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REPORT OF THE PROJECT FOR THE COURSE ELECTRIC POWER SYSTEM

Photovoltaic Systems Integrated with Energy Storage: A Comprehensive Financial Evaluation Model for Sustainable Investments in Italy

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1. Abstract

Photovoltaic technology is the fastest growing technology in the world. In order to achieve net-zero emissions by 2050, there has to be a further increase in the average annual generation growth which will require stronger policies and more efforts from the public and private stakeholders. The stakeholders measure the value of the investment in terms of its profitability. The profitability of a photovoltaic system depends on the performance of the photovoltaic system and there are several factors which affect the power generation. This report incorporates some of the factors and proposes a mathematical model to evaluate the financial feasibility of a photovoltaic integrated with an energy storage system in Italy.

2. Introduction

The global capacity of solar PV generation has nearly tripled over the last half-decade, increasing from 304.3 GW in 2016 to 760.4 GW in 2020. Solar power has been the fastest-growing power source globally, comprising 50% of global investment in renewable energy from 2010 to 2019 and ranking first in net added generation capacity.

Photovoltaic generation increased by a record 156TWh (23%) in 2020 to reach a total of 821 TWh which demonstrates the second largest absolute generation growth of all renewable technologies in 2020. However, the Net Zero Emissions by 2050 Scenario shows average annual generation growth of 24% is required between 2020 and 2030 which will require strong policies and more efforts from both public and private stakeholders[1]. Installing a photovoltaic system is a considerable amount of investment and the value of any investment is measured by computing the profitability of the investment.

Therefore, the profitability of PV-integrated battery systems is a topic discussed in the work. In this report, the net present value is an indicator which is being used. It has been shown that profitability varies in a meaningful way and

Self-consumption is one of the most crucial parameters. It has been shown how the PV generation increases with a decrease in self-consumption. This report investigates the financial feasibility of a photovoltaic system alone and also for a photovoltaic system integrated with energy storage system(ESS) in an Italian region. Incorporated variables are PV plant size, Irradiation at the location, load, costs(PV and tariffs) energy storage size, self-consumption values and useful lifetime of the energy storage system(ESS). MATLAB is used for the complete analysis. For the analysis and optimization to size a suitable photovoltaic system and energy storage, MATLAB is used. The report is divided into different sections. Section 3 summarises the mathematical model used to evaluate the financial feasibility of the photovoltaic systems with and without the energy storage system. Section 4 explains the base case for evaluating the net present value, base case being the case when the project is not installed. Section 5 and Section 6 summarise the methodology used to calculate the yearly expense for the project in which only the photovoltaic system is installed and for the project in which the photovoltaic system is integrated with the energy storage system. Then from the yearly expense, NPV(Net present value) is evaluated for both the projects. Section 7 presents the results obtained and contains the concluding remarks.

3. Methodology

The mathematical model that is incorporated in this study is called Discounted Cash Flow which is a valuation method to estimate the value of an investment based on the expected future cash flows. An incremental approach which considers only cash inflows and outflows and an appropriate cost opportunity of capital is used to aggregate the cash flows. The financial index which is used in this project is NPV (Net present value) which is the difference between the present cash inflows and the present cash outflows and is used to measure the feasibility of the project.

In the discounted cash flow model, the monetary value to be received in the future has to be discounted to the present value based on the Interest Swap Rate. For example, the value of 100 cents may reduce in the future to today's value of 50cents due to inflation. The discounted price is then added to calculate the net present price (NPV).

The general cash flow scheme can be visualized in the fig1;

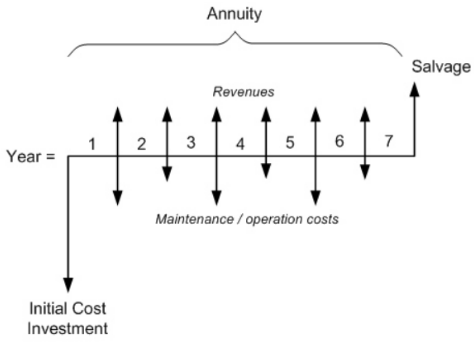


Figure 1: General cash flow scheme

Investments such as initial cost and maintenance costs are considered negative cash flow whereas the estimated revenues are considered positive cash flow. Cash flows estimated in future are discounted to the current value and then summed up to evaluate the net present value of the project. In this report, first, the base case is evaluated by considering all the negative cash flows in 20year which are essentially the bills paid towards the electricity consumption. Then this NPV is compared with the other projects.

