual parts used in the system are over 7 years old, meaning that they have already suffered some forms of degradation affecting the energy output and efficiency of the system. (De Sisternes F. J., 2016) The plant is based on a combination of feed-in tariff (FiT) revenue and electricity sales per kilowatt-hour (kWh) revenue. However, in the case of the re-equipment of the plant by increasing the peak capacity of the plant, then the feed-in tariff will display the following formula:

New FiT = Current FiT / (1+ % Increase in peak power by revamping)

Such a decrease in FiT is such that it is extremely important to consider whether the economic benefit from the revamping of the PV plant can surpass the amendment to the tariff and investment expenses. (De Sisternes F. J., The value of energy storage in decarbonizing the electricity sector, 2016)

The objective of this study is to examine the energy performance of the existing PV system and approximate how the annual energy production may increase in different revamping scenarios. This reflects calculating the amount of energy that is currently curtailed due to the 2.8 MW cap, and how much of this energy might be reclaimed due to increased PV energy and storage combination. Different revamp scales will be taken into account in boosting peak power and determining the consequences upon generation and clipping. (Denholm, Eichman, Margolis, & Feldman, Evaluating the technical and economic performance of PV plus storage power plants, 2017)

The second objective is to measure the technical integration of BESS with the refurbed PV plant. The BESS will be utilized to store the clipped energy during peak generation periods and discharge during periods when PV production is more than the 2.8 MW export limit. Individual sizes of batteries ranging between 250 kWh -1500 kWh will be experimented to determine which size can be used to recover energy optimally and to play a valuable role in helping to smooth out the grid export.

The third goal is to develop a financial model to evaluate the profitability of the best-case scenario of revamping + BESS system. Accordingly, the model will accommodate the cost of investments in both PV revamp and battery storage, when the rates of feed-in tariffs and energy selling rates, operation and maintenance, and other financial parameters are taken into consideration. (Denholm P. M., Solar energy curtailment and grid integration, 2015)

The fourth and last goal is to confirm the optimal setup with the System Advisor Model (SAM) software. SAM will simulate detailed hourly energy production, battery charging and discharging processes, and power export to the real world, analyzing the outputs of the selected scenario under real-world conditions. The output of the simulations will assist in justifying the presence or absence of the revamp and BESS solution chosen under dynamic loads and sunlight conditions.

The results will provide a comprehensive decision-making model to revamp and storage integration for the PV plant operators presented in the thesis. The study concepts are based on offering practical insight into how to maximize the value of existing PV resources while also fulfilling the requirements of grid flexibility and green energy policies.

3.2 Methodology:

This chapter evaluates methods of evaluating the feasibility of upgrading an already existing photovoltaic (PV) plant that is already rated at 3.0 MW and the determination of the most suitable size of battery energy storage system (BESS) when there is a limitation to grid export. The study consists of empirical data on the long-term production of plants in the time series and the systematized analysis of techno-economic conditions offered in a spreadsheet platform in the System Advisor Model (SAM). This hybrid design combines the transparency and versatility of the spreadsheet-based screening, and the chosen optimal configuration of the research put to test running the model of the physically consistent operational simulation (Denholm P. M., Solar energy curtailment and grid integration, 2015).

3.3 General structure of research and workflow.

3.3.1 Description of the existing PV plant.

Its starting point is an existing PV plant that was commissioned in 2011 and 7 years of historical production record. This type of data will provide an empirical foundation, which will depict the real-world behavior of the system, losses, availability, operational constraints and weather effects.

3.3.2 Definition of revamping and storage cases.

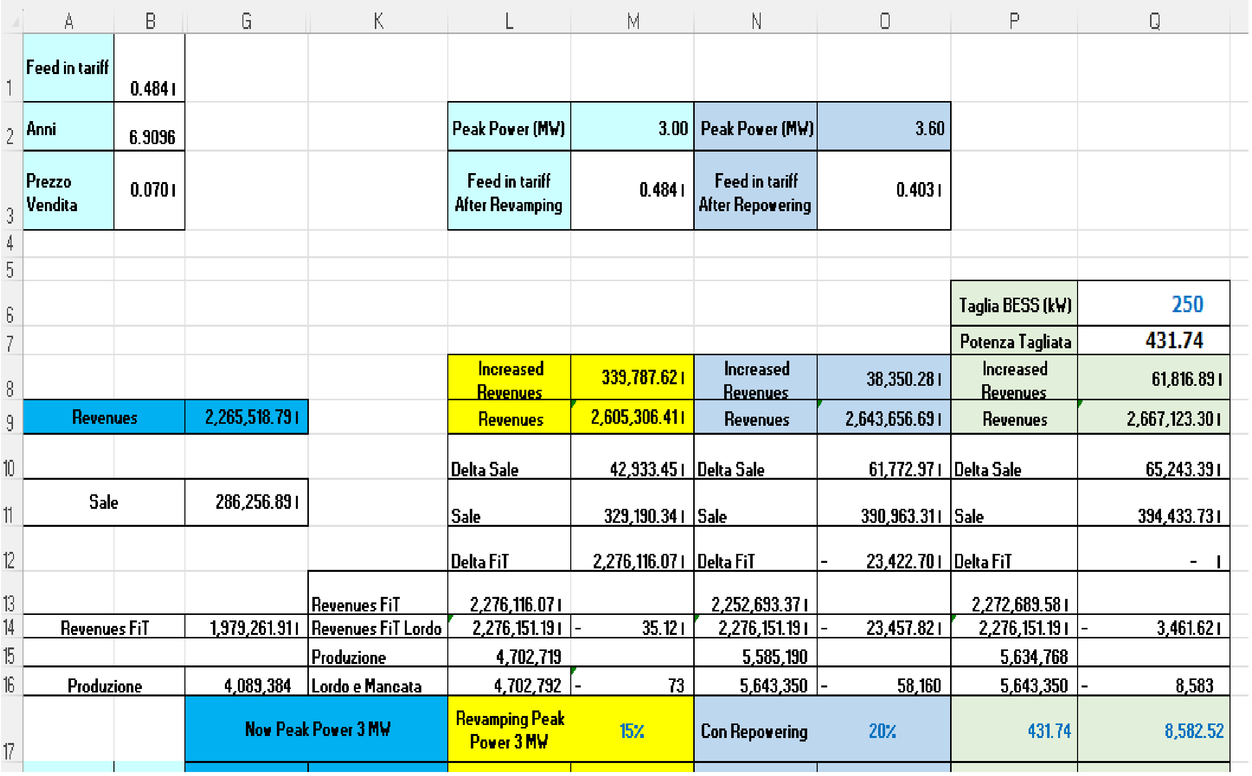
Different PV revamping options were defined as percentage increases in the initial plant's peak capacity: 20%, 25%, 30%, 35%, 40%, and 50%. At the same time, different BESS power ratings were also considered (250 kW, 500 kW, 750 kW, 1,000 kW, and 1,500 kW)

3.3.3 Economic screening in Excel

An Excel model was used to analyze the feasibility of individual revamping levels and BESS size combinations, including all values of the original nominal power, FiT rate, selling rate, BESS size, and revenue before and after the revamping, as well as the resulting revenue delta.

The following are some points related to the screening process in Excel.

1) The sheet contained 7 years' production data.
2) First, the original feed-in tariff rate and selling price were set for the calculation.
3) The formulas were set to calculate the new peak power and the updated feed-in tariff. Total Revenue is the sum of revenue from feed-in-tariff and the selling price.
4) An increase in efficiency due to technological advancement in PV was set to be 15%.
5) By setting revamping percentage as 20,25,30.35.40, and 50%, the increase in revenue was noted down. This value was used in the selection of the revamping value, which would be cost-effective among all considered options.
6) The selection of BESS capacity was chosen from 250kW, 500kW, 750kW, 1000kW and 1500kW. The most suitable option was selected, which causes the BESS system to be used to most of its capacity. In the case of 500kW, 750kW,1000kW and 1500kW, there was almost no storage of energy in BESS, leaving 250kW the only option to be considered for the study, in which 430kW were stored during the 7-year operation of the PV plant.



	A	B	G	K	L	M	N	O	P	Q
1	Feed in tariff	0.484 I								
2	Anni	6.9096			Peak Power (MW)	3.00	Peak Power (MW)	3.60		
3	Prezzo Vendita	0.070 I			Feed in tariff After Revamping	0.484 I	Feed in tariff After Repowering	0.403 I		
4										
5										
6									Taglia BESS (kW)	250
7									Potenza Tagliata	431.74
8					Increased Revenues	339,787.62 I	Increased Revenues	38,350.28 I	Increased Revenues	61,816.89 I
9	Revenues		2,265,518.79 I		Revenues	2,605,306.41 I	Revenues	2,643,656.69 I	Revenues	2,667,123.30 I
10					Delta Sale	42,933.45 I	Delta Sale	61,772.97 I	Delta Sale	65,243.39 I
11	Sale		286,256.89 I		Sale	329,190.34 I	Sale	390,963.31 I	Sale	394,433.73 I
12					Delta FiT	2,276,116.07 I	Delta FiT	- 23,422.70 I	Delta FiT	- I
13				Revenues FiT	2,276,116.07 I		2,252,693.37 I		2,272,689.58 I	
14	Revenues FiT		1,979,261.91 I	Revenues FiT Lordo	2,276,151.19 I	- 35.12 I	2,276,151.19 I	- 23,457.82 I	2,276,151.19 I	- 3,461.62 I
15				Produzione	4,702,719		5,585,190		5,634,768	
16	Produzione		4,089,384	Lordo e Mancata	4,702,792	- 73	5,643,350	- 58,160	5,643,350	- 8,583
17			Now Peak Power 3 MW		Revamping Peak Power 3 MW	15%	Con Repowering	20%	431.74	8,582.52

Figure 1 Excel screening

In the figure above, we can see that, using 250kW and 20 percent revamping, 430kW was stored in the battery during the first 7 years of operation of the PV plant. In the case of 500kW, 750kW, 1000kW, and 1500kW with the same revamping (20%) 181kW, 0kW, 0kW,0kW were stored during the first 7 years of operation of the PV plant. For 500kW, 750kW, and 1000kW, the energy stored was negligible, leaving only the 250kW BESS as the viable option to study and verify in SAM.

The reason for choosing 20% revamping option was the highest delta revenue among all the options. In cases of 20%, 25%, 30%, 35%, 40%, and 50%, the delta revenue was 38350€,32452€, 20901€, 5062€, 13720€ and -56,378€ respectively, making 20% revamping the best cost-effective option.

The purpose of this step was to briefly compute a promising case under the same assumptions and establish an initial optimal case with respect to financial criteria.

3.3.4 Validation during its operations in SAM Financial validation in SAM.

The most suitable option for revamping + BESS was then simulated in SAM using production time-series data. The SAM simulation could be used to ensure the project's financial sustainability over 20 years.

3.4 Data sources and baseline plant characterization

3.4.1 Historical production dataset

The data analyzed in this thesis is production data from the 3.0 MW PV plant over a 7-year period. The production data is used for:

- Baseline energy characterization: The performance of a plant makes it clear how the plant has performed over the years, together with interannual variation, which could be associated with weather variation and operational variation.
- Loss inclusive representation: The past production data already reflects the cumulative effect of conversion losses, auxiliary consumption, maintenance losses, and other losses at the plant level.

Due to a lack of detailed site data (location, module technology, inverter specifications), the study will provide a data-driven representation of performance rather than a bottom-up physical model in which irradiance and component performance data are converted to performance. Such an option is more realistic, as the analysis is based on observed plant behavior and the risk of errors arising from component assumptions is reduced.

3.5 Grid export limitation:

The plant has a nominal capacity of 3.0 MW. The interconnection to the grid has a fixed limit (2.8MW), which is taken to restrict the export capacity. This is the main limitation of the revamping process because revamping production increases and may result in curtailment. The strategy, in turn, includes the export restriction as a major technical constraint on monetizable energy**.**

3.6 Scenario definition: PV revamping and BESS sizing

3.6.1 PV revamping levels

The revamping plan considers different capacity addition cases, as a percentage increment to peak power on the first 3.0 MW power plant. The steps of revamping were examined for the following cases

20%, 25%, 30%, 40%, and 50%.

The reason behind considering these cases is to cover moderate-revamping decisions, and vigorous capacity accumulation in which grid limitations are expected to happen more frequently.

3.6.2 Technology improvement.

To estimate the performance increase associated with new PV technology, the methodology assumes a higher energy yield of the new modules relative to the old plant. A technology factor is applied to the peak capacity ratio to identify greater and more performance characteristics of subsequent modules. The assumption is applied homogeneously across any revamping scenario.

3.6.3 BESS sizes investigated

To determine the contribution of storage to economic viability, a series of BESS power ratings were analyzed:

250 kW, 500 kW, 750 kW, 1,000 kW, and 1,500 kW.

The range will be used to assess the sensitivity of profitability to storage power capability and to determine which BESS size and power rating are the most cost-effective option.

3.7 Economic model and assumptions:

3.7.1 Revenue mechanisms

The two streams that were modelled were plant revenues:

- Sales revenue of electricity
- feed-in tariff revenue, which depends on the revamping level.

This methodology assumes a fixed price for electricity sales; hence, the economic comparison can focus on the impacts of energy volumes (increases in production and reductions in curtailment) rather than on market price variability.

3.7.2 Energy export limitation:

Grid export cap enforcement is a key factor in this study. Under each scenario:

- when there is no instantaneous generation exceeding the export limit, the energy is all monetizable; and
- When the generation exceeds the limit of export, the surplus energy is suppressed unless it is taken up by storage.

3.7.3 Cost assumptions and project horizon.

It analyses 20 years of project period. Capital and operating cost is reflected by:

BESS CAPEX, based in capacity of energy storage or power capability.

O&M costs, comprising mostly the capacity-based annual fixed costs.

- In line discounting, inflation and tax assumptions are those that are associated with the financial model implementation related to Italy.

A performance-based replacement rule is used in SAM to evaluate battery replacement. The equipment replacement timing and degradation modelling are considered in the simulation chapter, whereas the approach to the structure and how battery lifetime assumptions can be included in the economic assessment are defined in the methodology chapter.

3.8 Spreadsheet-based screening:

The initial quantitative evaluation step was created in Excel to ensure it can be executed quickly and analyze numerous situations. In each combination of percentage of revamping and BESS size, the model compute:

- energy after refurbishing and technology upgrading, production per annum,
- exportable energy, which permits the limitation of the grid,
- incomes from electricity sales, as well as the tariff mechanism.

