NOVA SCHOOL OF BUSINESS & ECONOMICS

Economic analysis of a residential photovoltaic system in Padova, Italy.

Lorenzo De Chiara

Work project carried out under the supervision of

João Pedro Pereira

MSc in Management

2024

Campus de Carcavelos
Rua da Holanda 1,
2775-405 Carcavelos, Portugal

(+351) 213 801 600
info@novasbe.pt
novasbe.pt

Summary of rooftop solar analysis

Location: Padova, Italy **Date of analysis**: May/2024

Recommendation*: install 12 solar panels (23.4 m^2), for a net present value of 7070 euros, with a payback of 13.39 years.*

Main economic results

Financing	NPV (EUR)	Payback (years)	IRR (%/year)	LCOE (EUR/kWh)
Gov. subsidies and 75% bank debt				
PV System w/o Battery	7070	13.39	9.44%	0.069
PV System w/ Battery (4.6 kWh capacity)	7262	13.09	8.88%	0.084
Gov. subsidies and 100% equity	8072	11.82	9.44%	0.064
No gov. subsidies and 100% equity	6658	14.04	7.71%	0.075

(All rows are for the same number of panels)

Additional results

A system of 13 panels, together with a battery of 4.6 kWh, requires an initial investment of 13135€, but provides an NPV of 8072 euros, with a payback of 13.09 years.

Main inputs and assumptions

Household and Economics

Electricity Consumption	3970	kWh/year	Inflation	2.0%	per year
Electricity price – buy	0.2724	EUR/kWh	Bank loan interest rate	7.6%	per year
Electricity price – sell	0.061	EUR/kWh	Bank loan maturity	5	years
			Equity cost of capital	2.74%	per year

PV panels

Peak power	430	W/panel	System losses	14%	of output
Panel area	1.95	m^2/panel	Degradation with age	0.5%	Per year
Useful life	25	Years	Maintenance costs	15	EUR/ panel

Total cost of optimal installation size (without subsidies)	9360	EUR
Total cost of optimal installation size (after subsidies)	5160	EUR

Government subsidies

Government subsidies for photovoltaic panels include a deduction of 50% of the costs for the installation of the panels, up to a maximum of 96,000 EUR. This amount will be redistributed over 10 years in 10 equal installments.

INDEX

1. Introduction

In recent years, the transition towards renewable energy sources has become imperative for environmental sustainability and energy independence. Solar energy, in particular, has emerged as a cornerstone of this transformation. This thesis presents a comprehensive economic analysis of rooftop solar installations, assessing their viability within the context of a residential setting in Padova, Italy. The urgency of the subject is highlighted by the ongoing global energy crisis and the need to mitigate the impact of climate change. With this backdrop, the study provides crucial insights into the economic incentives and outcomes of adopting photovoltaic (PV) systems for households.

The analysis is rooted in an effective data collection and evaluation of numerous variables, including household electricity consumption, solar irradiation, PV panel efficiency, government subsidies, and the changing landscape of electricity prices. The central objective is to determine the optimal size of a PV installation that maximizes the financial return through metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), and the Levelized Cost of Energy (LCOE).

The main result from this work indicates that there is a quantifiable economic benefit to household rooftop solar installations. Moreover the reader will discern that, despite fluctuations in energy prices and market volatility, solar installations remain a resilient and worthwhile investment. While the thesis offers robust recommendations based on current conditions, it also gives a broader overview considering the sensitivity of changes in the energy sector or individual consumer behaviour .

2. Data and Assumptions

In this section, we will conduct a detailed analysis of the various inputs provided to our model, aiming to fully understand the origins and the reasoning behind each of them. The inputs include detailed hourly data regarding consumption profiles and solar irradiation collected over an entire year. Additionally, we consider energy prices, which encompass both the revenue from selling excess production and the costs associated with purchasing energy. Economic variables such as inflation rates and interest rates are also integral to our analysis. Finally, we examine the cost functions associated with the installation of domestic photovoltaic (PV) systems, both with and without energy storage options. This comprehensive review will help us to better assess the viability and financial implications of renewable energy investments in residential settings.

2.1 Load Profile

The process of establishing a consumption curve that accurately reflects real-world conditions involved a meticulous and structured approach, executed in two distinct phases to ensure the highest level of reliability.

The first phase entailed defining an hourly percentage distribution for each hour of the day across all days of the year. This was crucial for mapping out the temporal dynamics of energy usage, which varies significantly at different times and seasons. By systematically breaking down the year into hourly increments, we were able to capture a granular and precise portrayal of consumption patterns, facilitating an understanding of peak and off-peak usage periods.

In the second phase, the focus shifted to estimating a nominal annual consumption figure. This nominal figure served as a baseline onto which the previously determined hourly percentages could be applied. The aim here was to translate these percentages into actual consumption figures by multiplying them by the nominal annual consumption. This method provides a more dynamic and adaptable model of energy consumption, capable of reflecting variations in both time and intensity of use throughout the year.

For the detailed estimation of relative consumptions, we relied on the comprehensive data provided by the ARERA website[1], the Regulatory Authority for Energy, Networks, and Environment. As an independent administrative authority of the Italian Republic, ARERA's role is pivotal in promoting competitive market developments. The authority's detailed consumption analysis for domestic customers is categorically divided by various demographic and geographic parameters such as region, province, power class, market type, and the customer's residence. Leveraging this rich dataset enabled us to extrapolate hourly consumption data relative to the total annual consumption for each hour of every day over the course of the year.

In assessing actual annual consumption, we analyzed utility bills from multiple residential units, paying special attention to the characteristics that significantly influence energy consumption. These characteristics included the size of the housing unit, the number of occupants, and the types and efficiencies of systems used for heating water, cooking, and air conditioning. By integrating these real-life factors into our analysis, we were able to adjust the theoretical model to better align with observed energy consumption behaviors, thereby enhancing the accuracy of our consumption curve.