If the net present value of the project is better than the base case then the project is considered profitable. The following table summarizes the concept of NPV:

Years	Cash Flows	Discount Factors @10%	Present Value
0	- Initial Investment	100.00%	
1	+ Revenue	90.90%	
2	- Maintenance	82.60%	
: :		75.10%	
		NPV:	∑ Sum of all elements in the column

Table 1: Methodology to compute NPV

Therefore, the following are the steps that compose the decision-making process:

1. The base case is taken as the reference with the PV system and ESS not being installed and the energy directly being bought from the grid. The electricity being drawn from the grid is priced at 30€cent/KWh. NPV is calculated based on the price to be paid in 20 years, this NPV can be called NPV(Base).

2. After the installation of the photovoltaic system(PV), NPV is evaluated by computing the yearly cash inflow and outflow. This NPV can be termed NPV(PV). If NPV(PV)> NPV(Base case) then the project is considered to be profitable.

3. If installing PV is considered profitable then the investor may also opt to install the energy storage system integrated with the PV system. Therefore, the profitability of the PV-integrated battery system is evaluated, if NPV(PV + ESS) > NPV(PV) then the project is considered profitable, However, if the NPV(PV + ESS)<NPV(PV) then the project is discarded as installing only the PV plant is more profitable.

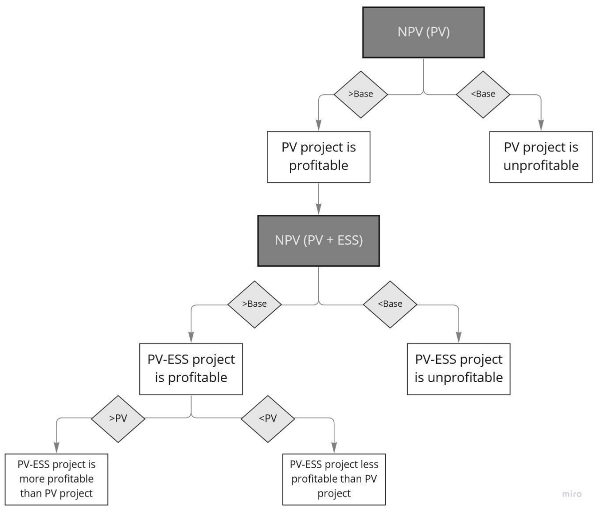
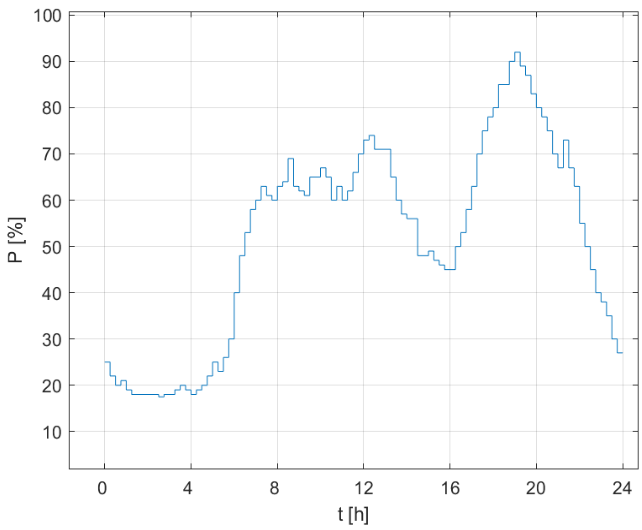


Figure 2: Decision-making process

4. Base Case Analysis

In this section, a cost analysis of base-case is presented. The base case is the system without PV and Energy storage system installed. To analyze the case, load data has to be considered. There can be different kinds of loads and depending on that there can be different load profiles. In general, there can be two kinds of load profiles, commercial and residential. In this report, the residential load is being analyzed. To analyze the load in each 15 min time block, the nominal value of a 2.5KW residential load is considered which is

Figure 3: Load profile



then multiplied by the residential load profile given in percentages of the nominal value in each time block. Figure 3 represents the load profile of a residential type load in the percentage of its nominal value. The total price paid in a day is given by the sum of the product of consumption unit in each time block and the unit price which is considered to be 30€c/KWh.

$$\Sigma\,(Consumption\ units(KWh)\ \times\ Unit\ price(€/KWh\,))$$

This sum is then multiplied by the number of days in a year to calculate the total price paid towards the electricity consumption in a year. Based on this value, discounted cash flow method is used to calculate the NPV for 20 years.