The screening tool is Excel, which attempts to identify the configuration that yields the highest NPV under constant assumptions. This phase is also critical to transparency: It enables stepwise verification of revenue logic, constraint management, and the calculation of financial metrics, and takes the simulation process into a more complex environment.

3.9 SAM simulation setup

3.9.1 Rationale for using SAM

SAM is used in the validation of the configuration that is chosen, as it offers:

- capabilities of time-series simulations on PV + storage systems that are hybrid,
- explicit physical representation of grid interconnection constraints/curtailment,
- adjustable storage dispatches plans (i.e., peak shaving),
- consolidated financial modeling in numerous year horizons.

3.9.2 PV generation profile modelling.

Since the data about the location of the PV plant was not available, the real production data was imported in SAM. This provides a realistic model of PV plant production and does not rely on the assumed weather data or the performance curves of the various components. An important decision is that, in SAM, plant losses are set to zero based on real production data, since the imported profile already accounts for plant losses.

3.9.3 Modeling and dispatch strategy Battery:

The BESS system is modeled using lithium iron phosphate (LFP) chemistry that is aligned with the use of utility-scale energy storage in modern times. The battery will have some power and energy parameters, which are both relevant to the problem definition and realistic conversion efficiencies.

A peak-shaving dispatch strategy is implemented to represent the control strategy for peak suppression and net production control, compared with the constraint. The dispatch setup is regarded as a part of the methodological design as it determines whether storage will be used primarily to curtailment alleviation, peak reduction or energy shifting.

3.9.4 Degradation Factor.

SAM is used to model annual analysis through the full 20-year time spectrum with the effects of PV annual degradation as well as battery life. This allows the study to be used to record long-term performance deterioration and replacement calamities, thereby strengthening the feasibility research.

4 Case Study:

This thesis is about the feasibility of the revamping of a 3.0 MW photovoltaic (PV) power plant that has already been operational since 2011. The exact location of the plant in Italy has not been specified but it is considered that the plant is located in the climatic and regulatory conditions that prevailed over Italy during the Conto Energia period- the period that was characterized by the high rate of installation of solar PV because of generous feed-in-tariff (FiT) incentives. This system was initially rated at 3.0 MW, and since start-up, there has been an export cap of 2.8MW.

4.1 Operational Characteristics and Assumptions.

The PV plant under study is ground mounted system which has connection to the utility grid. Although the specifics, such as the type of panels, inverter brand, and the way the arrays are organized, the performance of the system over time and the place where it is installed can be easily concluded on a daily basis based on the history of its producer.

The plant revenue is received from 2 major sources:

- Energy Market Sales: The quantity of power that is sold to the grid is sold in the market or the unit price of power. In this regard, it assumes that it is 0.07€/kWh in all years to concentrate on the study.
- Feed-in Tariff: The FiT for this PV plant was set to be 0.484€/kWh at the time of commissioning. In case of revamping the following equation is used to calculate the FiT:

$$\mathrm{FiT_{new}} = \frac{\mathrm{FiT_{2011}}}{1 + \Delta P}$$

where ΔP is the increase in nominal power due to revamping.

4.2 Historical Production Trends (2011–2018)

The plant's performance over its first 7 years is summarized in the table below, based on the average daily energy production (kWh/day): (Louwen A. v., 2019)

Year Average Daily Production (kWh/day)

Year	Production (average kWh per day)
2011	454.63

2012	434.86
2013	405.10
2014	399.37
2015	550.71
2016	412.66
2017	440.48
2018	487.14

The initial four years show that there is an decreasing trend in the daily production with the production level reducing to 399.37 kWh/day in 2014 compared to the 454.63 kWh/day in 2011. (Short W. P., A manual for the economic evaluation of energy efficiency and renewable energy technologies, 1995) This pattern is in line with anticipated reductions in overall performance of aging PV systems which are generally 0.5-1 percent annually because of age effects in modules, to inverter effects as well as external effects like soiling or thermal stress.

However, there is a significant rise in output in 2015, 550.71 kWh/day, indicating that the plant could have received some partial parts replacement, cleaning, or temporary work on performance. This is preceded by more stabilized but variable outputs in the following years. In 2018, the plant has a relatively good yield of 487.14 kWh/day, as compared to the year of commissioning, and this may have been a result of further improvements or good climatic conditions in that year. (Tsanakas J. A., Re-powering of photovoltaic plants: A review., 2017) (Zakeri B. &., Electrical energy storage systems: A comparative life cycle cost analysis., 2015)

In order to convert daily averages into annual production figures, 365 days per year are used to make a conversion and would give:

- 2011: 165,440 kWh/year
- 2018: 177,801 kWh/year

This range suggests a convenient framework of measuring the effect of suggested revamping and battery integration scenarios.

4.3 Motivation for Revamping and Battery Integration

The 2.8 MW export cap and the historical performance of PV plants highlight that the plant has been constrained by this cap, making it economically less viable. The system was also able to produce more than 2.8 MW during the peak hours when the sun is at its peak, and this causes clipping losses, which are the energy that the system produces but cannot be passed to the grid due to the export limit. The old technology makes the plant less efficient over time and less able to take advantage of high-irradiance days. This, in its turn, brings about a valid rationale for redesigning the PV system to:

Recovery: Maximize the power output by replacing the damaged modules or inverters. This can also involve increasing the plant's DC capacity with the latest technology, PV panels while keeping in mind the regulatory export cap.

It is also accompanied by the incorporation of a Battery Energy Storage System (BESS) to reclaim the clipped energy and deliver power on a time-shift basis to periods when output is low, in order to maximize total revenue without violating the 2.8 MW grid export cap. The second half of the current research is based on the techno-economic viability of various combinations of BESS sizes (250 to 1500 kWh) and PV revamp options.

4.4 Restructuring Scenarios and Assumptions.

The 3.0 MW PV plant under study presents the challenge of aging and its declining performance. As shown in the production data, the system is more than 10 years old, which is producing energy with less than nominal power due to degradation of the system, system inefficiency and limitation of the grid. To calculate the said problems, the revamping plan would be proposed to re-engineer the work of the plant and enhance its performance, i.e., in connection with the increase in peak power capacity, and the implication of a battery energy storage system (BESS). The revamping scenarios considered in the research are presented in this paragraph, along with the technical and financial assumptions that underpin simulation and analysis.

4.5 Revamping Capacity Scenarios.

The foundation of the revamping strategy is based on an incremental percentage increase in peak power of 3MW. Taking into consideration the recent advancements in the photovoltaic technology over the past decade, in particular, the increase of the efficiency of the modules, energy density, and reliability, the availability of the replacement or supplement of the existing PV panels by current ones would allow the increase the energy output without having to increase the occupancy rate of the area, without having to substantially change the plant layout. Several revamping levels were taken into consideration:

No.	New Installed Capacity	Percentage Increase Over Original
R1	3.60 MW	20%
R2	3.75 MW	25%
R3	3.90 MW	30%
R4	4.20 MW	40%
R5	4.50 MW	50%

Each scenario represents a hypothetical intervention in which more efficient PV modules are used, either by replacing the current array or by adding additional capacity. The percentage by which the output energy is going to be increased in each case is determined by the capacity boost and also a presupposed performance enhancement of the modules.

4.6 Assumption: Improvements of Technological Performance.

Latest generation PV modules have a conversion efficiency of 19 to 22 percent as compared to PV panels of 2010 having efficiency between 13 to 16 percent. This increase in efficiency is due to higher-quality silicon, a half-cut cell structure, an Anti-Reflective coating, and temperature coefficients.

To get the benefits of these developments, the study assumes 15 percent increase to the output of energy per unit of installed capacity, as is required to use the modern modules. Thus, all the revamping scenarios have not only gained higher installed power but also greater energy per megawatt. This is modelled as a multiplicative gain:

E_revamp = E_original *percentage increase due to revamping*1.15

This evaluation will ensure that the gains in DC capacity and energy production are realistic and justified by the panels' enhanced performance.

4.7 Financial Assumptions

The following are the main economic assumptions that are portrayed to be constant in all the situations to be clear and consistent in the course of the study:

- Selling Price of Electricity: Electricity market: The market price of electricity that is sold out at the grid is 0.07€per kWh. The market may be fluctuating but since this would be the fixed rate, the analysis could be less dependent on the fluctuation of the market and the revamping configurations would be comparatively easier.
- Feed-in Tariff (FiT) Adjustment: The original FiT of 0.484€/kWh that had been provided in the year 2011 was worked out as a standard rate of utility-scale PV systems installed in the Italian Conto Energia incentive phase. The Italian GSE regulations of the modern stipulate that recalculation of the FiT is necessary as far as an increase of peak capacity is involved, according to the following formula

$$\mathrm{FiT}_{\mathrm{new}} = \frac{\mathrm{FiT}_{2011}}{1 + \Delta P}$$

- Regulatory Framework Stability: It is assumed that there would be no change in the FiT recalculation formula, grid constraint, and regulatory environment over the financial analysis period. Though that may not be a perfect depiction of a shift in future policies, there is an option to create a stable setup for comparison.

4.8 Technical Constraints: Grid Export Limitation.

- The maximum grid export capacity of the system is 2.8 MW. Regardless of the DC capacity of the PV plant and the amount of solar irradiance it receives, the PV plant can contribute to the grid in AC capacity, limited to 2.8 MW. This capacity causes clipping of power, particularly at noon, when the sun's power is high.

- The surplus energy beyond this limit will be wasted without BESS. The clipping effect is more pronounced as the plant increases in capacity unless mitigated with storage. This grid constraint can therefore be an extremely significant element of the characterization of the margin worth of an extra MW of installed PV capability.

4.9 Modeling Assumptions in SAM

- All the simulation of the revamping configurations was performed on the System Advisor Model (SAM), one of the software development programs designed by the U.S. National

Renewable Energy Laboratory (NREL). SAM enables one to model PV system performance at a deep level, including financial and energy flows. Some of the key assumptions were made:

- Losses not previously taken into account: The System losses are not taken into account in the inputs of simulations; losses such as those caused by inverter inefficiency, soiling, shading or wiring are not considered in the inputs. This is the case because historical production data (2011-2018) already accounts for such losses, and actual information is used to test the model, thereby reducing uncertainty.
- Explicitly Clipped Model: SAM represents loss in clipping with adequate accuracy due to inverter or grid export limits, and so lost energy based on a specific revamping circumstance can be evaluated.

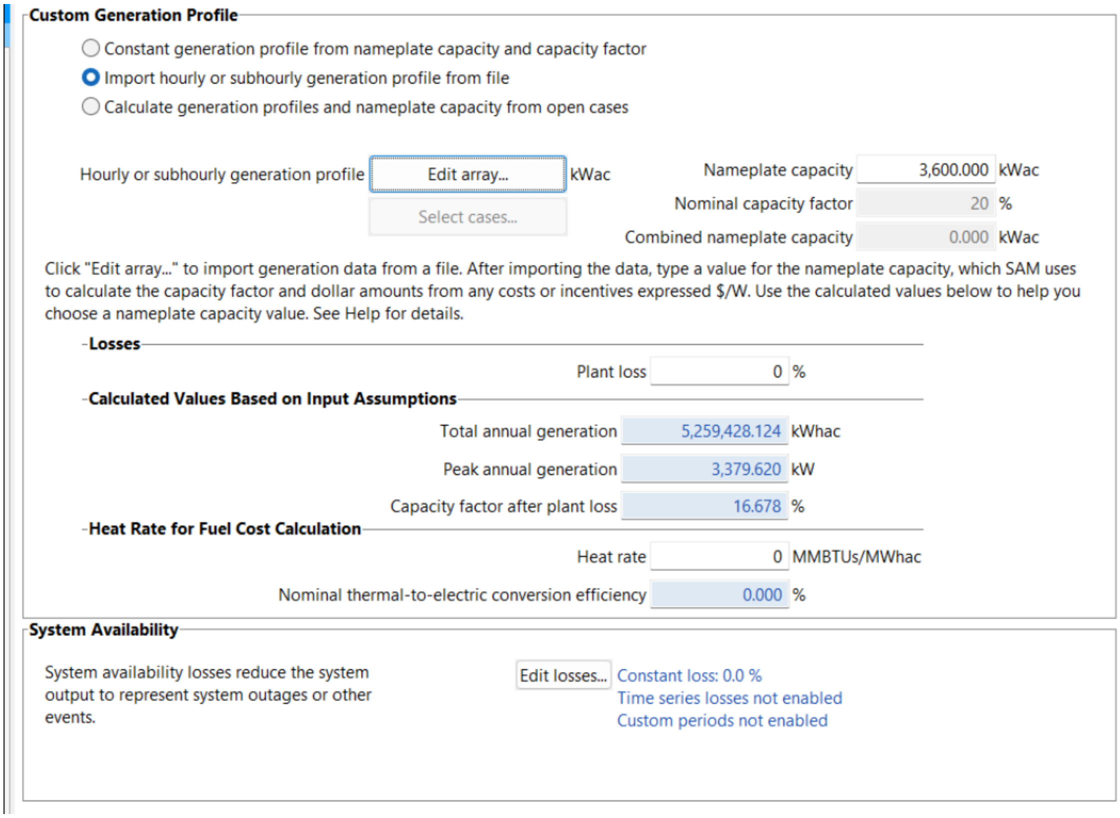
4.10 Implications for Optimization

The combined effects of the FiT reduction, grid clipping, and declining marginal returns to energy generation create a classical optimization problem. In cases where the revamping levels are moderate (5-15%), the FiT is relatively close to the original price, and the additional energy generated can also fall within the scope of export capacity. In the case of a 30 to 40 percent revamp, energy clipping becomes significant, and the price per unit of output in kWh is lost. Therefore, increased upgrades may not result in corresponding increases in profit without battery storage.

The main objective of this study is to determine the optimal combination of PV capacity increase and BESS scale to maximize profit for the net, while satisfying technical and financial feasibility. The simulation will allow the study to identify the optimal configuration that will be a more economically viable option.

5 Simulation with System Advisor Model:

5.1 Simulation setup in SAM for the optimal configuration (20% revamp + BESS)



Custom Generation Profile

○ Constant generation profile from nameplate capacity and capacity factor
● Import hourly or subhourly generation profile from file
○ Calculate generation profiles and nameplate capacity from open cases

Hourly or subhourly generation profile: Edit array... kWac
Select cases...
Nameplate capacity: 3,600.000 kWac
Nominal capacity factor: 20 %
Combined nameplate capacity: 0.000 kWac

Click "Edit array..." to import generation data from a file. After importing the data, type a value for the nameplate capacity, which SAM uses to calculate the capacity factor and dollar amounts from any costs or incentives expressed $/W. Use the calculated values below to help you choose a nameplate capacity value. See Help for details.