[1] Data can be found at this link

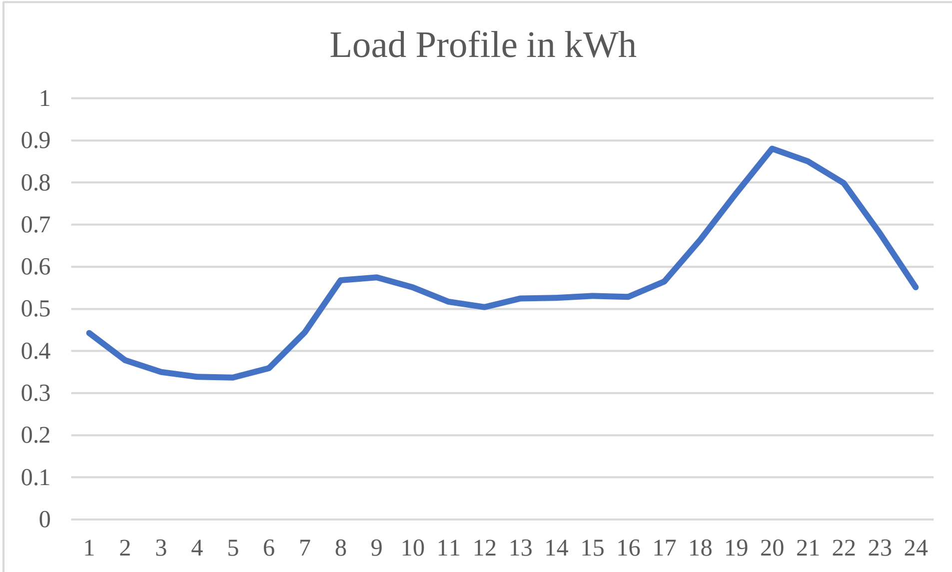

Figure 1: Average hourly Padova's household consumption in kWh

The typical daily load profile, as depicted in *Figure 1*, illustrates the pattern of electricity consumption within a household. Consumption hits its lowest point during the night, hovering at minimal levels as the household rests. As the morning progresses and the residents wake up, there's a noticeable uptick in energy usage. The profile then enters a period of relative stability from 10 AM to 6 PM, averaging around 0.55 kWh, likely corresponding to the time many families are away from home. Activity picks up again in the evening, peaking between 8 and 9 PM with consumption reaching 0.9 kWh per hour as families engage in domestic activities and leisure before gradually tapering off towards the night, eventually halving as the household settles back into the night-time.

2.2 Radiation

Regarding solar irradiance and the potential energy generated by PV systems, we utilized data provided by the European Joint Research Center. The solar radiation data given by PVGIS, a powerful solar radiation calculation program developed by the European community, includes hourly values over several years, derived from satellite and reanalysis data. This software also calculates the energy generated by a photovoltaic system based on various parameters such as the type of mounting, the slope and azimuth, the power, and the technology of the panels. Moreover, the software accounts for system losses, which are considered at 14%[2].

The data provided extends up to the year 2020, thus we have considered the average of the last eight years, from 2013 to 2020, for this analysis. This temporal scope allows for a comprehensive understanding of recent trends and variability in solar radiation, facilitating a robust assessment of potential PV system performance. By integrating these detailed solar irradiance datasets with system-specific parameters and loss assumptions, the software provides an accurate estimation of the energy output, which is crucial for planning and optimizing PV installations.

2.3 Electricity Prices

When considering energy prices, it is essential to analyze both the purchase price for private citizens and the price at which surplus energy is sold. The surplus refers to the excess energy that is not consumed domestically but is generated by solar panels. This dual perspective on pricing helps understand the dynamics of energy cost from both consumption and production standpoints.

2.3.1 Electricity cost

In terms of energy purchase price, the benchmark[3] price provided by ARERA (Regulatory Authority for Energy, Networks, and Environment), an independent administrative authority of the Italian Republic, has been taken into account.

[2] This percentage reflects both the degradation of the panels over time and the loss of efficiency.
[3] the benchmark is issued quarterly

ARERA is stating that from January 1, 2024, the reference price for electricity for the typical customer will be 0.2524 euro per kilowatt-hour, taxes included. This price is broken down as follows:

Cost of energy material:

- 12.21 euro cents (48.4% of the total bill) for energy procurement costs, a reduction of 22.7% compared to the fourth quarter of 2023;
- 2.16 euro cents (8.6% of the total bill) for retail marketing, unchanged from the fourth quarter of 2023.

Cost for transportation and meter management:

- 4.53 euro cents (17.9% of the total bill) for distribution services, measurement, transport, transmission and distribution balancing, and quality; an increase of 13.5% compared to the fourth quarter of 2023.

System charge costs:

- 3.24 euro cents (12.8% of the total bill) for system charge expenses, an increase of 9.2% compared to the fourth quarter of 2023.

Taxes:

- 3.10 euro cents (12.3% of the total bill) for taxes, which include VAT and excise taxes.

This detailed breakdown provides an understanding of the various components that contribute to the total cost of electricity for consumers, reflecting changes in pricing from previous periods and the different charges applied to the electricity bill.

In addition to this base price there is a markup applied by Italian energy companies, such as Enel or Edison, which is approximately 0.02 euro per kilowatt-hour. This markup increases the final price for the consumer to 0.2724 euros per kilowatt-hour. This additional cost reflects the operational and administrative expenses incurred by energy providers in delivering electricity to consumers, as well as their profit margins.

2.3.2 Electricity selling price

Regarding the price of the energy sold, we have taken into account the two methods of withdrawal currently available in Italy: "Ritiro Dedicato" (Dedicated Withdrawal) and "Scambio sul Posto" (Net Metering). Since the net metering incentive is set to end at the close of 2024 and will no longer be applicable to new photovoltaic systems, we have considered the Dedicated withdrawal method which offers an alternative route for selling electricity for producers of renewable energy who operate facilities under 10 MW in capacity. Unlike traditional bilateral contracts or trading on the power exchange, this method involves feeding all the energy produced by the plant directly into the grid. The Gestore Servizi Energetici (GSE) then withdraws this energy, compensating the producer at a rate per kWh. This rate is assured to be no less than the minimum price levels established annually by the GSE which for 2024 are set at €0.044/kWh for a total energy sold up to 1500 MWh. This arrangement provides renewable energy producers with a dependable and equitable return, shielding them from the fluctuations of the market and fostering further investment in sustainable energy technologies.