5. Photovoltaic system

5.1 Location

To analyze a project with a PV system installed, information about the location is of the utmost importance as the global horizontal irradiation varies from one location to other due various geological factors. In this report, the selected location is in the region of Sicily,Italy. The irradiation data in 15 min resolution is collected for each day and each month. For the analysis, one representative day is taken from each month and time blocks from 5 AM to 7 PM are considered (a total of 57-time blocks) for each month i.e. January to December. Therefore mathematically a matrix of the size 57 X 12 is analyzed. Fig. demonstrates the varying irradiation levels of each month in a year in W/m^2

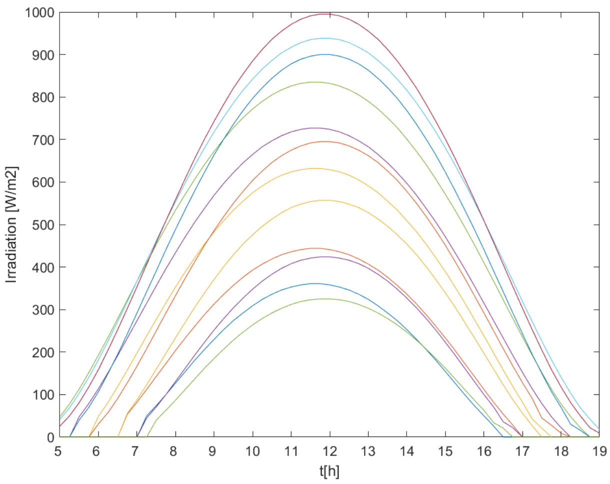


Figure 4: Irradiation in W/m^2 for each month

5.2 Different Technologies:

The relationship between the irradiance (W/m^2) and power obtained (W) may not be linear in nature and it depends on the technology that has been chosen.

Mathematically, the relationship between irradiance and power can be given by the following equations:

- Mono-crystalline silicon (mc-Si):
  $0.000898 \text{ X } Irr - 0.0138$
- Amorphous silicon (a-Si):
  $0.001 \text{ X } Irr - 0.074$
- Copper indium gallium selenide (CIGS):
  $-0.0000004 \text{ X } Irr^2 + 0.0012 \text{ X } Irr - 0.0187$

In the figure it can be seen that as the irradiance value is increasing, non-linearity is more prominent in case of cylindrical CIGS than the other two technologies. In this report, mc-Si technology is opted for the analysis.

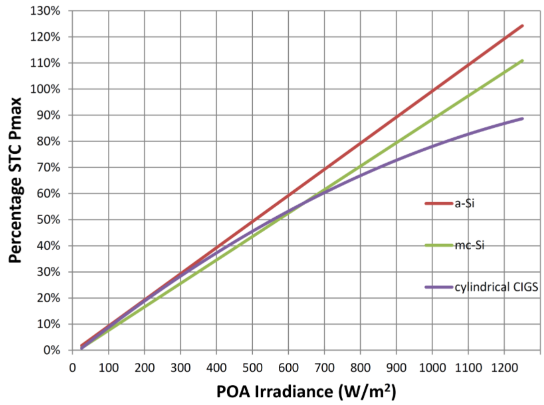


Figure 5: Percentage STC vs Irradiation

5.3 From Irradiance to Power

To demonstrate the power produced for a given technology, efficiency, η is set to 90% and the nominal value of the PV is assumed to be 1. Other variables like mounting position, tilt and azimuth angle are assumed to be at optimal conditions having optimum values. Thus, power generated by PV can be calculated using the following equations,

Power produced by PV (mc - Si) :

$$\eta*(0.000898 \text{ X } Irr - 0.0138) *y$$

Power produced by PV (a-Si) :

$$\eta*(0.001 \text{ X } Irr - 0.074) *y$$

Power produced by PV (CIGS):

$$\eta*(-0.0000004 \text{ X } Irr^2 + 0.0012 \text{ X } Irr - 0.0187)*y$$

Based on the above equations, the following graphs are plotted for each technology:

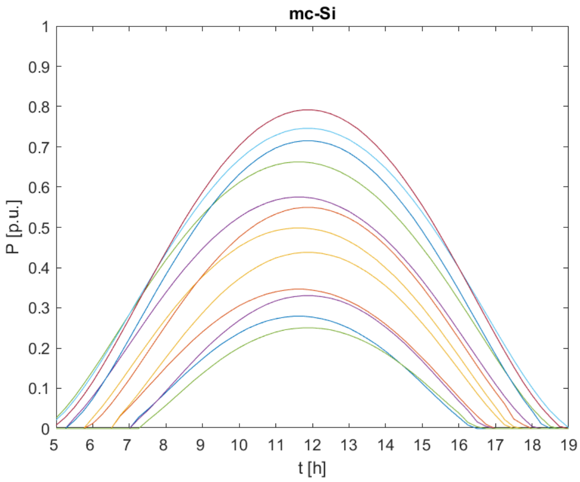


Figure 6: Power in PU for each time block for Mono-crystalline silicon technology