Losses

Plant loss: 0 %

Calculated Values Based on Input Assumptions

Total annual generation: 5,259,428.124 kWhac
Peak annual generation: 3,379.620 kW
Capacity factor after plant loss: 16.678 %

Heat Rate for Fuel Cost Calculation

Heat rate: 0 MMBTUs/MWhac
Nominal thermal-to-electric conversion efficiency: 0.000 %

System Availability

System availability losses reduce the system output to represent system outages or other events.

Edit losses...
Constant loss: 0.0 %
Time series losses not enabled
Custom periods not enabled

Figure 2 Generation Profile

5.1.1 Generation Profile:

In this study, as geographic location and component characteristics were unknown, weather files or PV performance sub-models were not used. Instead, the simulation or the custom generation profile is more of a data-based approach: the PV energy production is imported in the form of a custom generation profile.

This approach is unique because the data of production used in the study is based on real plant production and already contains the combined effect of the site irradiation, temperature, soiling, wiring, mismatch, conversion losses introduced by inverters, availability and operation constraints which have already occurred in the field. The model is pegged based on actual plant behavior and not a hypothetical performance estimate.

5.1.2 Definition of nameplate capacity (3.6 MWac)

After the generation profile is imported, SAM requires the quantity for each case nameplate capacity. This has been set as 3,600 kWac, which is the condition of revamping, where there has been a nominal peak power of +20%. Such a value is extremely important because it is deployed by SAM to compute both the performance measures (and in particular the capacity factor) and also to size appropriately any cost or incentive measures that are going to be expressed in terms of units of capacity.

5.1.3 Essential production and implied capacity factor on an annual basis.

With the imported profile, assuming the input values are provided on the panel of Calculated Values Based on Input Assumptions, the total annual generation of 5,259,428.124 kWhac in the 3.6 MWac case would be obtained. The reported loss of capacity factor is also 16.678%.

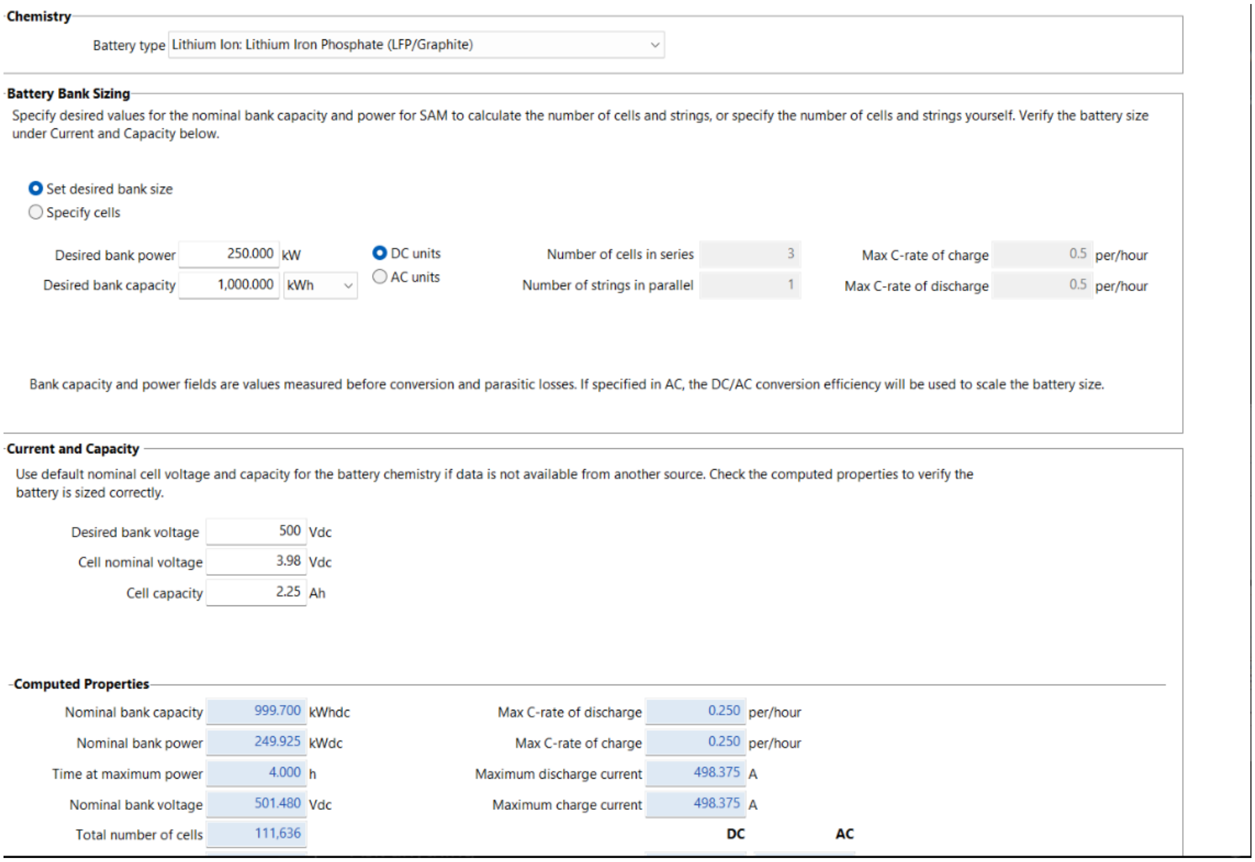
The same panel also shows peak annual generation of 3397.62kWhac, which can be said to be the same as the imported AC generation profile that is at times near the 3.6 MWac nominal rating, but is not always necessarily the nameplate. This is narrated to occur in real PV information due to variations in irradiance, temperature effects, and working limits.

In the system availability section, the plant loss value is 0. The given is a modeling decision that is consistent with the thesis assumption, that the profile of generation is imported which already takes into account the product of loss factors (efficiency of inverter, wiring losses, operating point mismatch, downtimes, etc.) .)

5.1.4 Plant losses set to zero (0%)

If plant losses were reintroduced within SAM, the model would count them during simulation. As the production data already constitute the losses, we consider plant losses to be 0.

5.2 Battery model: chemistry selection and bank sizing



Chemistry

Battery type: Lithium Ion: Lithium Iron Phosphate (LFP/Graphite)

Battery Bank Sizing

Specify desired values for the nominal bank capacity and power for SAM to calculate the number of cells and strings, or specify the number of cells and strings yourself. Verify the battery size under Current and Capacity below.

● Set desired bank size
○ Specify cells

Desired bank power: 250.000 kW
Desired bank capacity: 1,000.000 kWh
● DC units
○ AC units
Number of cells in series: 3
Number of strings in parallel: 1
Max C-rate of charge: 0.5 per/hour
Max C-rate of discharge: 0.5 per/hour

Bank capacity and power fields are values measured before conversion and parasitic losses. If specified in AC, the DC/AC conversion efficiency will be used to scale the battery size.

Current and Capacity

Use default nominal cell voltage and capacity for the battery chemistry if data is not available from another source. Check the computed properties to verify the battery is sized correctly.

Desired bank voltage: 500 Vdc
Cell nominal voltage: 3.98 Vdc
Cell capacity: 2.25 Ah

Computed Properties

Nominal bank capacity: 999.700 kWhdc
Nominal bank power: 249.925 kWdc
Time at maximum power: 4.000 h
Nominal bank voltage: 501.480 Vdc
Total number of cells: 111,636
Max C-rate of discharge: 0.250 per/hour
Max C-rate of charge: 0.250 per/hour
Maximum discharge current: 498.375 A
Maximum charge current: 498.375 A

Figure 3 Battery Cell and System

5.2.1 Battery chemistry: LFP (Lithium Iron Phosphate)

In our case study, LFP was used as a battery type for BESS. The selection aligns with utility-scale practice of storage, where LFP is often used due to:

- low thermal stability, and improved safety,
- their capability to handle frequent battery cycling
- reduced reliance on rare elements such as cobalt
- suitable for daily cycling.

LFP can be taken as a suitable choice, especially when a PV plant is situated in a place where there is an export cap

5.2.2 Sizing of battery bank in SAM.

SAM is used to define the set of parameters that configure the battery, such as the desired bank size. The desired values of the screenshot are:

- Desired bank power: 250 kW
- Desired bank capacity: 1,000 kWh
- Unit selection: DC units

What this configuration means is that the battery can provide nominal power for four hours. This battery configuration is ideal for reducing PV clipping and peak shaving. It is economically more feasible than larger systems and can store energy during the daytime.

5.3 Electrical characteristics.

In the current and capacity section, SAM computes internal electrical parameters that are required to build the same cell model. The show displays:

- Nominal bank power 249.925 kWdc (it seems to be 250 kW)..
- Nominal bank capacity: ~999.700 kWhdc
- Nominal bank voltage: ~501.480 Vdc
- Total number of cells: 111,636
- Maximum discharge/charge current: = 498.375 A.
- Highest C-rate (rate/discharge): 0.250 hourly.

This output is also needed to make sure that the bank is internally consistent to the size adopted of the 250 kW/1,000 kWh. In particular, a 0.25 C-rate corresponds to a 4-hour discharge time: the BESS would be able to supply the maximum power continuously for 4 hours. This is aligned with, but not ultra-fast, ancillary services storage system containing primary power management and peak-shaving functionality.

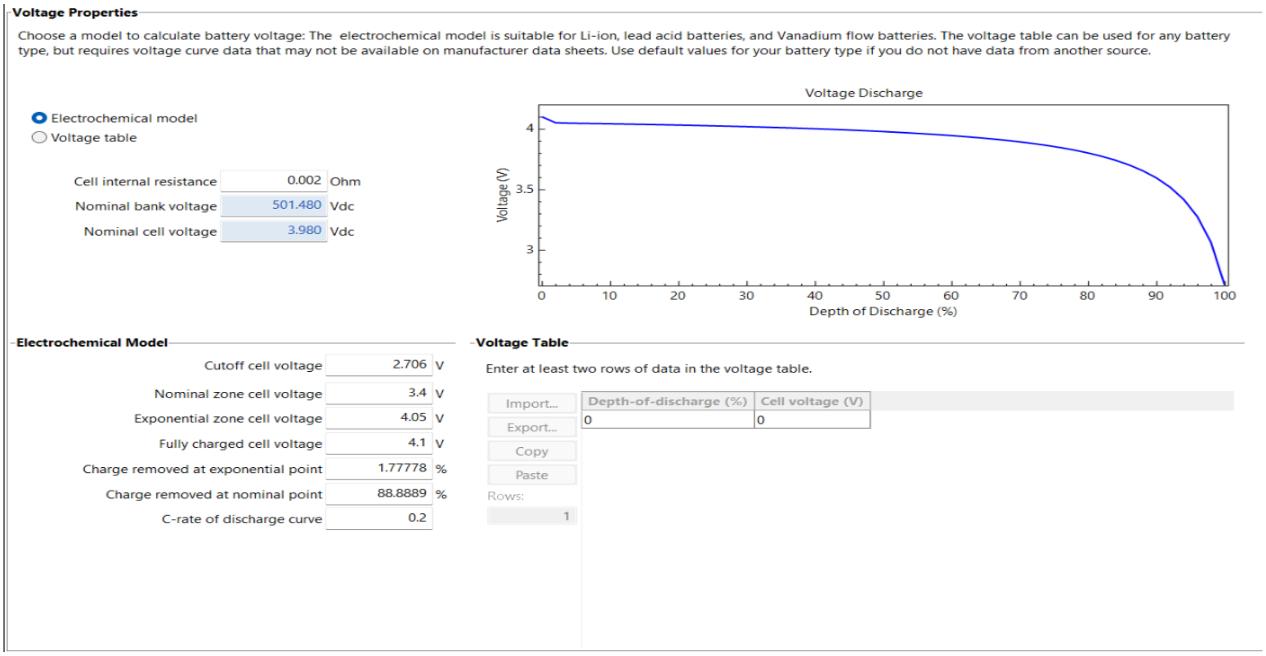
5.4 Power conversion efficiency (AC↔DC)

Along with the size of the battery bank, the efficiencies are given as follows

- AC - DC efficiency: 96%
- DC - AC efficiency: 96%

These efficiencies are crucial for understanding how effectively the energy from PV panels is stored and how efficiently it can be converted back to AC.

5.5 Battery voltage behavior: electrochemical model and voltage–DoD curve



Voltage Properties

Choose a model to calculate battery voltage: The electrochemical model is suitable for Li-ion, lead acid batteries, and Vanadium flow batteries. The voltage table can be used for any battery type, but requires voltage curve data that may not be available on manufacturer data sheets. Use default values for your battery type if you do not have data from another source.

● Electrochemical model
○ Voltage table

Cell internal resistance	0.002	Ohm
Nominal bank voltage	501.480	Vdc
Nominal cell voltage	3.980	Vdc

Electrochemical Model

Cutoff cell voltage	2.706	V
Nominal zone cell voltage	3.4	V
Exponential zone cell voltage	4.05	V
Fully charged cell voltage	4.1	V
Charge removed at exponential point	1.77778	%
Charge removed at nominal point	88.8889	%
C-rate of discharge curve	0.2	

Voltage Table

Enter at least two rows of data in the voltage table.