Beyond the secured minimum price framework, the GSE enables the trading of energy at a dynamic rate, mirroring the fluctuations and patterns of the market prices. This dynamic pricing is sophisticated, as it is segmented according to distinct market zones. These zones are classifications based on the geographic location of the photovoltaic installations, with each zone featuring unique pricing influenced by local supply and demand dynamics. Specifically, our project is situated within the "Nord" market zone, which has its own set of pricing considerations.

Further distinctions arise with the introduction of the Hourly Zonal Price (PUN, "Prezzo Unico Nazionale"), a variable rate dictated by the electric market. The PUN rate varies throughout the day, fluctuating based on the specific time when energy is fed into the grid. Energy prices, as in *Table 1*, are segmented into three distinct time bands: F1, F2, and F3. Each band represents a different period of the day and is associated with a unique price level. The price bands are categorized from 1 to 3, with higher band values corresponding to higher selling prices.

Fasce orarie

Le fasce orarie sono definite dalla deliberazione AEEG 181/06 in relazione agli orari giornalieri e giorni della settimana.

<table>
<tr><th></th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th></tr>
<tr><td>lunedì-venerdì</td><td colspan="7">F3</td><td>F2</td><td colspan="11">F1</td><td colspan="4">F2</td><td>F3</td></tr>
<tr><td>sabato</td><td colspan="7">F3</td><td colspan="16">F2</td><td>F3</td></tr>
<tr><td>domenica/festivi</td><td colspan="24">F3</td></tr>
</table>

Table 1: PUN timebands

Moreover, it's crucial to address the fiscal implications of selling energy as a private citizen. Although the revenue generated from such sales does not attract value added tax (VAT), it is nonetheless subject to income tax under IRPEF—Italy's personal income tax. Consequently, this income must be declared on the annual tax return. The net financial benefit derived from these sales is determined after adjusting for the marginal tax rate. This rate modifies the taxable income in accordance with the tax bracket the individual falls into. Considering Italy's median per capita income, which is around 40000€, an ordinary taxpayer is often placed in the 35% marginal tax rate bracket. Recognizing this tax bracket is crucial for our analysis because it has a substantial impact on the actual take-home profit from the energy sold, which, in turn, affects the financial metrics we are taking into account to evaluate the PV system.

The formula used for calculating the selling price is as follows:

$$P_{SELLING} = [weight_{F1} \cdot P_{F1} + weight_{F2} \cdot P_{F2} + weight_{F3} \cdot P_{F3}] \cdot (1 - tax)$$

where:

- $weight_{F1}, weight_{F2}, weight_{F3}$ denote the proportion of annual hours attributed to each time band relative to the total number of hours in the year where the supply of PV energy exceeds the demand.
- P_{F1}, P_{F2}, P_{F3} are the monthly average prices, for each category, available for the first months of 2024.
- tax is the marginal tax rate, representing the tax percentage to be applied to the revenue generated from energy sales.

2.4 Economic Variables

Regarding the economic variables, we have taken into account an inflation rate of 2%, which aligns with the objectives of the ECB (European Central Bank) as well as the average inflation over the last decade. In terms of debt, we have considered a loan with a five-year term. Several estimates have been obtained from local and non-local Italian banks such as UniCredit and Intesa Sanpaolo, resulting in an average APR of 7.6% per annum.

For the Equity (household) cost of capital we took into account the 10-year EURIBOR Swap Rate which is 2.74%.

2.5 Installation costs

2.5.1 PV Panels

Regarding the photovoltaic panels, the LONGI Hi-MO 6 model has been used as a reference. This model boasts a power capacity of 430 watts over an area of 1.95 square meters, thus offering an efficiency of 22%. Furthermore, LONGI provides a 25-year warranty and guarantees a minimal annual power degradation of just 0.4%.

To calculate the cost of the photovoltaic panels, we began with actual quotes, both from websites and by phone, for PV systems with nominal power ranges between 1 and 6 kW, as it can be seen in *Table 2*.

Installation Costs			
Peak Power (W)	Number of panels	Real Quotes €	Interpolation
860	2		2209.43
1290	3	3144	2924.47
1720	4		3639.51
2150	5		4354.55
2580	6		5069.59
3010	7	5576	5784.63
3440	8	6465	6499.67
3870	9		7214.71
4300	10		7929.75
4730	11		8644.79
5160	12	8986.36	9359.83
5590	13		10074.87
6020	14	11187	10789.91
6880	16		12219.99
7740	18		13650.07
8600	20		15080.15
9460	22		16510.23

Table 2: Real quotes and Interpolated prices

To create a versatile cost function applicable to photovoltaic systems of various capacities, we engaged in a process of linear interpolation using established ratios. The resulting function, expressed as $y = 715.04x + 779.35$, models the cost structure of a photovoltaic installation. The equation delineates a fixed installation cost of 779.35 euros, representing base expenses that do not vary with system size. In addition to this, a variable cost of 715 euros per panel is identified, reflecting the incremental expense associated with each additional panel.

It's important to note that the market prices for solar panels have been subject to significant fluctuations. This variability was largely influenced by government subsidies available until 2021, which offered a reimbursement of 110% of the investment in solar panel installation. This policy led many installation companies to significantly inflate their prices, with the strategy of claiming the subsidies for themselves. Consequently, customers were not charged for the installation. Following the discontinuation of these subsidies, the market prices for solar panels have stabilized and now align more closely with the general prices observed across the European market. This change marks a return to more standard pricing practices in the industry, reflecting the true cost of solar panel technology without the distortion caused by hefty government incentives.