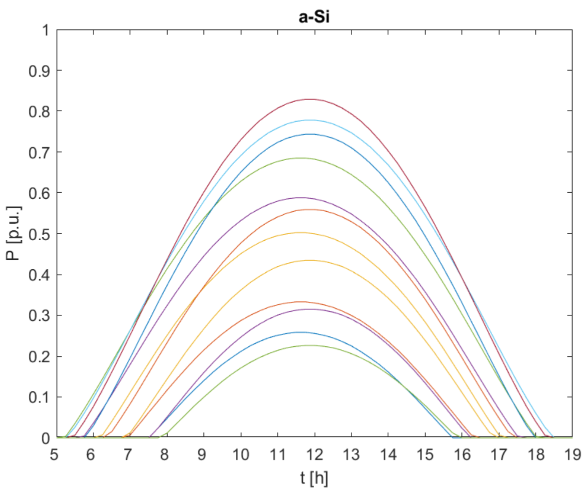


Figure 7: Power in PU for each time block for Amorphous silicon

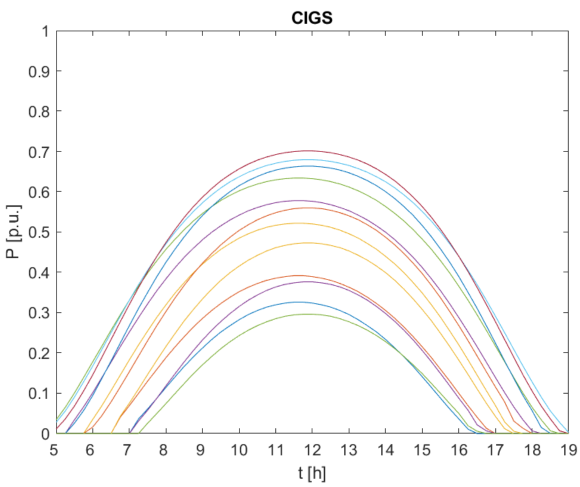


Figure 8: Power in PU for each time block for Copper indium gallium selenide

5.4 PV Window:

PV window can be defined as the time during which global horizontal irradiance reaches the earth's surface in other words, only during this time the panels can produce electricity among 96-time blocks. For each month the PV differs significantly therefore the amount of load that can be supplied by the PV system is different for each month. In the following figure, the PV windows are marked for each month,

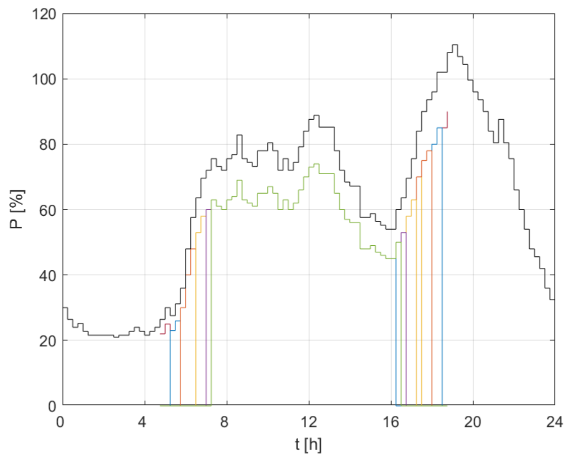


Figure 9: Load values that can be supplied in each month

Different colours represent different months, and maximum power can be yielded in the months of May, June and July.

5.5 Load vs PV based on self-consumption

Photovoltaic self-consumption occurs when stakeholders consume the energy produced by the photovoltaic system installed by them which leads to a reduction in their electricity bills. There are two types of photovoltaic self-consumption:

1. Self-consumption without surpluses
2. Self-consumption with a surplus

In the first case, installation prevents excess energy from being exported to the grid. The energy storage system is not required as 100% of the electricity is consumed by the local load.

Nominal power of the PV system is selected based on the self consumption value using the constrained nonlinear optimization in MATLAB.
After the nominal power of PV based on the self consumption value is estimated, then for the

mc-Si technology, power generated in each month for given irradiation is plotted and compared against the load values of each month which varies depending on the PV window of different months as shown in fig 9. Figure 10, represents the case when self-consumption is 100%. The power produced on an average matches the average value of the load in a day. But since the irradiation is lower in other months, the power supplied by the PV falls short compared to the load.