Depth-of-discharge (%)	Cell voltage (V)
0	0

Figure 4 Battery Voltage

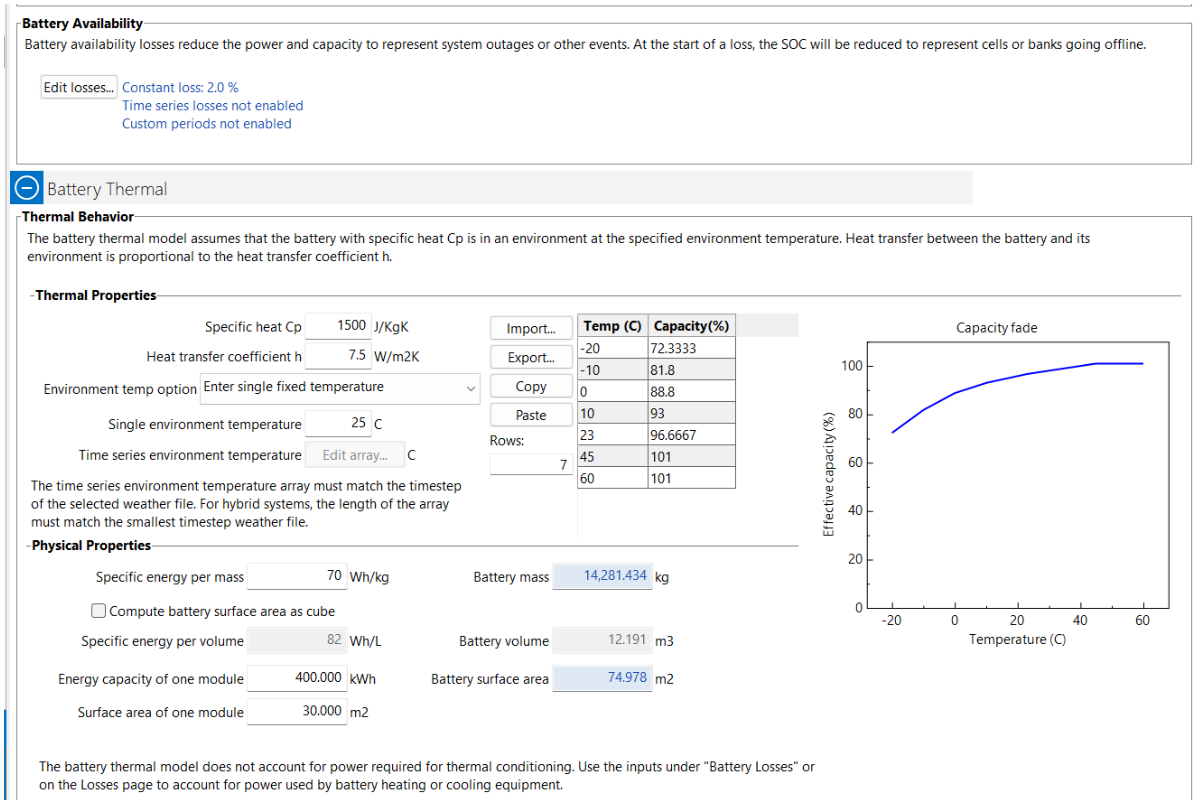
5.5.1 Selection of electrochemical model

The modeling technique selected has been the electrochemical model. This is a suitable option to adopt in case of voltage curves are unavailable and it ensures that batteries vary with state of charge/depth of discharge in a physically significant way.

Model parameters will be:

- Cell internal resistance: 0.002 Ohm
- Nominal cell voltage: 3.980 Vdc
- Bank nominal voltage: ~501.48 Vdc

5.6Availability and thermal behavior:



Battery Availability

Battery availability losses reduce the power and capacity to represent system outages or other events. At the start of a loss, the SOC will be reduced to represent cells or banks going offline.

Constant loss: 2.0 %
Time series losses not enabled
Custom periods not enabled

Thermal Behavior

The battery thermal model assumes that the battery with specific heat Cp is in an environment at the specified environment temperature. Heat transfer between the battery and its environment is proportional to the heat transfer coefficient h.

Thermal Properties

Specific heat Cp: 1500 J/KgK
Heat transfer coefficient h: 7.5 W/m2K
Environment temp option: Enter single fixed temperature
Single environment temperature: 25 C
Time series environment temperature: Edit array... C

The time series environment temperature array must match the timestep of the selected weather file. For hybrid systems, the length of the array must match the smallest timestep weather file.

Rows: 7

Temp (C)	Capacity(%)
-20	72.3333
-10	81.8
0	88.8
10	93
23	96.6667
45	101
60	101

Physical Properties

Specific energy per mass: 70 Wh/kg
Battery mass: 14,281.434 kg
☐ Compute battery surface area as cube
Specific energy per volume: 82 Wh/L
Battery volume: 12.191 m3
Energy capacity of one module: 400.000 kWh
Battery surface area: 74.978 m2
Surface area of one module: 30.000 m2

The battery thermal model does not account for power required for thermal conditioning. Use the inputs under "Battery Losses" or on the Losses page to account for power used by battery heating or cooling equipment.

Figure 5 Battery Availability and thermal behavior

5.6.1 Battery availability loss (2% per year)

The Battery Availability section has a constant loss of 2.0. It is the fraction of battery capacity that is out of service due to scheduled maintenance, outage, or auxiliary losses. This assumption can be important in a peak-shaving application, as even a small interruption in availability might cause major effects on the amount of clipped PV energy that can be captured.

5.6.2 Thermal and Physical Properties:

The Battery Thermal section has the following data:

- Ambient temperature: 25°C
- Specific heat (Cp): 1500 J/kgK
- Coefficients of heat transfer (h): 7.5 W/ m^2K.

The assumption of a constant ambient temperature is a simplistic but feasible assumption, and which aims at modeling a normal operating condition where a site-specific meteorological time series is not available.

5.7 Capacity vs. temperature.

The capacity vs temperature curve has reduced effective capacity in lower temperatures and then becomes nominal with an increase in temperature

The curve has several important implications:

- maximum power that the battery can store at low temperatures
- It shows how much power can be shed during the peak shaving period.

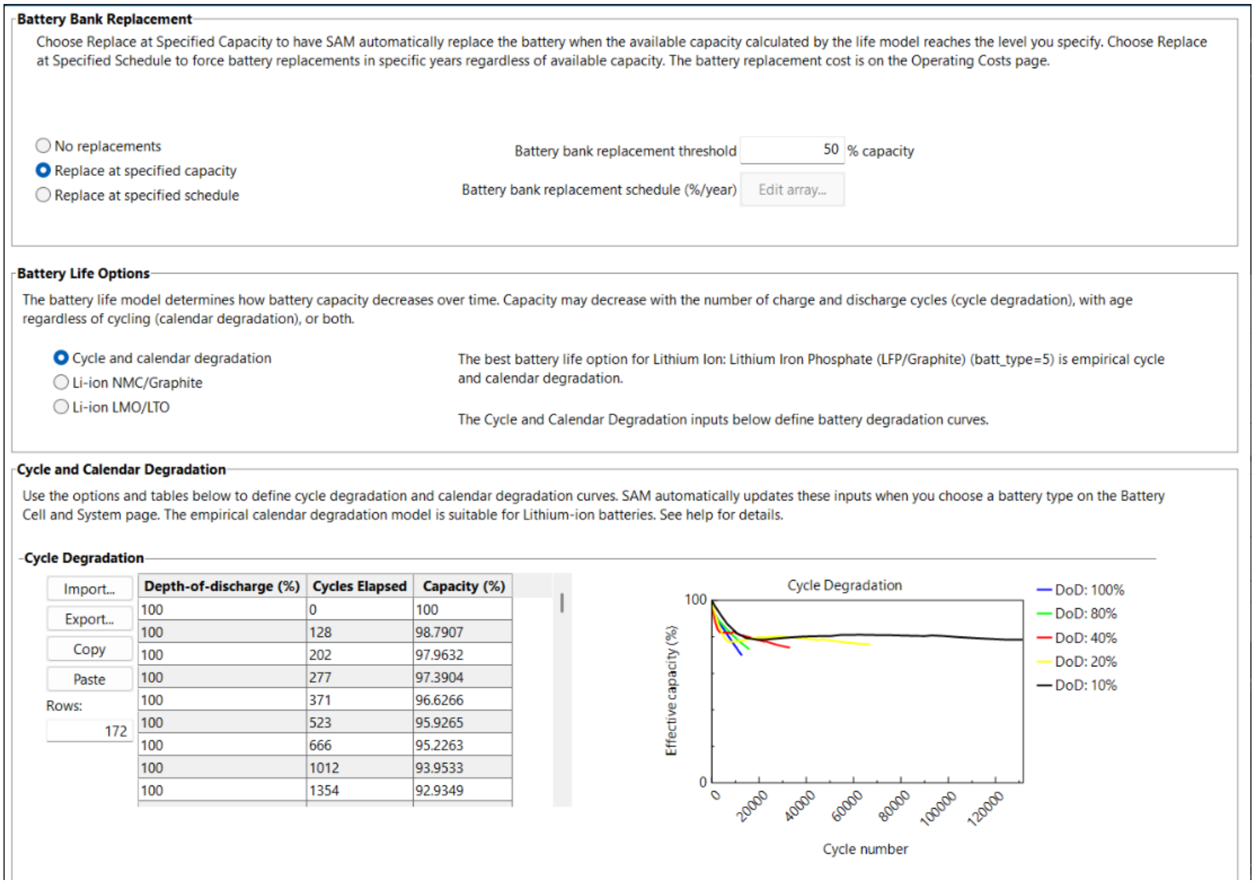
5.7.1 Physical properties: mass, volume, and surface area

Physical characteristics of BESS report physical characteristics that are consistent with known energy capacity and assumed energy density:

- Particular energy: 70 Wh/kg.
- Battery mass: ~14,281 kg
- Battery volume: ~12.191 m3
- Battery surface area: ~74.978 m2
- Module power output: 400kWh

These physical properties are used to calculate thermal characteristics of BESS, such as heat transfer area and heat capacity. Also, this data provides the reader with information on the size and mass of a BESS containerized system.

5.8 Battery replacement and cycle degradation:



Battery Bank Replacement

Choose Replace at Specified Capacity to have SAM automatically replace the battery when the available capacity calculated by the life model reaches the level you specify. Choose Replace at Specified Schedule to force battery replacements in specific years regardless of available capacity. The battery replacement cost is on the Operating Costs page.

○ No replacements
● Replace at specified capacity
○ Replace at specified schedule

Battery bank replacement threshold 50 % capacity

Battery bank replacement schedule (%/year) Edit array...

Battery Life Options

The battery life model determines how battery capacity decreases over time. Capacity may decrease with the number of charge and discharge cycles (cycle degradation), with age regardless of cycling (calendar degradation), or both.

● Cycle and calendar degradation
○ Li-ion NMC/Graphite
○ Li-ion LMO/LTO

The best battery life option for Lithium Ion: Lithium Iron Phosphate (LFP/Graphite) (batt_type=5) is empirical cycle and calendar degradation.

The Cycle and Calendar Degradation inputs below define battery degradation curves.

Cycle and Calendar Degradation

Use the options and tables below to define cycle degradation and calendar degradation curves. SAM automatically updates these inputs when you choose a battery type on the Battery Cell and System page. The empirical calendar degradation model is suitable for Lithium-ion batteries. See help for details.

Cycle Degradation

Rows: 172

Depth-of-discharge (%)	Cycles Elapsed	Capacity (%)
100	0	100
100	128	98.7907
100	202	97.9632
100	277	97.3904
100	371	96.6266
100	523	95.9265
100	666	95.2263
100	1012	93.9533
100	1354	92.9349

Figure 6 Battery Life

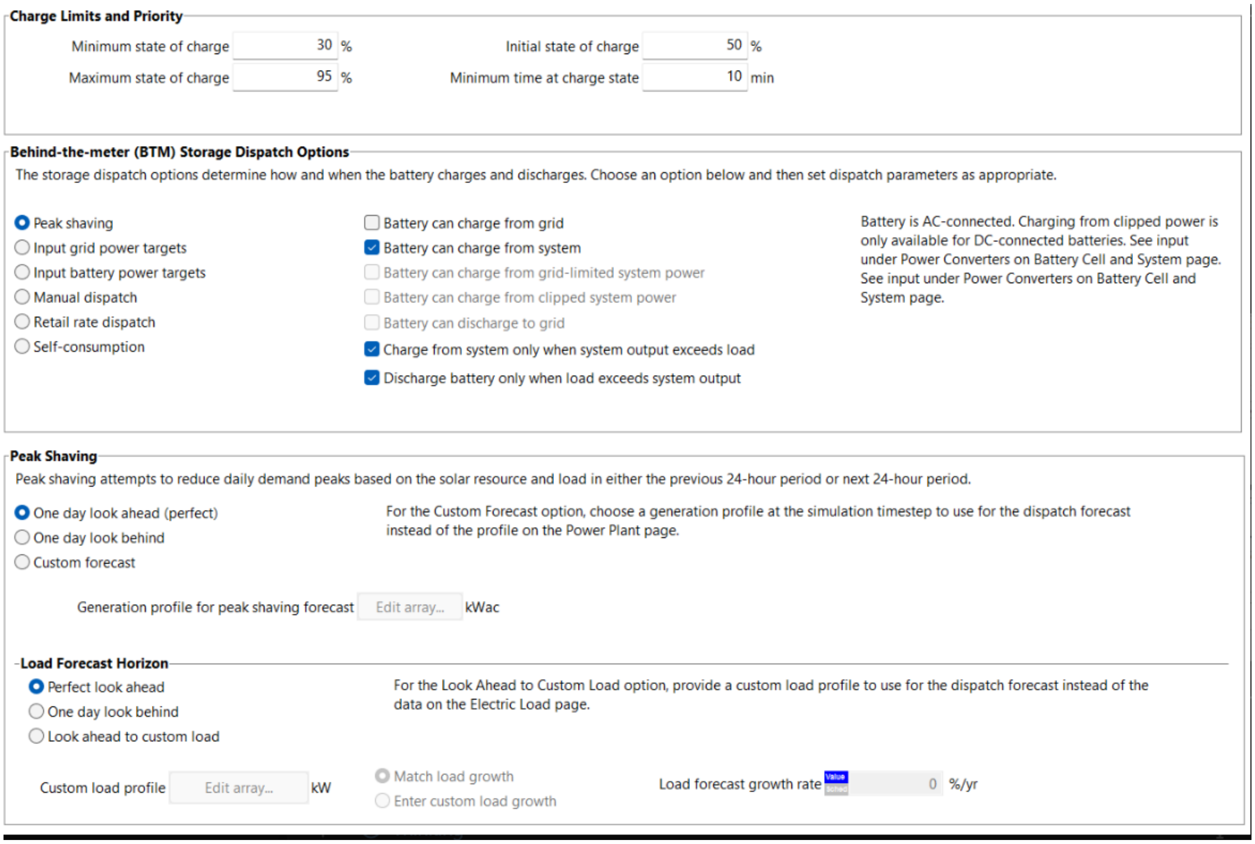
The battery bank is replaced when its capacity decreases to 50 percent of its original capacity. This means that SAM always keeps track of available battery capacity during simulation, and if the available capacity has been reduced by half or more, it automatically swaps its battery. In practice, this is also followed: when a battery has depleted itself beyond about half of its useful charge capacity, it becomes operationally inefficient and, in most cases, will be replaced.

Cycle and calendar degradation are a result of the fact that lithium-ion batteries have a reduction in capacity owing to two concurrent processes:

Cycle degradation is related to the extent of battery charge/discharge (energy throughput, number of cycles, depth of discharge). Calendar cycling refers to the battery's aging over time due to factors such as electrochemical aging.