2.5.2 Batteries

For photovoltaic installations with storage systems—specifically those utilizing batteries to conserve generated energy for non-immediate use—we have undertaken a methodologically similar approach. The reference model for our study is the SOLAREDGE Home Battery 48V

PRICES	PANELS																
BATTERY	2	3	4	5	6	7	8	9	10	11	12	13	14	16	18	20	22
2	3522.91	4237.95	4952.99	5668.03	6383.07	7098.11	7813.15	8528.19	9243.23	9958.27	10673.3	11388.4	12103.4	13533.5	14963.6	16393.6	17823.7
3	4194.65	4909.69	5624.73	6339.77	7054.81	7769.85	8484.89	9199.93	9914.97	10630	11345.1	12060.1	12775.1	14205.2	15635.3	17065.4	18495.5
4	4866.39	5581.43	6296.47	7011.51	7726.55	8441.59	9156.63	9871.67	10586.7	11301.8	12016.8	12731.8	13446.9	14877	16307	17737.1	19167.2
4.6	5269.43	5984.47	6699.51	7414.55	8129.59	8844.63	9559.67	10274.7	10989.8	11704.8	12419.8	13134.9	13849.9	15280	16710.1	18140.2	19570.2
5	5538.13	6253.17	6968.21	7683.25	8398.29	9113.33	9828.37	10543.4	11258.5	11973.5	12688.5	13403.6	14118.6	15548.7	16978.8	18408.9	19838.9
6	6209.87	6924.91	7639.95	8354.99	9070.03	9785.07	10500.1	11215.2	11930.2	12645.2	13360.3	14075.3	14790.4	16220.4	17650.5	19080.6	20510.7
7.5	7217.48	7932.52	8647.56	9362.6	10077.6	10792.7	11507.7	12222.8	12937.8	13652.8	14367.9	15082.9	15798	17228	18658.1	20088.2	21518.3
9.2	8359.44	9074.48	9789.52	10504.6	11219.6	11934.6	12649.7	13364.7	14079.8	14794.8	15509.8	16224.9	16939.9	18370	19800.1	21230.2	22660.2
11	9568.57	10283.6	10998.7	11713.7	12428.7	13143.8	13858.8	14573.9	15288.9	16003.9	16719	17434	18149.1	19579.1	21009.2	22439.3	23869.4
13.8	11449.4	12164.5	12879.5	13594.6	14309.6	15024.6	15739.7	16454.7	17169.8	17884.8	18599.8	19314.9	20029.9	21460	22890.1	24320.2	25750.2
15	12255.5	12970.6	13685.6	14400.7	15115.7	15830.7	16545.8	17260.8	17975.9	18690.9	19405.9	20121	20836	22266.1	23696.2	25126.3	26556.3
18.4	14539.4	15254.5	15969.5	16684.6	17399.6	18114.6	18829.7	19544.7	20259.8	20974.8	21689.8	22404.9	23119.9	24550	25980.1	27410.2	28840.2
20	15614.2	16329.3	17044.3	17759.4	18474.4	19189.4	19904.5	20619.5	21334.6	22049.6	22764.6	23479.7	24194.7	25624.8	27054.9	28485	29915
23	17629.5	18344.5	19059.5	19774.6	20489.6	21204.7	21919.7	22634.7	23349.8	24064.8	24779.9	25494.9	26209.9	27640	29070.1	30500.2	31930.3

Table 3: Price for combinations of X Panels and Y Battery's Capacity

BAT-05K48, which offers a 10-year warranty and boasts peak charging and discharging efficiency of 94.5%. We gathered multiple quotes for storage battery systems of varying sizes, ranging from 3 to 22 kWh, and performed linear interpolation to derive a new cost function tailored to the batteries alone. By decoupling the cost of batteries from the panels, we can explore, as seen in *Table 3*, a comprehensive array of price combinations for each nominal power rating of an installation and each battery storage capacity. This allows for a more complete investigation into the most cost-effective pairings of battery storage and PV system capacity.

Maintenance costs for the solar panels have been estimated at 15 euros per panel each year. This estimate includes regular upkeep, like cleaning to maintain efficiency, as well as unexpected repairs or replacements needed to keep the system running smoothly. This method ensures all anticipated and possible extraordinary maintenance costs are accounted for, offering a practical cost outline for long-term maintenance of the photovoltaic system.

2.6 Government Subsidies

In the landscape of government incentives for the installation of PV systems, two principal initiatives stand out, each offering significant financial benefits to encourage the uptake of solar energy.

The first initiative is a reduction in the VAT rate for PV systems and related materials. Historically, the standard VAT in Italy has a rate of 22%. However, under the new scheme, the rate for these items is reduced to 10%. This incentive applies to all photovoltaic kits and components involved in setting up a renewable energy generation system.

The second initiative offers a financial incentive in the form of a 50% tax credit on personal income tax (IRPEF) for building renovations that incorporate the installation of both PV systems and battery storage solutions.. Installation of a PV system is considered a renovation activity, and as such, it qualifies for this substantial tax break. The initiative allows homeowners to reclaim half of their PV system's cost through tax deductions spread over the ten years following the installation. The maximum expenditure eligible for this 50% tax relief is set at €96,000 per property, meaning up to €48,000 can be deducted in ten equal annual installments for each property. The deductible amount is evaluated on an annual basis and per individual project.

It's important to note that these tax deductions act as a tax shield, effectively reducing the taxable income for an individual or corporation by allowing for certain deductions, such as the installation of a PV system in this case. Tax shields lower the total amount of taxes payable by an individual taxpayer, depending on their marginal tax rate, which, following the average per capita income in section 2.3.2 , in Italy averages around 35%.

3. Economic Analysis

3.1 Government Subsidies

Regarding the economic analysis, our initial step was to identify all the various cash flows that would impact the project, starting from the annual savings attributed to the installation of PV panels. To achieve this, we estimated for every hour of the year how much energy would be drawn from the grid and how much would be generated by the PV system.

This analysis enabled us to determine the savings on our electricity bills, which arise from two key sources: the energy sold back to the grid and the energy used for self-consumption. It's important to note that an increase in the number of panels does not proportionally increase the amount of energy used for self-consumption. This is because, in systems without a storage solution (battery), the energy produced by the panels must be used immediately. As a result, there tends to be an excess of energy produced during sunlight hours, while in the evening, purchasing energy from the grid remains necessary. As in *Figure 2* , self-sufficiency typically ranges from 30% to 40% as the number of panels increases relative to our current energy usage.