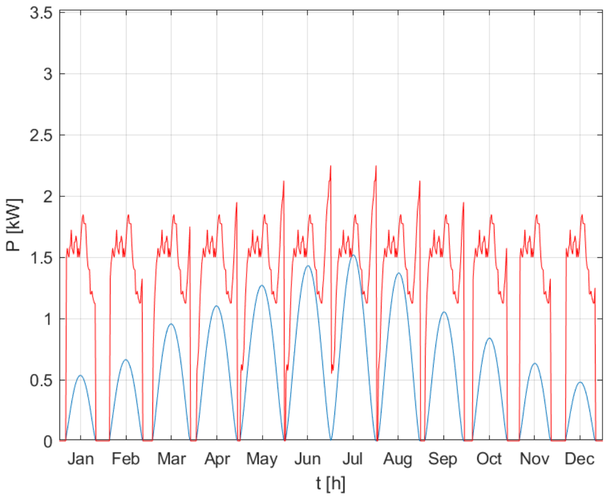


Figure 10: Load values that can be supplied each month self-consumption @ 100%

In the case of self-consumption with a surplus, installations allow the generation of surplus energy which can be exported to the grid to gain benefit from the profits made by selling the electricity to the grid. Furthermore, energy storage systems can also be installed to store the energy produced instead of selling it to the grid. Installing an energy storage system can have numerous benefits like demand charge reduction, maximization time of use rates, emergency backups etc.

The following figure represents the case when self-consumption is 90%. The power produced on an average is 10% higher than the average value of the load.

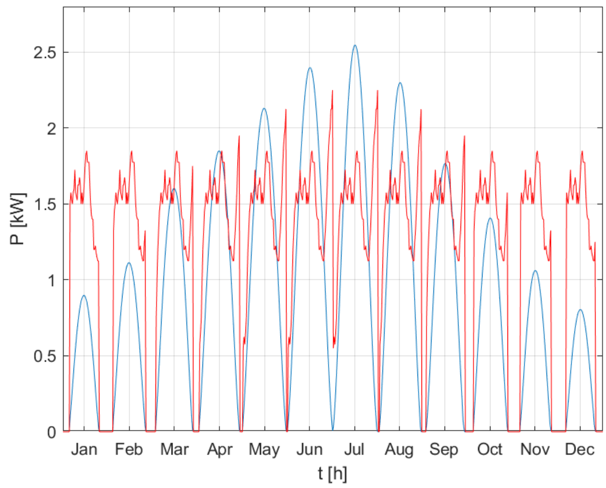


Figure 11: Load values that can be supplied each month, self-consumption @ 90%

The above analysis proves that in order to gain more profits from the PV system, the self-consumption value has to be as less as possible, however, that also means the size of PV has to be increased significantly which means a very high initial investment. The following figure represents the trend of initial investment required to install a PV system versus the self-consumption percentage.

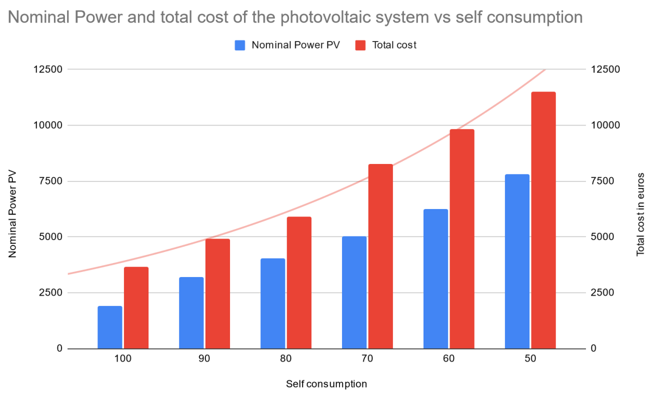


Figure 12: Initial investment based on self-consumption value

In the above figure, it can be witnessed that the cost of the PV system rises exponentially with every decrease in self-consumption value.

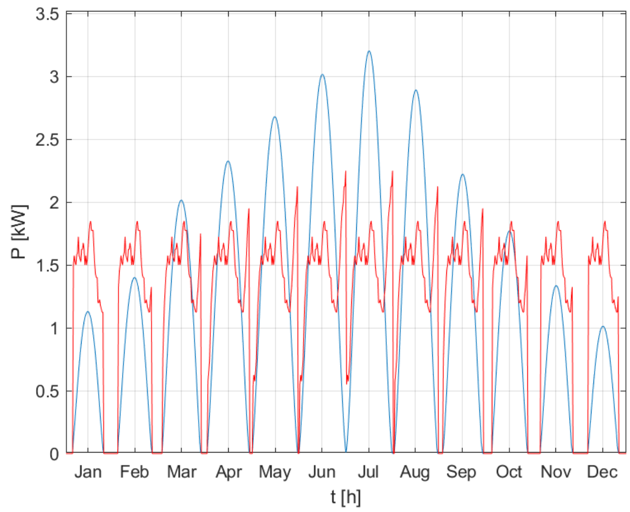


Figure 13: Load values that can be supplied in each month self-consumption @ 80%

With 80% as self-consumption, the load is being supplied by PV in the majority of the months at minimal installation cost. Profits can also be made apart from serving the load as there's a high yield of power from PV during the months in which there is high irradiation. More profits are expected with the decrease in self-consumption values however there's a high installation cost associated with it. Therefore, for further analysis self-consumption of 80% is considered.