The simulation accounts for both cycle and calendar degradation. These degradations are necessary to consider for BESS, which experiences gradual degradation due to cycling and time.

5.9 Dispatch strategy and operational constraints



Charge Limits and Priority

Minimum state of charge 30 %
Maximum state of charge 95 %
Initial state of charge 50 %
Minimum time at charge state 10 min

Behind-the-meter (BTM) Storage Dispatch Options

The storage dispatch options determine how and when the battery charges and discharges. Choose an option below and then set dispatch parameters as appropriate.

● Peak shaving
○ Input grid power targets
○ Input battery power targets
○ Manual dispatch
○ Retail rate dispatch
○ Self-consumption

☐ Battery can charge from grid
☑ Battery can charge from system
☐ Battery can charge from grid-limited system power
☐ Battery can charge from clipped system power
☐ Battery can discharge to grid
☑ Charge from system only when system output exceeds load
☑ Discharge battery only when load exceeds system output

Battery is AC-connected. Charging from clipped power is only available for DC-connected batteries. See input under Power Converters on Battery Cell and System page. See input under Power Converters on Battery Cell and System page.

Peak Shaving

Peak shaving attempts to reduce daily demand peaks based on the solar resource and load in either the previous 24-hour period or next 24-hour period.

● One day look ahead (perfect)
○ One day look behind
○ Custom forecast

For the Custom Forecast option, choose a generation profile at the simulation timestep to use for the dispatch forecast instead of the profile on the Power Plant page.

Generation profile for peak shaving forecast Edit array... kWac

Load Forecast Horizon

● Perfect look ahead
○ One day look behind
○ Look ahead to custom load

For the Look Ahead to Custom Load option, provide a custom load profile to use for the dispatch forecast instead of the data on the Electric Load page.

Custom load profile Edit array... kW

● Match load growth
○ Enter custom load growth

Load forecast growth rate 0 %/yr

Figure 7 Dipatch Strategy

5.9.1 Charge limits:

The lower limit of state of charge is 30 percent, and the upper limit is 95 percent. This provides safe working conditions compared with the 0-100% functioning. It is a common modeling approach of lithium-ion systems because:

- Very Low or high SOC is not suitable because it can contribute to accelerated degradation and

The initial SOC shall be 50 and this is the fact that the battery is initially half-charged in the simulation. This will prevent the introduction of artificial bias in the simulation's early days that would have occurred if the battery had been either full or empty at the start.

A minimal charge of 10 minutes also exists. This is operationally useful in order to counteract chatter in control overrun (between charge and discharge cycles), and to ensure that the dispatch algorithm has significant choice with which to simulate realistic controller behavior and power electronics reaction.

5.9.2 Dispatch logic:

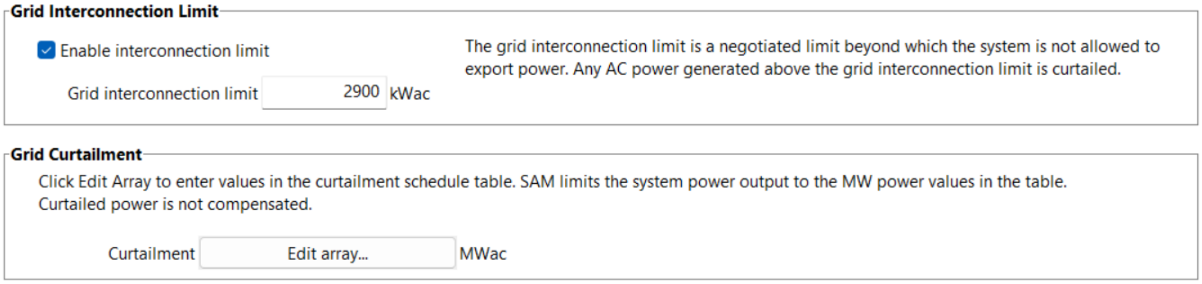
Peak shaving is selected under the Behind-the-Meter (BTM) Storage Dispatch Options. Peak shaving in SAM reduces grid or point-of-interconnection peaks based on expected load and generation profiles. This strategy addresses the export limitation efficiently and optimizes the plant's net output.

The checkbox options indicate that the battery will not charge from the grid but rather from the PV system. In this arrangement, there is no grid charging. This would be in line with PV-integrated BESS, the primary objective of which is to absorb surplus PV production.

The following two logic constraints are being realized:

- Charging is allowed when the system output exceeds the load.
- Discharge is only permitted when the load exceeds the system output.

5.10 Grid Limit



Grid Interconnection Limit

☑ Enable interconnection limit

Grid interconnection limit 2900 kWac

The grid interconnection limit is a negotiated limit beyond which the system is not allowed to export power. Any AC power generated above the grid interconnection limit is curtailed.

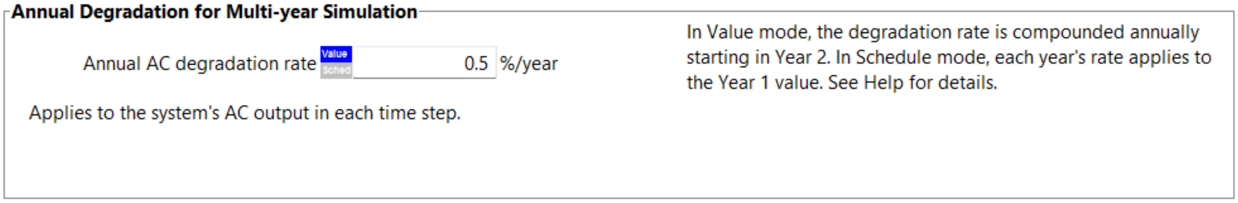
Grid Curtailment

Click Edit Array to enter values in the curtailment schedule table. SAM limits the system power output to the MW power values in the table. Curtailed power is not compensated.

Curtailment Edit array... MWac

The interconnection limit is 2900 kWac. SAM would enforce a rigid constraint where the interconnection point was reached: the overload would be capped in case the AC output of the system exceeded more than 2.9 MW. This is a center-stage environment in this case study because economic incentives are to add-storage which is tightly linked with the export limits: the bigger the PV capacity by means of revamping, the more often there is a possibility of over-exporting and the more serious the risk of curtailment unless the storage has a battery to absorb the energy and hold it until later times.

5.11 Annual degradation:



Annual Degradation for Multi-year Simulation

Annual AC degradation rate: 0.5 %/year

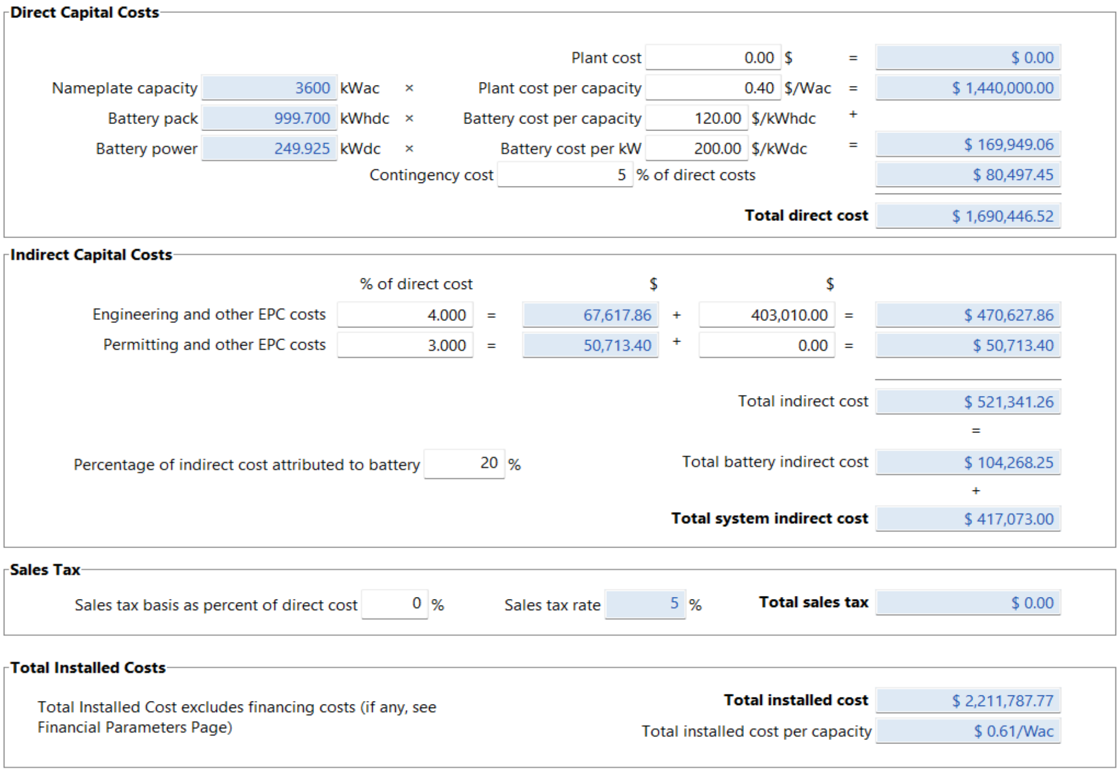
Applies to the system's AC output in each time step.

In Value mode, the degradation rate is compounded annually starting in Year 2. In Schedule mode, each year's rate applies to the Year 1 value. See Help for details.

Figure 8 Battery Degradation

In this section, SAM reduces the PV plant's energy output over time. The percentage of degradation of AC is considered 0.5 percent per year and SAM applies it directly upon the AC output of the system at every step of the simulation. In real life, this is the PV generation profile that is in a smoother year-by-year decline to indicate a long-term performance degradation following the first simulated year.

5.12 Installation cost:



Direct Capital Costs

			Plant cost	0.00 $	=	$ 0.00
Nameplate capacity	3600 kWac	×	Plant cost per capacity	0.40 $/Wac	=	$ 1,440,000.00
Battery pack	999.700 kWhdc	×	Battery cost per capacity	120.00 $/kWhdc	+	
Battery power	249.925 kWdc	×	Battery cost per kW	200.00 $/kWdc	=	$ 169,949.06
			Contingency cost	5 % of direct costs		$ 80,497.45
					Total direct cost	$ 1,690,446.52

Indirect Capital Costs

	% of direct cost		$		$		
Engineering and other EPC costs	4.000	=	67,617.86	+	403,010.00	=	$ 470,627.86
Permitting and other EPC costs	3.000	=	50,713.40	+	0.00	=	$ 50,713.40

Total indirect cost: $ 521,341.26

=

Percentage of indirect cost attributed to battery: 20 %

Total battery indirect cost: $ 104,268.25

+

Total system indirect cost: $ 417,073.00

Sales Tax

Sales tax basis as percent of direct cost: 0 %

Sales tax rate: 5 %

Total sales tax: $ 0.00

Total Installed Costs

Total Installed Cost excludes financing costs (if any, see Financial Parameters Page)

Total installed cost: $ 2,211,787.77

Total installed cost per capacity: $ 0.61/Wac

Figure 9 Installation Cost

5.12.1 Direct capital costs

Such a direct cost is used according to the system sizes

- PV nameplate capacity: 3,600 kWac

Capacity of battery pack: ~999.7 kWhdc.

- Battery power: ~249.9 kWdc

The direct costs are established in unit prices:

- Plant cost per capacity: 0.40 $/Wac

This causes the PV plant to cost one, 440,000 dollars in the 3.6 MWac system. This value is the upgrade CAPEX of the PV plant

- Price/kWhdc of batteries: 120 $/kWhdc

This imposes a cost on the energy component of the battery (cells/ modules, racks, enclosures). This contributes to direct cost with six figures, with a controllable amount of 1, 000 kWhdc.

- Battery cost per kW: 200 $/kWdc

The contingency costs will be five percent of the direct costs. This is a typical project development to cover uncertainties such as variations in site work, procurement risk, and installation/commissioning risk. The inclusion of contingency would add flexibility to the feasibility study, preventing the model from becoming an overly optimistic engineering estimate.

This is then combined with SAM so that the total direct cost equals $1,690,446.52.

5.12.2 Indirect capital costs

Engineering and EPC costs: 4 percent of direct costs.

Permitting and any other EPC expenses: 3 percent of the direct cost.

These costs are not costs directly associated with the quantity of equipment (engineering design, project management, documentation, permitting, inspections, EPC overhead). SAM adds them to the indirect cost of 521, 341.26.

5.13 Sales tax handling in the installation cost page

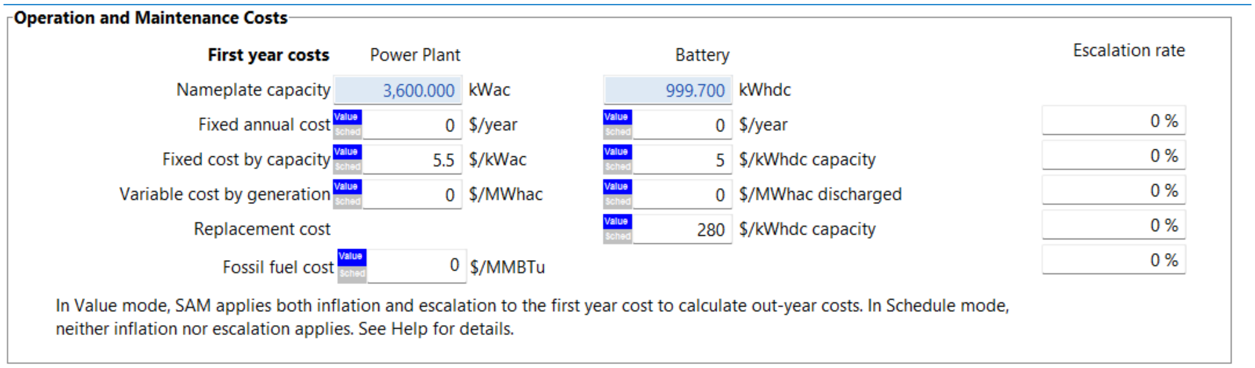
The sales tax, as a percentage of direct cost, is 0, for simplicity of the analysis.

5.14 Total installed cost

Finally, SAM reports:

- Total installed cost: $2,211,787.77
- Total Installed cost per capacity: $0.61/Wac.

5.15 Operating, maintenance, and replacement cost assumptions



Operation and Maintenance Costs

First year costs	Power Plant		Battery		Escalation rate
Nameplate capacity	3,600.000	kWac	999.700	kWhdc	
Fixed annual cost	0	$/year	0	$/year	0 %
Fixed cost by capacity	5.5	$/kWac	5	$/kWhdc capacity	0 %
Variable cost by generation	0	$/MWhac	0	$/MWhac discharged	0 %
Replacement cost			280	$/kWhdc capacity	0 %
Fossil fuel cost	0	$/MMBTu			0 %

In Value mode, SAM applies both inflation and escalation to the first year cost to calculate out-year costs. In Schedule mode, neither inflation nor escalation applies. See Help for details.