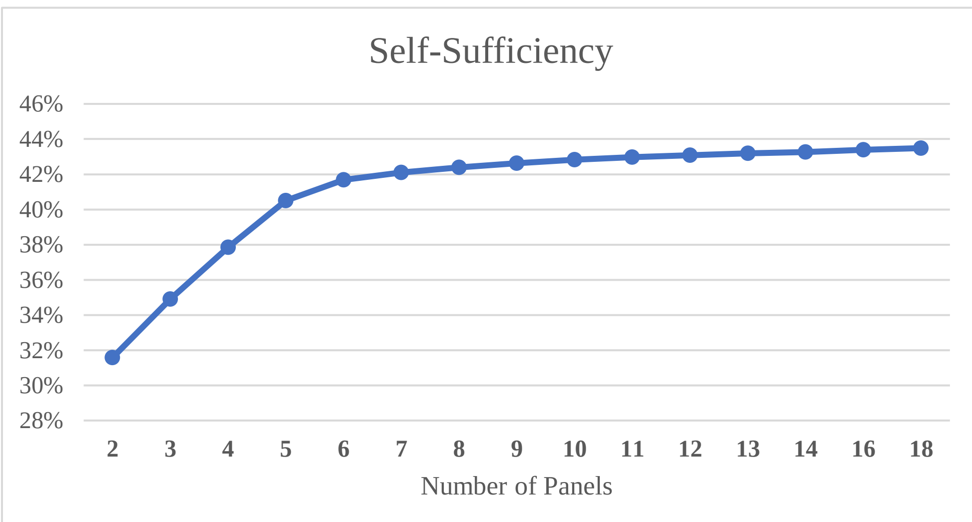

Figure 2: Panel Count vs. Household Energy Independence

3.2 Cashflows

After calculating the savings generated by the PV system, we can move forward with depicting and calculating our projected cash flows. Our analysis spans a 25-year horizon, aligned with the warranty period of the panels, providing a long-term view of the financial benefits. Our benchmark case is to finance 25% of our investment with equity and the remaining 75% through a loan that has a 5-year maturity and an interest rate of 7.6% based, as said in section 2.4, on actual rates provided by Italian banks.

As in *Figure 3*, our cash flow components, besides saving calculated above, include the initial equity investment, repayment of the loan over five years, and inflows from government subsidies, which help offset some of the upfront costs. We will also factor in ongoing maintenance costs, adjusted for inflation, to ensure we capture the true long-term expenditure associated with the system

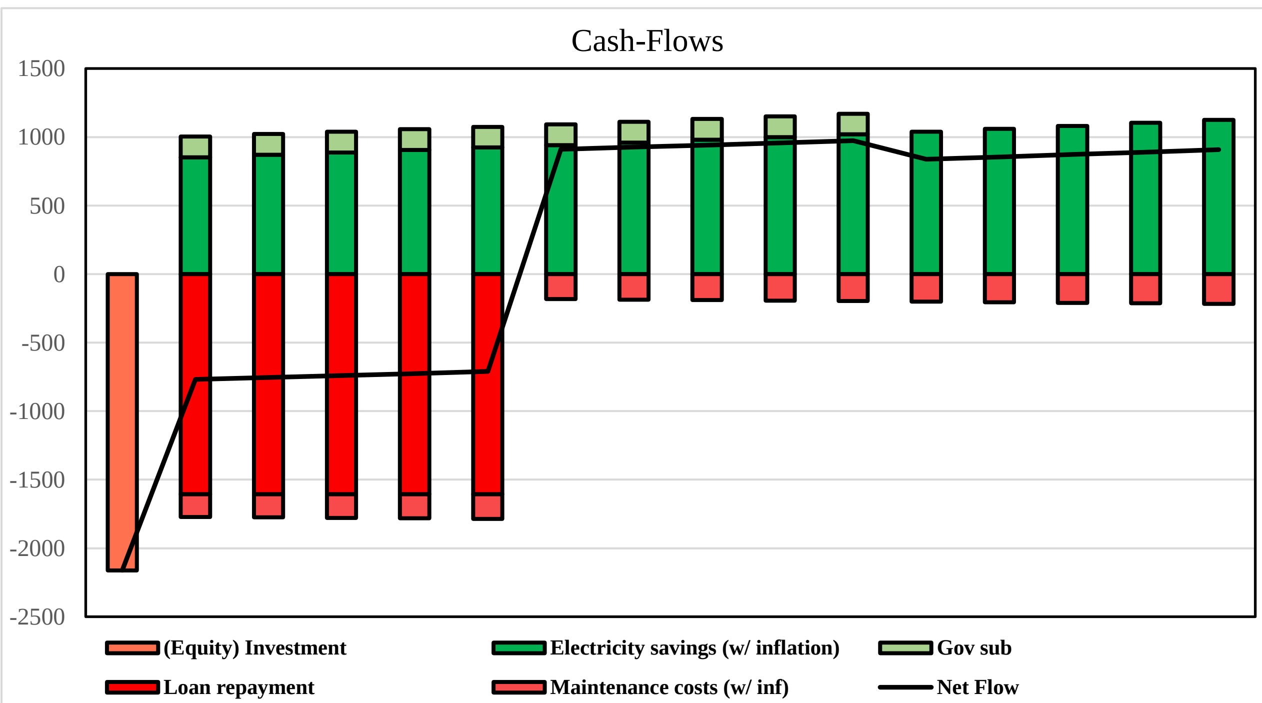

Figure 3: Cashflows representation of our optimal system size, 12 panels

From these elements, we can derive the annual cash flows and calculate their present values, which adjust future cash flows to reflect their value in today's terms. This process helps us understand the time value of money and the impact of inflation on our investment.

3.3 Financial Metrics Analysis

The most crucial metric in our financial analysis is the Net Present Value (NPV) which is essential for assessing whether the PV system project is financially viable over the long term. A positive NPV indicates that the project is expected to generate more wealth than it consumes, after accounting for the cost of capital, making it a financially sound investment.