5.6 Methodology to compute the NPV for the project with the photovoltaic system.

In the base case scenario, the load is supplied by the grid. When the photovoltaic system is installed, the load is being supplied by the grid only when the power produced by the photovoltaic system is less than the power consumed by the load i.e., power produced by PV - power consumed by the load is negative. This difference is negative during the time when the sun is not shining, which is from 7 PM - 5 AM (Non-PV window). The difference is also negative in the PV window when the irradiance is not enough for high power yield which is mostly the case in winter months as indicated in fig 13. When generation from the photovoltaic system is not higher than the load, part of the load is supplied by the photovoltaic system and part of it is supplied by the grid which helps in bill reduction.

A high yield of power is expected during the summer months, surplus power generated is then can be sold to the grid to make more profits. The surplus power is sold to the grid at national PUN prices.

The pseudo algorithm of the matrix operations that are done in MATLAB is as follows:

Algorithm: Calculate the yearly price for the PV project

Power difference = PVoutput - load
Energy difference = Power difference/4
for all the elements in 96 X 12 matrix of Energy difference :
  if Energy difference < *0* **then**
    Bill paid = Energy difference *grid_price
  else
    revenue = Energy difference*monthly_PUN

Sum bill paid and revenue for each day and for each month (column) of the year to calculate the yearly price.

With the help of the above algorithm, the net price paid to the grid is evaluated for each year and the discounted cash flow method is applied to calculate the NPV for 20 years.

6. Photovoltaic system integrated with energy storage system

As mentioned earlier, if the PV project is considered profitable then investors can opt to install the energy storage system for all the benefits it brings in. Operators seek to maximize the returns from their PV systems however after the installation of an energy storage system there is a big challenge of storage degradation which forces the investors to do more investments which means negative cash flow in the 20 years run.

Storage degradation is a huge economic problem which will vary according to how the battery is used, and which leads to various problems like reduced energy capacity, power efficiency etc. For the sake of simplicity, the only factor that is considered is the number of cycles. A number of cycles in this work define after how long the storage has to be replaced by new storage which will increase the cost. The number of cycles is kept at 5000 cycles. Specific energy is kept at 200 Wh/Kg and the specific power is kept at 300 W/Kg.

The following equation is used to evaluate the number of cycles,

$$\frac{\sum_{\tau=1}^{N-1} \left|\mathrm{SoC}\left(\tau+1\right)-\mathrm{SoC}\left(\tau\right)\right|}{2\left(\mathrm{SoC}_{\max}-\mathrm{SoC}_{\min}\right)}$$

To select the nominal power and energy for the energy storage system, the following equation is used,

$$\begin{aligned}\bar{P}_{\mathrm{nom}}^{\mathrm{ESS}} &= \max_{\tau}\left(P_{\mathrm{pv}}\left(\tau\right)-P_{\mathrm{load}}\left(\tau\right)\right)\\ \bar{E}_{\mathrm{nom}}^{\mathrm{ESS}} &= \Delta t \max_{w} \sum_{\tau=k}^{k+N-1}\left(P_{\mathrm{pv}}\left(\tau\right)-P_{\mathrm{load}}\left(\tau\right)\right),\\ & k=1+N\left(w-1\right),\ w=1,\ldots,365\ N\in\{24,96\}\end{aligned}$$

From March to October, during the non PV window of the day (7 PM - 5 AM) the energy is bought from the grid and during the PV window load is supplied by the PV. The surplus energy is stored in the energy storage system. Considering the SOC to be at 0%, the energy storage starts charging when the PV energy is greater than the load and starts discharging right when the PV energy becomes less than the load. Therefore, compared to the previous case, where the surplus energy is sold to the grid, in this case, the surplus energy is stored in the energy storage system. This surplus energy is stored and discharged right after the difference between PV and load is negative. Once completely discharged, energy is then bought from the grid for the subsequent time blocks. To evaluate the state of charge, the following equation is used,

$$\mathrm{SoC}\left(\tau\right)=\mathrm{SoC}\left(\tau-1\right)+\frac{\Delta t P_{h}^{\mathrm{ESS}}}{E_{\mathrm{nom}}^{\mathrm{ESS}}}$$

This means after a point in a day when PV is not able to supply the load completely and only a part of the load is supplied by the PV, the other part of the load is either taken care of by the energy storage system which is limited to the amount of energy stored or by the grid. The price to be paid during the charging and discharging of the ESS is null. In this way installing a storage system can help further reduce the energy bills as instead of selling the energy at a lower price compared to the buying price of the grid, the energy system allows for the consumption of the surplus units when the load is greater than the PV production.