Figure 10 Operating Cost

5.15.1 PV O&M (Power Plant column)

- Fixed annual cost: 0 $/year
- Fixed cost by capacity: 5.5 $/kWac
- Variable cost, generation: 0$/MWhac.

This implies that the PV O&M cost will be modeled in terms of a linear approach and no additional cost in the model variable will be based on the level of generation. The variable cost would be zero, which means that the model does not penalize an increase of production through the form of wear and tear costs and performance-based service costs. These values are appropriate while considering the feasibility analysis of the revamping option

5.15.2 Battery O&M (Battery column)

- Cost of replacement: 280 $/kWhdc capacity.
- Fixed annual cost: 0 $/year
- Capacity cost: 5$//kWhdc capacity

At this point, there are two points to be noted:

Battery O&M is predominately capacity based. And O&M cost of PV plant is based on installed energy capacity.

6.15.3 Escalation rates

The escalation rates are 0 (no escalation) in battery O&M items and PV. This also means that in such a setup, the O&M costs do not increase or decrease in real terms over the periods that the analysis is performed, or any increase in cost caused by inflation is not reflected at the O&M line-item. This is the normal assumption that is commonly applied in order to make the cost model more conservative.

5.16 Financial Parameters

5.16.1 Project Term Debt

Debt percentage: 0% in which the loan term and loan rate is not used.

It implies that this project is being calculated as an equity based. In terms of feasibility, this completely cuts out the impact of financing structure.

Analysis period, and discount rates.

Analysis period: 20 years

It corresponds to the revamp + storage options horizon of which we are comparing.

- Inflation rate: 2.5%/year
- Real discount rate: 6.4%/year
- Nominal discount rate: 9.06%/year

These values guarantee how subsequent cash flow is valued at the present worth. The difference between the real and the nominal discount rate is consistent with the factor of inflation consideration.

5.16.2 Taxes and insurance

There are income tax settings contained in the panel:

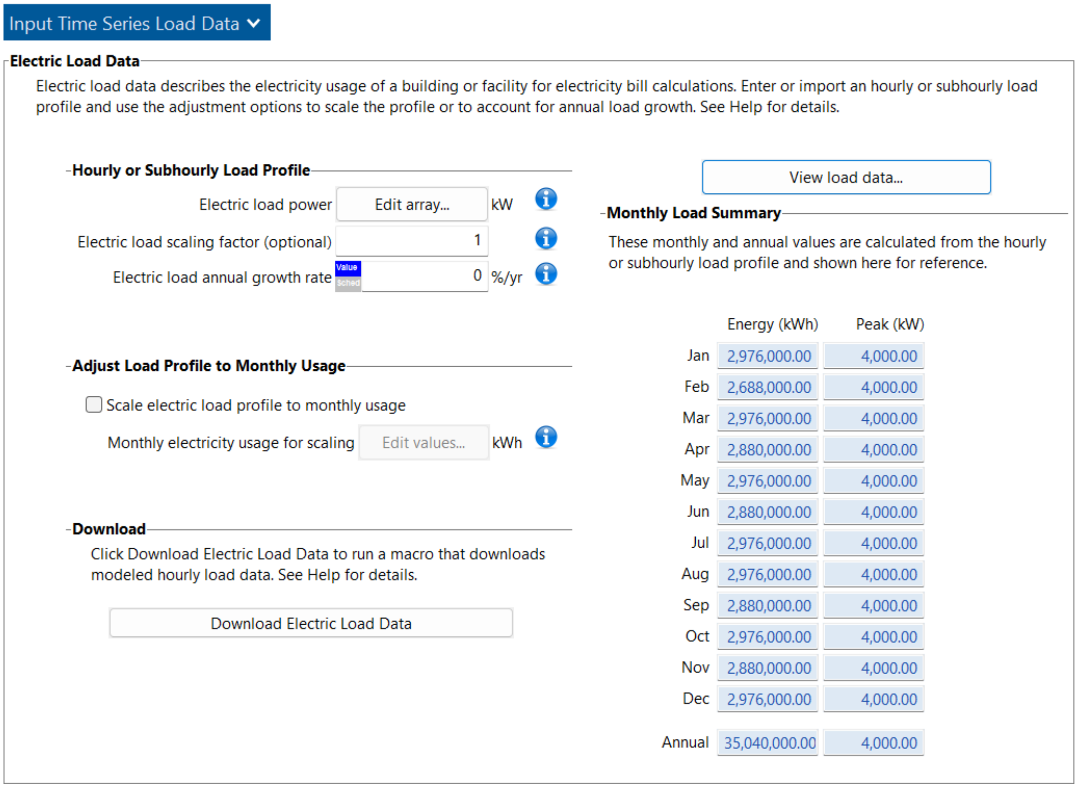
- Federal income tax rate: 0%
- State income tax rate:0%

These values appear to be defaults for the European market in SAM. It has zero property tax and insurance and, therefore, these sources of costs are not included.

5.16.3 Depreciation

Depreciation will be the straight-line type, with 7 years being selected. This affects the net cash flow in the first years regarding the taxable income. The use of the reduced depreciation is likely to increase, in practice, an early tax shield and has the potential to improve discounted measures.

5.17 Electric Load Data:



Electric Load Data

Electric load data describes the electricity usage of a building or facility for electricity bill calculations. Enter or import an hourly or subhourly load profile and use the adjustment options to scale the profile or to account for annual load growth. See Help for details.

Hourly or Subhourly Load Profile

Electric load power: Edit array... kW

Electric load scaling factor (optional): 1

Electric load annual growth rate: 0 %/yr

Adjust Load Profile to Monthly Usage

☐ Scale electric load profile to monthly usage

Monthly electricity usage for scaling: Edit values... kWh

Download

Click Download Electric Load Data to run a macro that downloads modeled hourly load data. See Help for details.

Monthly Load Summary

These monthly and annual values are calculated from the hourly or subhourly load profile and shown here for reference.

	Energy (kWh)	Peak (kW)
Jan	2,976,000.00	4,000.00
Feb	2,688,000.00	4,000.00
Mar	2,976,000.00	4,000.00
Apr	2,880,000.00	4,000.00
May	2,976,000.00	4,000.00
Jun	2,880,000.00	4,000.00
Jul	2,976,000.00	4,000.00
Aug	2,976,000.00	4,000.00
Sep	2,880,000.00	4,000.00
Oct	2,976,000.00	4,000.00
Nov	2,880,000.00	4,000.00
Dec	2,976,000.00	4,000.00
Annual	35,040,000.00	4,000.00

Figure 11 Electric Load

SAM provides the calculation of a Monthly Load Summary on the right-hand side based on the input of a time series of load. The monthly reports on the values consist of the two values reported:

Currently, monthly energy (kWh): average between 2.688-2.976 million kWh/month.

- Annual total energy: 35,040,000 kWh
- Annual peak: 4,000 kW

These statistics suggest that the import load profile achieves its peak demand of 4 MW. The reason of choosing this 4MW was that the main purpose of our study is to find the optimum battery size and while analyzing in Excel it showed that the production of PV plant will never be more than 3.6MW and we choose 4MW load because it will cover the maximum production of PV plant showing us as a result when the battery will be used (charged/discharged)

5.18 Energy Rate

Number of entries: 1

Period	Tier	Max. Usage	Max. Usage Units	Buy ($/kWh)	Sell ($/kWh)
1	1	1e+38	kWh	0	0.07

Weekday

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Feb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Apr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nov	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Weekend

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Feb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Apr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nov	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 12 Electricity Rates

This section determines the charge rates of energy that SAM uses in establishing the economic value of the flows of electricity. They may be time of use, season, weekday/weekend rates and usage rates of the tariff structure of SAM. It is observed that the rate of energy is assumed to be constant throughout the year.

6 Results:

This section discusses the results achieved from the simulation in the System Advisor Model (SAM). Specifically, it focuses on 20% revamping option with 250kW BESS.

Four main results are provided as follows

- After tax cash flow: The cash flow during the lifetime of the system
- Energy production =Monthly AC energy production vs monthly electric load in 1st year
- Hourly and daily heatmap of power output
- Annual Electricity Generation

6.1 The after-tax net cash flow over the system lifetime.

This section shows the 20-year analysis of after-tax cash flow for the project. Year 0 is the year of having massive negative cash flow, which is the total invested cost of the system. These would include the capital cost of the PV revamping, the battery system, the indirect EPC and the permitting costs. This initial capital cost is a burden in the start of the project, which is offset by the resulting operating income over time.

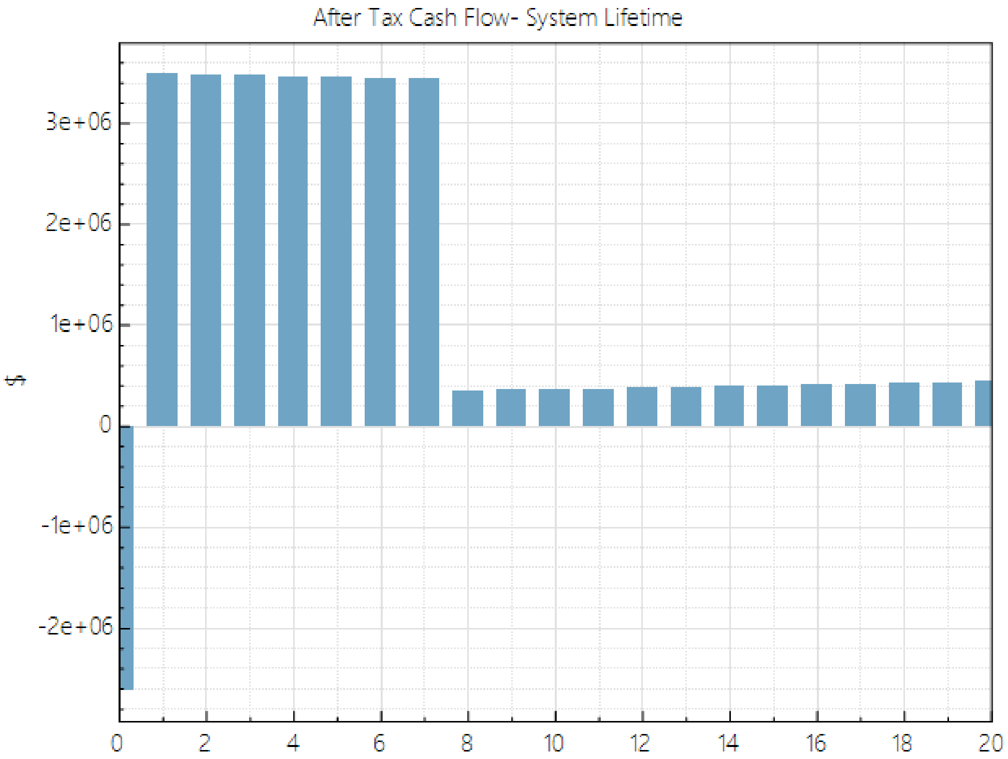


Figure 13 Cashflow of Project

Regarding the project analysis, starting in Year 1, the project has a positive after-tax cash flow, implying that income from electricity sales and incentives exceeds the project's operating and maintenance costs on an annual basis. The most evident fact on the cash flow plot is that the company's highest cash flow will be recorded in the first 7 years. This follows the depreciation scheme available in the financial model, making the amount taxable lower during the initial project years, hence higher after-sales net cash flows.

It can be seen that in the first 7 years, there is a very high net cash flow and it decreases, the reason is that feed in tariff will be paid for the first 7 years of operation as it was mentioned in the contract of PV plant that in case of revamping the updated feed in tariff will be paid for first 7 years and then the electricity will be paid as per electricity market rate. This is quite a significant decrease in revenue, as the purpose of such an incentive strategy is to discourage the revamping process. In the year in which this plant was built, the government policies were very supportive of shifting energy production from fossil fuel to renewable energy, and as the goal of the government has been achieved, in order to disincentivize the unnecessary revamping process, such policies are implemented.

The cash flow will also be financially relevant to assessing the significance of the project's initial operating performance for its net present value (NPV). Because cash flows vary over time, revenues in the initial years will have less impact on NPV than later years. Therefore, the dominating effects of Year 1 production, first degradation behaviour, and first CAPEX on the economy are evident.

6.2 Year 1 production of AC energy and electric load.

The graph about the monthly AC energy generation in relation to the monthly electric load of the first year of the operation will yield valuable information about the condition in which the PV-BESS system will be used.

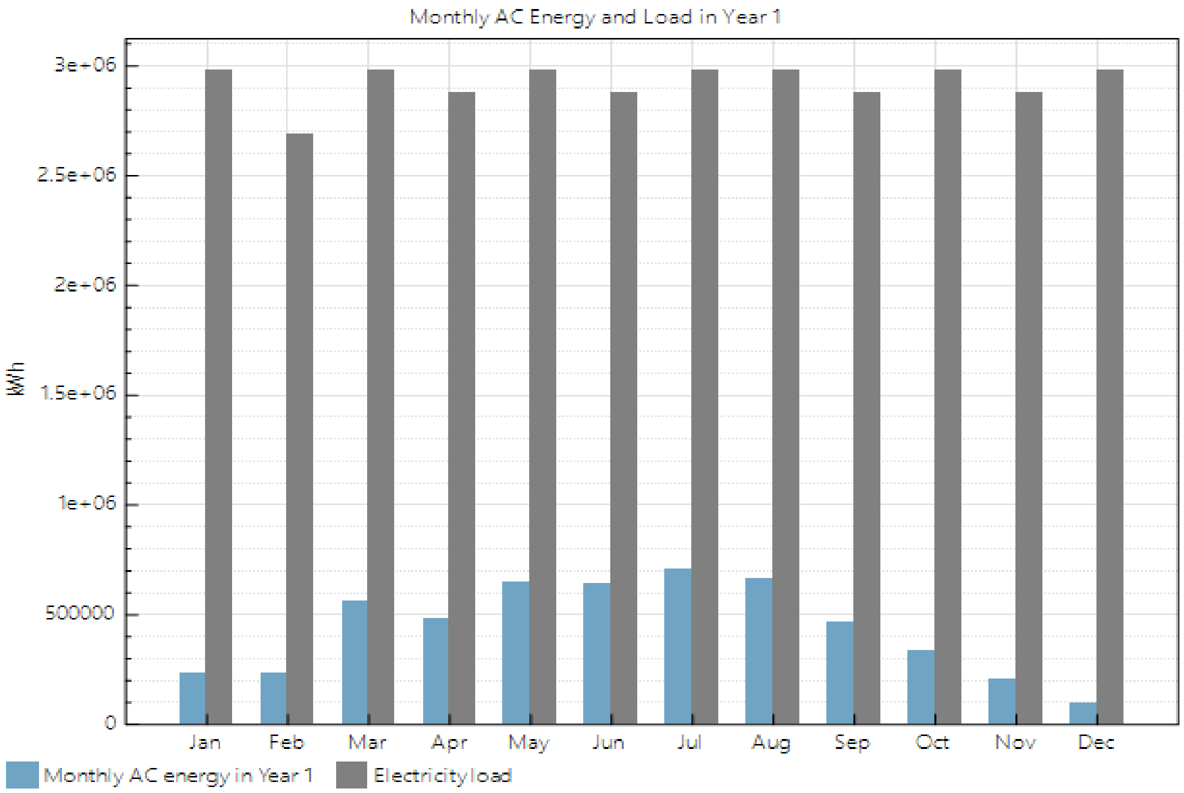


Figure 14 Production Vs Load

Peak demand is assumed to be constant throughout the year at 4MW. This is an assumption, and the reason for choosing this value is 1st that the load data were not available, 2nd that the 4MW is always above the 3.6MW nominal power. As we aim to study battery usage, this value aligns with the study's objective. As the maximum power generating capacity of the under-study PV plant is

3.6MW and the export limit is 2.8MW, the load we considered (4MW) will also exceed both the generation and export limits, allowing us to study battery usage.