In addition to the NPV, we consider other key financial metrics to thoroughly evaluate the viability of the PV system project. These include the Internal Rate of Return (IRR), the Payback Period, and the Levelized Cost of Energy (LCOE)..

LCOE is a measure of the average net present cost of electricity generation for a generating plant over its lifetime. It is calculated by taking the ratio of the total costs of the system to the total amount of energy it produces. The formula for LCOE is:

$$LCOE = \frac{Total\ Costs\ of\ the\ System}{Total\ Energy\ Output\ Over\ Life\ of\ the\ Systems}$$

Total costs include initial capital expenditures, operations and maintenance costs, and financing costs. LCOE is particularly useful when comparing the cost-effectiveness of different methods of electricity generation on a consistent basis. For a PV system, a lower LCOE means that the system is more cost-effective over its operational life.

By evaluating these metrics — IRR, Payback Period, and LCOE — alongside NPV, we can gain a comprehensive understanding of the financial performance of the PV system.

W/O BATTERY

N' Panels	NPV	IRR	PAYBACK	LCOE
2	5313	23.29%	6.95	0.089
3	6288	21.01%	7.48	0.081
4	6669	18.28%	8.26	0.077
5	6846	16.10%	9.04	0.074
6	6935	14.42%	9.76	0.073
7	6989	13.13%	10.48	0.071
8	7025	12.09%	11.16	0.071
9	7049	11.25%	11.79	0.070
10	7063	10.55%	12.36	0.069
11	7069	9.95%	12.90	0.069
12	**7070**	**9.44%**	**13.39**	**0.069**
13	7067	8.99%	13.85	0.068
14	7061	8.60%	14.28	0.068
16	7042	7.95%	15.05	0.068
18	7018	7.43%	15.72	0.067
20	6991	7.00%	16.32	0.067
22	6960	6.63%	16.85	0.067

Table 4: Financial metrics overview

A comprehensive overview of the economic metrics is given in *Table 4*, for different configurations of a PV system, ranging from 2 to 22 panels.

In *Figure 4* we can observe that the NPV follows a concave trajectory: as the number of panels increases, the NPV initially rises, peaks at the installation of 12 panels, and then begins to decline.

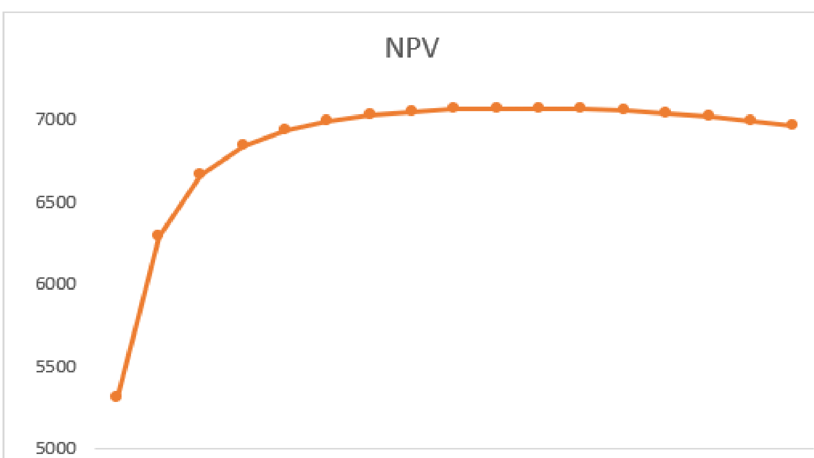

Figure 4: NPV as a function of number of panels

This trend indicates that while initially adding more panels generates higher savings, there comes a point where further additions yield diminishing returns.

To understand this phenomenon, it's crucial to analyze the relationship between savings and costs associated with the panels. As *Figure 5* shows, while installation costs tend to increase linearly with the number of panels added, savings do not scale in the same straightforward manner. Savings are heavily influenced by two factors: self-consumption and the energy sold back to the grid. However, these factors do not contribute equally to increasing savings.