However, energy storage will be considered non-profitable if the load is high and the surplus is low to charge the storage system. In that case, investors can make more profit by selling the surplus than consuming it in 2-3 time blocks. Therefore, if the amount saved by not paying 30 €c/KWh is greater than selling energy at PUN price then ESS is more profitable otherwise it's profitable if only install PV system is installed. Further, in the winter months when the PV generation is not higher than the load, part of the load is supplied by the PV and part of it is supplied by the grid and there is no involvement of the energy storage system during this period.

Algorithm: Calculate the yearly price for the PV+ESS project

```
Power difference = PVoutput - Power load
% for charging :
for all the elements in 96 X 12 matrix of
Power difference :
  if Power difference > 0 then
      SOC(t) = SOC(t-1) +
      0.25*(Power difference(+ve)/nominal energy)
      Stop at 100%
  % for discharging:
for all the elements in 96 X 12 matrix of
Power difference :
  if SOC(t-1)< 0 AND SOC(t) = = 0 then
      SOC = SOC +
      0.25*(Power difference(-ve)/nominal energy)
      Stop at 0%
  % Create a price matrix:
for all the elements in 96 X 12 matrix of
Price matrix
  if SOC > 0 then
```

4: Price = 0
5: else
: Price = grid_price

8: Total price = price*each element of energy differen
9: Sum of total price for each day for each month (col
of the year

7. Result and Conclusion

7.1 Sizing of the PV system and Installation cost

Considering the monocrystalline silicon technology and keeping 80% as the self-consumption value, the obtained nominal power output of the PV system is 4.043 kW and as per the quotation provided by Conergy, there can be 4 different options: 15 panels of 270W, 15 panels of 275W, 16 panels of 260W and 16 panels of 265W. The first option is more cost-efficient, therefore the PV system will consist of 15 panels of 270W. The name of the panel is CONERGY PE 270 M-R which is priced at 290.91€ for each panel. Therefore for 15 panels, the cost is 4363.65€ in total. The open-circuit voltage of each panel is 37.73 volts therefore the maximum input voltage of the inverter should be greater than 37.73 times the total number of inverters which is 556.95 volts. Therefore to connect 15 panels in series the ABB PVI -4.2 -TL-OUTD inverter is used which has a maximum input voltage of 600V and a maximum input power of 4.375 KW. The power output in AC is 4.2 KW with 96.8% efficiency. The total price of the inverter is 1351.02€. Including other variable prices such as installation kit, and extension cables, the total price to install a PV system is 5894.67€. Considering the subsidies, a 25% discount is given on the final price which is 4421€.

Net present value,

For the base case, electricity is priced at 30€c/KWh, therefore for a nominal load of 2.5KW, the daily consumption is 31.07 units (KWh) the price is to be paid for a year is 3403.05 Euros. Considering this expense, NPV for the base case is -65185.64 Euros.

After the PV system is installed the total price that is to be paid for electricity consumption is just 2013.86 €, along with that the surplus energy is sold to the grid at monthly PUN prices, therefore, the profit made by selling the surplus is 109.06 €. The following figure demonstrates the distribution of electricity bills paid in the base case (red), electricity bills paid after the photovoltaic system is installed(blue) along with the profits made in the summer month by selling the surplus at PUN to the grid (green).

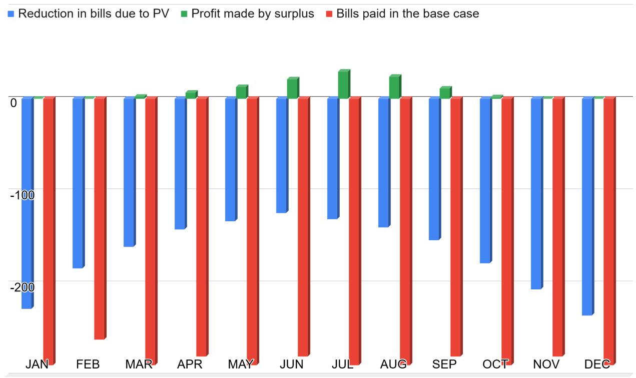


Figure 14: Distribution of the prices paid with and without PV

Considering the installation price, revenue made and the reduction in bills paid to the electricity to the grid, the NPV for 20 years for the PV only case is -39002.63€ which means there is a reduction of 26183.01€ which can be considered as the overall profit by installing the PV system. Figure 15 shows the comparison of discounted cash flows for the first five years between the PV system and the base case. The red bars represent the discounted cash outflows in the base case. The green bars represent the discounted cash inflows (revenue made by selling the energy to the grid at PUN). The blue bar represents the initial capital investment for setting up the project.