The PV AC energy generation, on the other hand, is highly seasonal, with maximum energy generated at the end of spring and through the summer, and minimum energy generated in the winter. This is an annual change driven by the distribution of solar irradiation and day length, which, in turn, aligns well with photovoltaic systems in Italian climates.

Among the notable findings is that PV production has been consistently too low relative to the monthly electric load. This means that the system is essentially load-dominated, that is. PV generation cannot meet demand at any given point in the year. As a result:

- the PV system will not cause permanent energy overflow; it will only cover a part of the load, and
- BESS is basically a peak shaving and energy management tool and not a long term energy storage system.

Since the main objective of BESS is to store excess energy. The fact that majority of the time load is higher than the PV generation, therefore implies that the battery cannot be used to put any significant excess in the seasonal energy.

6.3 Year 1 Hourly-Daily AC power output heatmap.

Year 1 Hourly-daily heatmap of AC power production is a more specific level of scale of the PV system behaviour; in a both diurnal and seasonal scale.

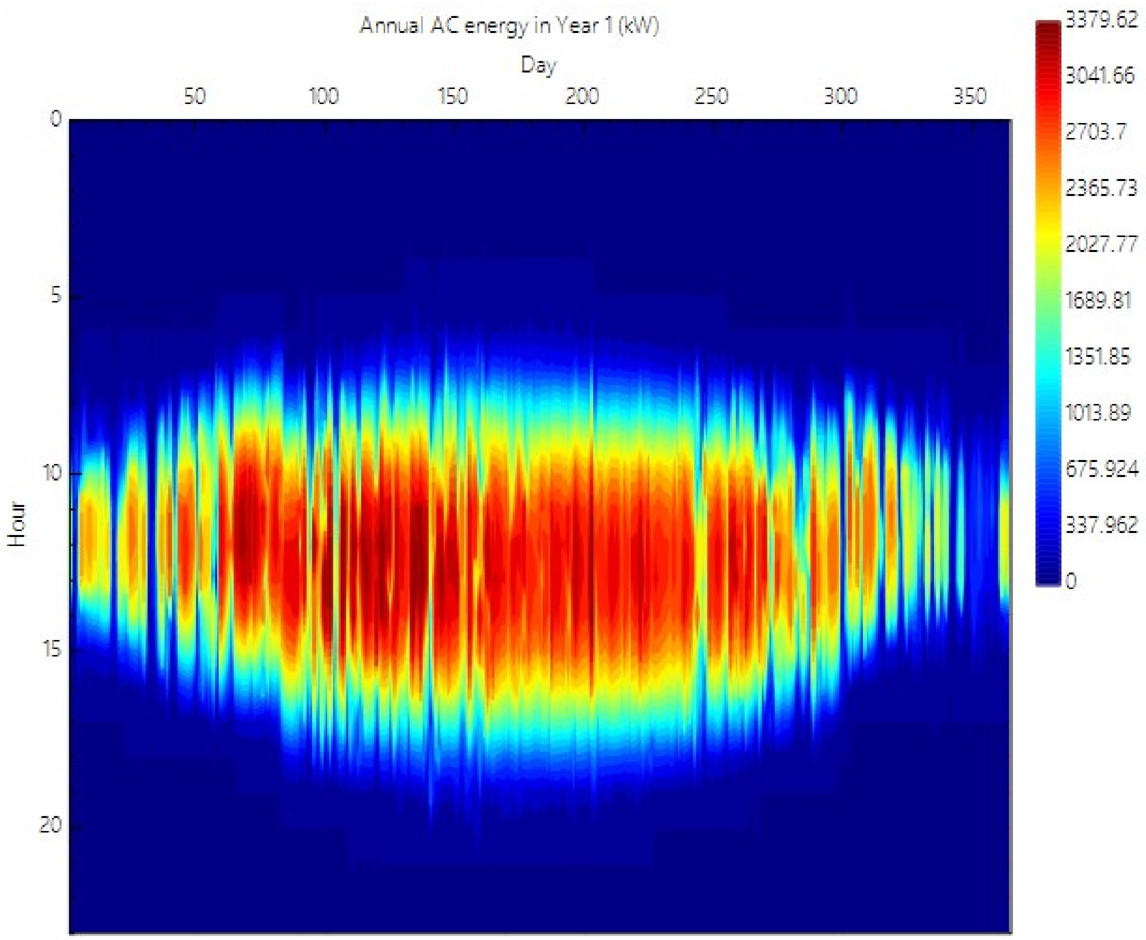


Figure 15 Production Heatmap

The heatmap indicates the production cycle is quite common in photovoltaic systems on a daily basis. During the morning, the rate of power production is high and low during the evening but zero at night. This trend can be followed throughout the whole year of 365 days, which shows the physical homogeneity of the profile of the imported generation.

One may also see seasonal effects. The power production range are higher (longer in terms of power peak) during the summer period. Conversely, winter seasons would show a reduction in production length, and peak production would be reduced. This is where seasonal modulation that is brought by the variation in the elevation and irradiance of the sun is achieved and confirms the factualness and authenticity of the simulated PV plant.

A heatmap can also be used to indicate the time of day when the PV system in use is producing successfully at or near its nominal power output. The graphical representation in this manner provides a clear physical explanation of why storage is increasing in value as PV capacity grows beyond the original PV capacity.

From the system integration perspective, the midday high-output shows that there is a strong probability of the battery being charged if the production is more than the export cap. This will attest the correctness of the BESS installation that has been selected in the management of peak power concerns as opposed to providing time-span energy storage.

6.4 Annual Net electricity generation over 20 years.

The plot under the annual net electricity generation provides the summary of the recalculated PV plant performance over the entire period of analysis.

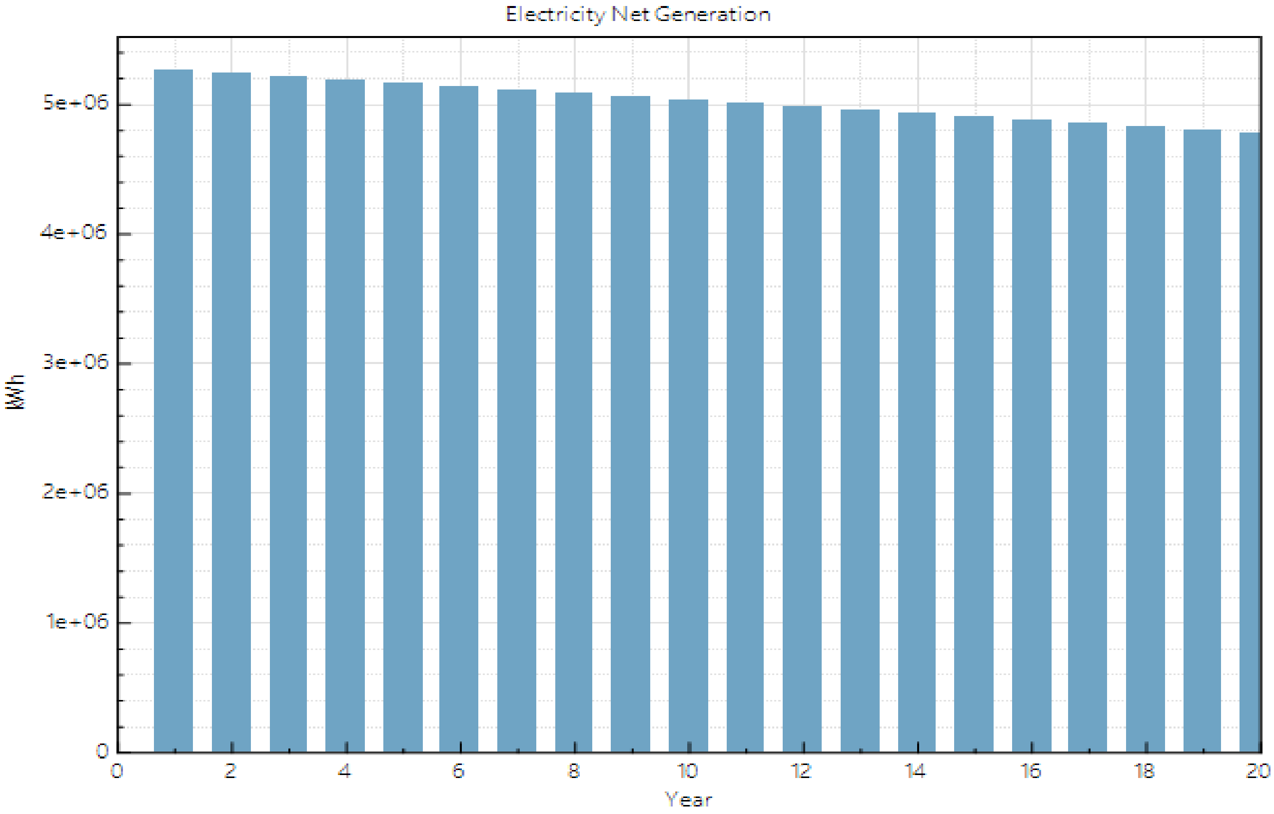


Figure 16 Electricity Net Generation

As can be seen from the plot, after Year 2, there is a smooth and gradual decrease of the annual production that follows rate of degradation set as 0.5%/year during the setup. This steady degradation could be attributed to the PV modules and other related balance of system equipment degradation, and fits with the available long-term average data of PV performance.

More important is that the decrease is not abrupt, but rather incremental, which will leave the system with a large percentage of productive potential yet to be realized, even at the project's end. It will contribute to the sustainability of the plan to revamp the plant: despite the reduction of the output to the level of degradation, even with the total 20-year life span of the plant, a lot of energy could still be extracted from the plant.

This reduction in the generation of electricity from the plant is cost-efficient but it correlates directly with a decline in annual revenue. The effect of degradation on NPV is not that significant, however, as future revenues are discounted at greater rate. This confirms the above result that the early years performance of the project is the most significant contributor of the project value though the contribution of the later years, performance is also significant but minimal.

6.5 Combination of technical and economic interpretations.

The simulation results provide a comprehensive and consistent rationale for the system's combined performance.

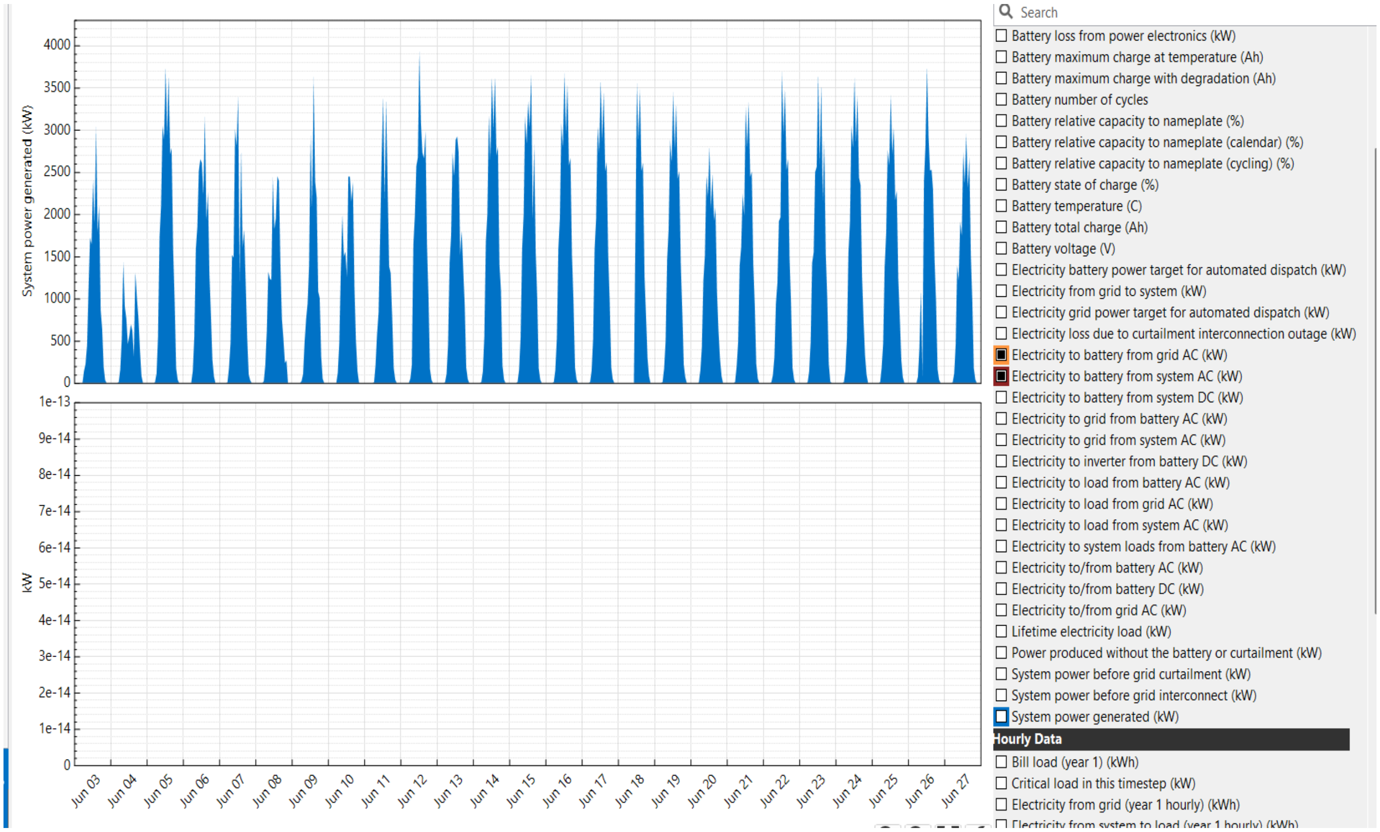
The characteristics of the revamped PV plant are high production of energy, real-life behavior on a daily and seasonal basis. The battery system primarily serves as a peak-shaving element, synchronised with PV generation and the load. Energy generation from PV is progressively reducing over time, as the system value is evaluated over the analysis period.