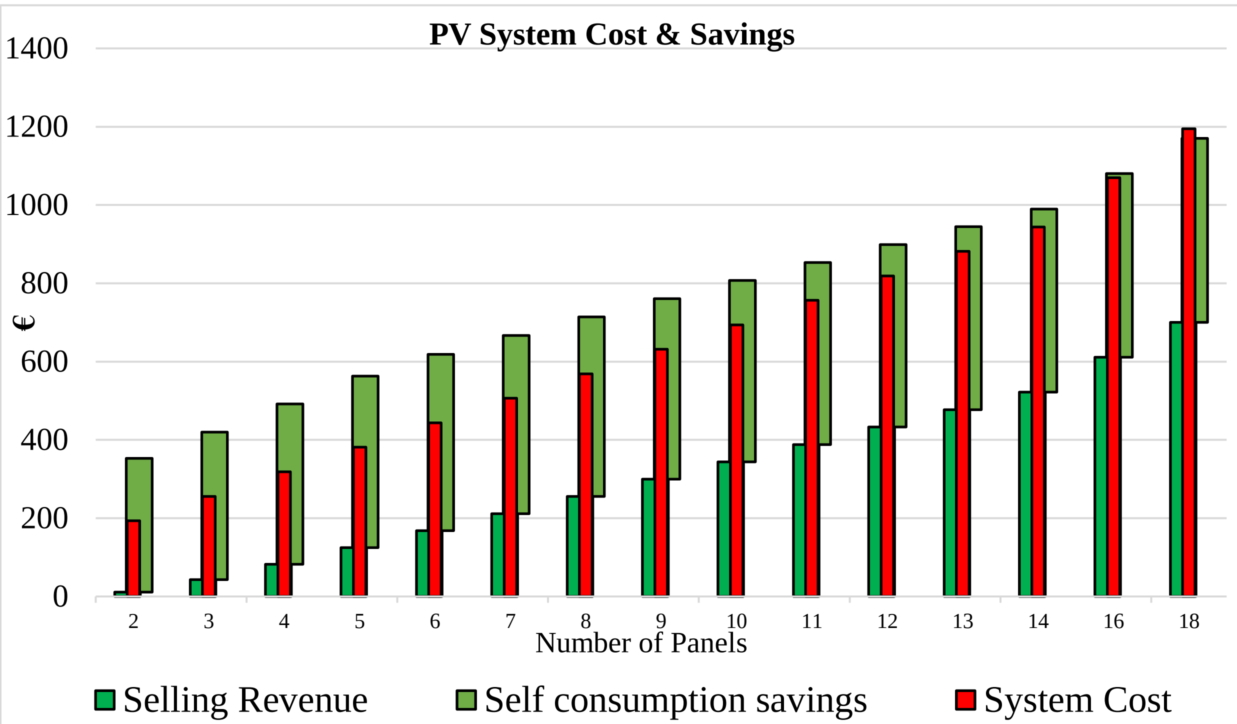

Figure 5: relationship between Costs, Savings and Revenues

Self-consumption provides a more substantial benefit compared to energy sold, especially from a financial perspective. As more panels are added, there's a threshold beyond which the percentage of self-consumed energy plateaus. Beyond this point, any additional energy generated is more likely to be surplus and sold back to the grid, which typically yields lower financial returns than energy consumed directly.

This imbalance explains why the NPV does not continually increase with the addition of more panels. Once optimal self-consumption is reached, additional panels primarily increase the energy sold rather than consumed. Since the financial return from selling energy is generally lower than that from self-consumption, the overall financial efficiency of the system begins to decline, hence the observed decrease in NPV beyond 12 panels.

Understanding this balance is crucial for designing an economically viable PV system. It underscores the importance of aligning the number of panels with actual energy needs and consumption patterns to maximize financial returns and avoid the inefficiencies of overcapacity.

Regarding the LCOE, we observe that it is inversely proportional to the number of panels installed. However, this might be counterintuitive to our analysis, potentially suggesting that installing the maximum number of panels is the optimal solution for our project. Yet, this is not accurate because, as previously explained, the percentage of self-consumption in our PV system does not increase proportionally with the number of panels. Instead, after reaching a certain threshold, any energy generated from PV is only sold, and at a price of 0.061€/kWh that is lower than the LCOE. This situation implies that the revenue from selling the generated electricity alone does not cover the average cost of its production, indicating that the energy production is not financially sustainable over the long term due to being sold at a loss.

3.4 Scenario Analysis

Scenario analysis is crucial for this project due to the multitude of variable inputs such as costs, energy prices, and load profiles. It allows for exploring the financial impact of different conditions, providing insights into potential risks and, by comparing different scenarios, decision-makers can determine the best course of action.

In assessing the impact of electricity cost on our PV system's financial viability, we analysed how incremental changes of 10% around the baseline price of €0.2724 would alter the NPV and consequently the ideal number of solar panels to install. *Table 5* shows that at an energy cost of €0.22064, the optimal configuration is 10 panels with an NPV of €5102, which rises to an NPV of €9252, when the energy cost is €0.3296, with the installation of 13. This finding is particularly pertinent given the recent high volatility in energy prices, driven by geopolitical tensions and conflicts. Despite the potential for significant price fluctuations, the robustness of our project's financial outlook stands firm, underscoring its resilience and the sustained attractiveness of the investment under a range of variable market conditions.

Electriciy Cost (in l/kWh)

NPV	2	3	4	5	6	7	8	9	10	11	12	13	14	16	18	20	22
0.22064	3821.5	4552.9	4835.7	4963.6	5026.3	5061.9	5083.8	5096.6	**5102.0**	5101.6	5096.9	5089.5	5079.8	5055.0	5026.7	4995.9	4962.4
0.24516	4528.2	5374.9	5704.3	5855.1	5930.7	5975.0	6003.4	6021.4	6030.9	**6033.7**	6031.6	6026.2	6018.3	5996.2	5970.0	5941.0	5908.9
0.2724	5313.3	6288.3	6669.4	6845.6	6935.5	6989.5	7025.3	7049.0	7063.0	7069.4	**7070.0**	7067.0	7061.0	7041.9	7018.1	6991.1	6960.5
0.29964	6098.5	7201.7	7634.6	7836.1	7940.3	8004.0	8047.1	8076.6	8095.1	8105.0	**8108.5**	8107.8	8103.8	8087.7	8066.3	8041.1	8012.1
0.3296	6962.2	8206.4	8696.2	8925.7	9045.6	9119.9	9171.1	9207.0	9230.5	9244.3	9250.9	**9252.7**	9250.8	9238.0	9219.2	9196.2	9168.9

Table 5: NPV changes varying electricity cost

With respect to variations in our consumption profiles, we evaluated both decreases and increases by 500 kWh. Given an initially high consumption profile of 3970 kWh, we paid closer attention to scenarios where consumption would decrease. As illustrated in *Table 6*, a reduction of approximately to 2470 kWh, which may not be entirely realistic for a four-person household considering average consumption and local climate conditions, shifts the optimal number of panels to 8, yielding an NPV of €4116. This emphasizes how critical the relationship between consumption patterns and the size of PV installations is to the economic feasibility and underscores that even with significant changes in consumption levels, the project can maintain financial soundness.

CONSUMPTION(in kWh)

NPV	2	3	4	5	6	7	8	9	10	11	12	13	14	16	18	20	22
2470	3700.9	3963.2	4049.8	4090.1	4110.4	4113.2	**4115.7**	4109.3	4099.2	4087.4	4074.4	4059.8	4044.1	4011.0	3975.9	3939.2	3901.2
2970	4350.7	4803.7	4961.7	5030.3	5068.5	5090.3	5100.0	**5101.5**	5097.8	5090.3	5080.1	5068.5	5055.8	5026.8	4994.4	4960.7	4925.1
3470	4886.4	5582.0	5837.3	5950.5	6010.1	6046.9	6069.8	6081.9	**6085.9**	6084.6	6079.5	6071.3	6061.0	6037.0	6009.1	5977.5	5944.5
3970	5313.3	6288.3	6669.4	6845.6	6935.5	6989.5	7025.3	7049.0	7063.0	7069.4	**7070.0**	7067.0	7061.0	7041.9	7018.1	6991.1	6960.5
4470	5642.1	6916.4	7455.0	7707.8	7841.9	7918.4	7968.7	8003.7	8028.1	8043.5	8051.9	**8054.5**	8053.4	8042.4	8022.8	7999.2	7972.7

Table 6: NPV changes varying consumption

Regarding the selling price for the excess energy produced by the panels, we have taken into account a increases or decreases of 10% from our baseline selling price. This factor, as we can observe in *Table 7*, introduces a high degree of variability in the outcomes. Specifically, a reduction of around 20% in the selling price would shift the project to an optimal installation of just 6 panels, yielding an NPV of €6,325. By examining the average annual prices from previous years, we see a clear correlation with market prices, which have been high due to geopolitical tensions. Therefore, due to their high volatility, selling prices are an important parameter to consider, particularly when preparing for a worst-case scenario where the market price could drop to the guaranteed minimum price of €0.044/kWh. In such a scenario, the NPV would become €6,080, and the optimal panel installation would decrease to 5 panels.