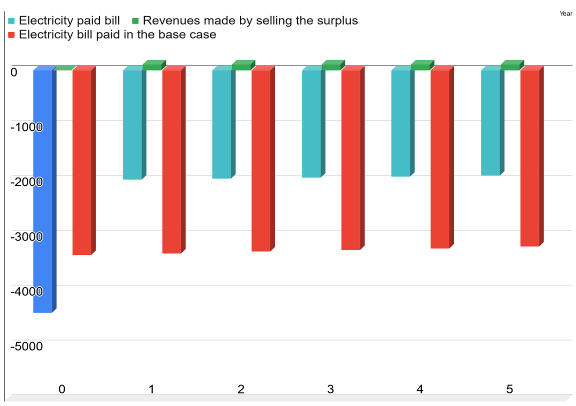


Figure 15: Comparison of the discounted cash flows for the first five years between the PV system and base case

As the photovoltaic system is considered profitable, there is a possibility to install the energy storage system. After the energy storage system of nominal energy value, 9.293 KWh is installed for 80% self-consumption, as mentioned earlier it is made a recharge from 0% after the difference between the PV and load is positive and it is made to discharge right after the difference becomes negative. Figure 16 shows the SOC distribution:

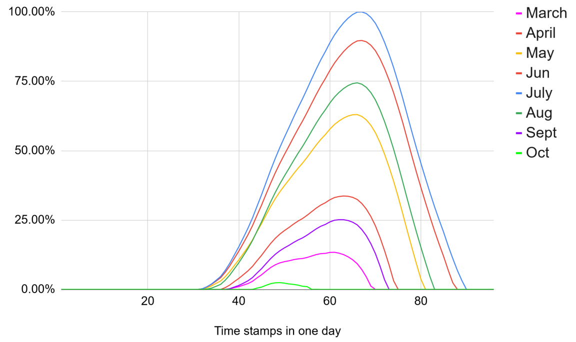


Figure 16: Distribution of state of charge for different months

It can be witnessed that the storage system is completely charged to 100% in the month of July. 5000 is the number of cycles that are possible with the storage system incorporated. The total number of cycles utilised in this case for one year is 128 which means the storage system does not need the replacement in 20 years. Therefore there is only one cost that is associated with the ESS which is the installation price of 2788.17€.

Considering the installation price of photovoltaic system and the storage system, the reduction in bills paid to the electricity to the grid, the NPV for 20 years for the project incorporating photovoltaic and energy storage system is -44761.64€ which means there is a reduction of 20424 € which is considered as the overall profit compared to the base case. Fig 17 which is the extension of fig 15 demonstrates the discounted cash flows for the first 5 years. The yellow bars represent the discounted cash flows associated with the photovoltaic and energy storage system project. It can be observed that the initial capital investment (initial negative cash flow represent by the yellow bar on the negative axis) for this project is bigger than the capital investment required to set up only the photovoltaic system as the price of the energy storage system gets added to the existing installation price of the photovoltaic system. It can also be observed that the amount saved by not purchasing the energy from the grid is smaller than the revenue made by selling the energy to the grid.

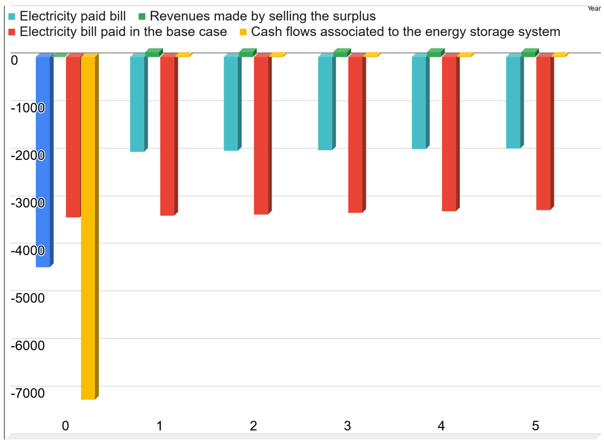


Figure 17: Comparison of the discounted cash flows for the first five years between the PV system, PV+ESS system and base case

Therefore, in conclusion, it can be stated that installing a photovoltaic system is profitable compared to the base case both with an energy storage system and without an energy storage case. However, for the nominal load of 2.5KWh, it is cost-efficient to install only the photovoltaic system and sell the surplus energy to the grid at the national PUN prices.

References

[1] Piotr Bojek, (November 2021) *Solar PV, More efforts needed,* 7th Annual Global Conference on EnergyEfficiency
https://www.iea.org/reports/solar-pv