The economic aspects of the project are:

- A large investment cost
- Positive cash flow starting from the 1st year
- reduction of long-term revenues, which is also profitable.

These factors support the conclusion that a 20 percent revamp level with the BESS size chosen is a mix of economic and technical solutions with the best net present value and real operating conduct to grid limitations.

6.6 System Power Generation and electricity to battery:



☐ Battery loss from power electronics (kW)
☐ Battery maximum charge at temperature (Ah)
☐ Battery maximum charge with degradation (Ah)
☐ Battery number of cycles
☐ Battery relative capacity to nameplate (%)
☐ Battery relative capacity to nameplate (calendar) (%)
☐ Battery relative capacity to nameplate (cycling) (%)
☐ Battery state of charge (%)
☐ Battery temperature (C)
☐ Battery total charge (Ah)
☐ Battery voltage (V)
☐ Electricity battery power target for automated dispatch (kW)
☐ Electricity from grid to system (kW)
☐ Electricity grid power target for automated dispatch (kW)
☐ Electricity loss due to curtailment interconnection outage (kW)
☒ Electricity to battery from grid AC (kW)
☒ Electricity to battery from system AC (kW)
☐ Electricity to battery from system DC (kW)
☐ Electricity to grid from battery AC (kW)
☐ Electricity to grid from system AC (kW)
☐ Electricity to inverter from battery DC (kW)
☐ Electricity to load from battery AC (kW)
☐ Electricity to load from grid AC (kW)
☐ Electricity to load from system AC (kW)
☐ Electricity to system loads from battery AC (kW)
☐ Electricity to/from battery AC (kW)
☐ Electricity to/from battery DC (kW)
☐ Electricity to/from grid AC (kW)
☐ Lifetime electricity load (kW)
☐ Power produced without the battery or curtailment (kW)
☐ System power before grid curtailment (kW)
☐ System power before grid interconnect (kW)
☑ System power generated (kW)

Hourly Data

☐ Bill load (year 1) (kWh)
☐ Critical load in this timestep (kW)
☐ Electricity from grid (year 1 hourly) (kWh)
☐ Electricity from system to load (year 1 hourly) (kWh)

Figure 17 System Power Generation and electricity to the battery

One of the key results of the simulation is the discrepancy between the battery system's operational behaviour and economic optimisation. The economic screening was conducted in Excel, and the scenario optimisation was performed through extensive simulation in the System Advisor Model (SAM). The scenario that made the highest Net Present Value (NPV) of all scenarios investigated in the case was the 20% PV revamping and the 250 kW BESS.

A glance at the bottom section of the graph above shows that, in such an arrangement, the battery is not used in the process at any point, and the AC output of the PV plant never approaches the required limit of the grid interconnection. This elaborates on this observation and why it may result in the conclusion that 20 percent revamping with no BESS will be the best and cost-effective consideration.

6.6.1 Operation of 20 percent revamping + 250 kW BESS case.

The timeseries plot of power generation shows the actual power produced by the system. The plot shows the peak energy production during the daytime as expected by the PV system. It is intriguing to note that the system output remains lower than the interconnection limit with the grid even when operating at the maximum irradiance during the entire life of the PV system.

This fact directly affects the operation of battery. The BESS main activity within the proposed control solution will be to absorb the surplus PV beyond the export limit at the peak output of the power production. As a result, we can conclude that there is no energy which will be capped by the export limit, thus there will be no incentive to have a BESS system.

The fact that the power in the battery was almost zero as measured in the simulation is confirmation that the BESS is virtually idle throughout its operating range. It implies that by performance consideration, the battery is not contributing in the energy recovery or peak shaving.

6.7 NPV Comparison:

BESS Power(kW)	BESS capacity(kWh)	NPV at 20% revamping (€)	NPV at 25% revamping (€)	NPV at 30% revamping (€)	NPV at 40% revamping (€)	NPV at 45% revamping (€)	NPV at 50% revamping (€)
250	1000	14278811	14226775	14174740	14070669	14018633	13966598
500	2000	14113319	14061283	14009248	13905177	13853141	13801106
750	3000	13948011	13895976	13843940	13739869	13687834	13635798
1000	4000	13909295	13730675	13678639	13574568	13522533	13470497
1500	6000	13451903	13399868	13347832	13243606	13191726	13139691

This section presents a comparison of NPV values computed over a 20-year lifespan of a PV plant to provide a comprehensive economic outlook of the revamping study. The simulations were conducted in SAM for all the options considered, which were 20%,25%,30%,40%,45%,50% revamping options and BESS configurations of 250kW, 500kW, 750kW, 1000kW and 1500kW having capacity of 1000kWh,2000 kWh, 3000 kWh,4000 kWh and 6000kWh, respectively. All of the NPV values are in euros with FiT for each case according to the formula mentioned in the above sections and a constant selling price.

The highest NPV was found for a 20% revamping with a 250kW BESS of 1000kWh capacity, yielding an NPV of 14278811€. This configuration has the highest NPV value as compared to other options due to the following reasons.

- The FiT penalty is lowest in the case of 20% revamping. In case of 20% increase in capacity, the FiT is reduced from 0.484€/kWh to 0.434€/kWh, but this reduction is still less than the other cases, making this case more cost-effective than others.
- This configuration has the least capacity among all the options, causing its direct capital cost to be lower than that of others. Since Figure 17 shows that the battery was idle throughout the PV plant's operation, as generation never exceeded the grid interconnection limit (2.8MW), this smaller battery incurs a lower capital cost and yields the highest NPV. Although we have already concluded that the BESS system will not be used, it will be an even more cost-effective option.
- The operating and maintenance costs depend on the battery capacity. During our study, we set 5$/kWh year as the O&M cost, so the 1000 kWh BESS will have 5000$ in O&M cost, and the 6000 kWh BESS will have 30,000$ in O&M cost. When this cost difference is discounted over the 20-year operating period, it makes a meaningful impact on NPV.

Now the question arises: why did we start with 20% revamping and 250kW BESS options? The reason for choosing 250kW was that commercial-level BESS starts at 250kW, and even though we choose 100kW or 50kW BESS, there will still be no energy available to store. During the Excel screening process, based on the first 7-year production data available, only 681kWh were available, which were capped by the export limit and needed to be stored; their value, compared to the total cost of the BESS system, is negligible, making the BESS system financially inefficient. If we choose 50kW, 200kWh BESS, a major portion of the capped energy(580kWh) can be stored, but still, compared to the investment, operation and maintenance cost, the benefits are very low, so we chose not to use any BESS system.

And the reason for choosing 20% revamp option was that we considered the increase in efficiency because of the panels upgrading to be between 15 and 20 per cent, making enough space to increase the capacity of the plant by 20 per cent. Although 10 per cent or 15 per cent revamping options were available, we wanted to make full use of the space available. It is quite possible that by increasing the capacity of the plant by 10 per cent, the NPV value is higher, but the space available will not be used, decreasing the NPV value again.

We can see that there is a clear and consistent pattern across all revamping scenarios, when the BESS power rating increases, NPV declines. This monotonic decline can be explained by the absence of revenue increase by increase of BESS power, because no surplus amount of energy is available to be absorbed. If we install a BESS with higher capacity, it just increases capital and O&M costs. The similar downward trend can also be noted in case of increase revamping level, which is that NVP decreases with increase in revamping capacity. This decrease is attributed due to decrease in NPV

The practical implementation is straightforward, in the PV plant under study, which is under restriction of interconnection to the grid and with decreasing FiT with increase in capacity, BESS addition is economically detrimental, making the option of revamping(20%) with no BESS the only viable option.

6.8 Discussion:

The thesis paper examined the technical and financial feasibility of revamping an existing 3.0 MW photovoltaic (PV) power facility and integrating it with a battery energy storage system (BESS) under grid export limitations. The study involved production analysis, parametric economic optimisation, and simulation of time-resolution using the System Advisor Model (SAM). At the end of the paper, the key findings obtained during the development of this coordinated approach are summarised, and implications of the findings in terms of redesign and the investment options available, referring to the plant upgrade strategies, are presented, and it is on the overall evaluation of the findings within the context of PV plant redesign.

6.8.1 PV revamping when limited by grid export cap.

One of the most important findings from the research is that moderate PV revamping can be useful to a considerable extent, even under the stringent export grid limitations. It can then generate more energy in a year. A 20 percent increase of the nominal rated installed capacity increases the energy yield while still operating within the grid interconnection limit. This challenges the common perspective that the grid export cap always acts as a rigid barrier to the economic growth of PV system.

The results show that combining high installed capacity with high module efficiency can increase energy yield without causing curtailment. This highlights that, for the current PV plants, revamping can be a highly effective step to extend lifetime revenues, without concern for changes to the grid limit, provided the degree of revamping is executed properly.

6.8.2 Role and limits of BESS integration

Identifying whether BESS integration would make PV revamping more viable under a grid export constraint was one of the aims of the thesis. Initial optimization results showed that the case that featured 20% PV revamping and 250 kW BESS was a cost-effective option. However, it was determined through simulation that in such an arrangement, the battery is not actually utilized.

This finding highlights a very significant point: the battery system is economically justified only when energy production exceeds the grid export limit. The grid constraint is not reached even at analysis before, and after revamping, i.e. there is no additional energy to absorb by the battery. Thus, the BESS does not contribute to an increase in energy sales, the minimisation of peaks, or operational flexibility.

From an engineering perspective, this reveals that storage is not a mandatory component of PV revamping. Instead, it relies on requirements that require the dependency of the systems, such as export cap, load patterns, market rates, and frequency of curtailment. In the absence of such drivers, storage becomes expensive and in addition that does not provide a sustainable benefit.

6.8.3 Relevance of integrating economic optimization and time-series simulation.

The lack of alignment between the prioritization offered by the NPV and the real operation of the system highlights the importance of accounting for the integration of both economic analysis and time-related particular time-series simulation. While a simplified economic model is useful to screening, it does not account for all the factors that influence the performance of a system under real-world conditions.

In this thesis, the use of SAM provided insight into detailed hourly and seasonal behavior, since the battery was not used in the most cost-effective manner. It shows that NPV alone is not a sufficient factor when making the optimal system design. A design may appear economical at the macro level, but it can include features that are not functional.

This is the mixed approach applied in this study: optimization, followed by a comprehensive simulation, which plays a crucial role in selecting the best solution based on economic and technical considerations. Future researchers who plan to carry out research on hybrid renewable energy systems can use such an approach as a guideline.

6.8.4 Investment and system design implications.

The results of this thesis for investors, PV plant owners, and the design team include the following:

- Revamping can be profitable: small increases in the power of PV, along with high-efficiency modules, can cause large changes in the economics of the project, without requiring grid upgrades.
- Storage should also be cost-effective: BESS is supposed to create sufficient opportunities during an event of energy shifting or peak management since there must be a curtailment, peak charge or variable price.
- Simpler systems can also be more appropriate: More complex systems are not always the most feasible way of solving. In certain cases, the system of proper optimization of PV-only revamping can be better than more complex PV-plus-storage systems.
- Grid limits should be taken into account dynamically: Static assumptions of grid limits may hinder the potential of making the changes. To determine whether constraints are binding, a time-series analysis is required.

6.8.5 Limitations of the study and future research:

Despite the clear and precise findings of this study, there are still some limitations. It analyses a predetermined electricity selling price and a simplified model to calculate the feed-in tariff. The value of the study would be enhanced by accounting for price volatility and the evolution of the regulatory environment in real markets. Further, the load profile is assumed to be steady, with no changes over time in the simulation, as demand growth or demand-side regulation can alter battery utilization trends.

Future research can be done based on this research by exploring the following areas:

- installing dynamic prices or time-of-use tariffs on electricity markets,
- Curtailment is an important consideration when the greater rates of revamping are studied.

- Considering other storage plans or hybrid storage systems.
- how regulatory incentives on flexibility services can impact the system.

6.9 Conclusion:

The technical and economic considerations of revamping an existing 3.0 MW photovoltaic (PV) power plant and integrating it with a battery energy storage system (BESS) to a controlled grid export situation were discussed in this thesis. This study was driven by the increased need to maximize energy generation and economic performance of the already available renewable energy sources, keeping the regulatory and other infrastructural limitations in mind. The combination of historical data about production, parametric economic analysis, and the detailed analysis with the assistance of the System Advisor Model (SAM), the thesis provides a comprehensive assessment of the revamping and storage approach and determines the most viable solution to the system of analysis.

The analysis began with 7 years of actual production data from the existing PV plant, which provided a strong foundation for assessing its performance. A series of revamping cases have been considered where percentage changes of PV capacity increase, which are moderate to significant. Another factor in demonstrating improvements was the technology improvement parameter, which claimed that the efficiency of the PV module and the price of the electricity sold are constant and stable throughout the project's life. The export grid imposed capacity limits on interconnections, which are realistic operational constraints for most existing PV installations.

To preliminarily screen the economics, a spreadsheet-based computation was performed to identify the most effective option for revamping. Based on this screening, the most promising configurations are now selected to be further detailed simulated in SAM, where time-series production with energy, battery behavior, degradation effect, and financial performance have been simulated over a 20-year horizon.

The results suggest that PV revamping increases net energy. In the scenarios which were evaluated, a PV capacity increase of 20 percent was unanimously considered good in the attainment of good economic output, in addition to the ability to remain under the grid export constraint. The first economic analysis showed high cost-effectiveness when battery storage was considered, with production at 250 kW BESS. However, in a more detailed simulation, when the battery was simulated, this setup assumed that the battery was not powering in use, since the PV system output cannot exceed the grid interconnection limit.

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