SELLING PRICE (in I/kWh)

NPV	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	16.0	18.0	20.0	22.0
0.044	5246.51	6025.51	6063.71	**6080.7**	5904.62	5689.79	5455.3	5207.84	4949.84	4683.62	4411.24	4134.84	3855.31	3288.5	2716.64	2141.23	1562.05
0.049	5267.3	6107.2	6318.4	6313.5	**6325.0**	6123.7	6013.2	5870.1	5606.6	5425.1	5237.6	5046.2	4851.6	4455.1	4053.5	3648.5	3239.9
0.055	5289.1	6193.0	6486.0	6538.1	6551.6	6568.0	**6575.8**	6481.2	6313.5	6204.0	6105.6	6003.4	5898.2	5680.4	5457.8	5231.8	5002.3
0.061	5313.3	6288.3	6669.4	6845.6	6935.5	6989.5	7025.3	7049.0	7063.0	7069.4	**7070.0**	7067.0	7061.0	7041.9	7018.1	6991.1	6960.5
0.067	5337.6	6383.6	6852.9	7123.0	7309.4	7460.9	7594.7	7716.9	7829.5	7934.8	8034.5	8130.6	8223.9	8403.4	8578.4	**8750.3**	8718.7
0.074	5364.3	6488.5	7054.7	7428.2	7720.8	7979.5	8221.2	8451.5	8672.7	8886.7	9095.4	9300.5	9503.0	9901.1	10294.8	10685.4	**11073**

Table 7: NPV changes varying selling price

3.5 PV Storage System

When it comes to the economic analysis of a PV system equipped with a battery, the assessment follows a procedure similar to the one outlined for systems without storage. The components within the cash flow are calculated in the same manner, with the exception of the savings component for several reasons.

The incorporation of energy storage allows us to store excess power in batteries to be used when our panels are not generating electricity. This capability significantly enhances our self-sufficiency levels, which can soar to as high as 95% with a storage system, compared to only about 40% for a system without storage. Consequently, our reliance on purchasing energy is substantially decreased. A factor to take into account is the charge and discharge efficiency of the battery, which, for our chosen SOLAREDGE Home Battery 48V BAT-05K48, is guaranteed to be at an impressive 94%.

Furthermore, since the battery's warranty spans 10 years, matching its projected lifespan, we've projected that the cash flow from savings for the subsequent 15 years will mirror that of a similar system without storage. This long-term perspective ensures that our economic analysis remains realistic and grounded in the actual operational lifespan of the system's components, thereby providing a clear and well-substantiated financial forecast for the PV system with battery storage.

After conducting the analysis, we are able to calculate the NPV for a PV system with battery storage. As illustrated in *Table 8*, the configuration that maximizes our NPV involves installing 13 panels along with a battery capacity of 4.6 kWh. With this setup, the NPV amounts to €7264, indicating that our investment would generate a greater return compared to a system without storage. A system with these specifications would achieve an 83% self-sufficiency level, allowing for an annual inflow to the battery of 1668.27 kWh and reducing the annual electricity bill from €1081, with no installation, to €187.

NPV	PANELS																
BATTERY	2	3	4	5	6	7	8	9	10	11	12	13	14	16	18	20	22
2	4393.0961	5964.15	6564.51	6865.96	7005.73	7081.77	7124.8	7154.1	7171.75	7180.3	7181.65	7178.59	7172.63	7153.52	7129.74	7102.66	7072.1
3	3750.9437	5599.25	6371.92	6769.18	6980	7087.53	7148.26	7183.63	7204.8	7215.87	7220.32	7219.55	7214.09	7194.99	7171.2	7144.12	7113.56
4	3108.7913	5056.93	6120.82	6599.84	6899.61	7062.92	7152.44	7203.9	7232.41	7247.4	7254.01	7255.27	7252.91	7236.33	7212.54	7185.46	7154.9
4.6	2723.4999	4680.46	5930.02	6476.31	6811.87	7020.76	7135.44	7199.66	7235.52	7253.23	7261.74	**7264**	7261.89	7248.21	7224.52	7196.99	7165.99
5	2466.6389	4424.64	5773.84	6366.51	6725.37	6964.75	7098	7173.62	7215.52	7237.71	7245.91	7249.18	7247.53	7234.62	7211.95	7183.93	7152.61
6	1824.4865	3782.49	5256.14	5969.58	6362.51	6640.87	6829.5	6936.36	6996.05	7028.51	7045.08	7048.95	7049.09	7037.27	7017.98	6990.77	6958.75
7.5	861.25788	2819.26	4339.86	5135.72	5567.78	5873.57	6114.09	6288.06	6392.64	6452.81	6485.54	6502.68	6509.17	6500.9	6482.33	6457.92	6427.94
9.2	-230.4012	1727.6	3266.08	4066.11	4502.43	4812.06	5064.31	5274.3	5417.26	5495.7	5543.38	5573.71	5589.33	5590.06	5571.46	5546.73	5518.27
11	-1386.276	571.726	2122	2917.48	3350.2	3666.3	3922.09	4131.55	4290.47	4383.4	4424.51	4444.44	4454.38	4451.52	4430.66	4405.92	4374.64
13.8	-3184.302	-1226.3	339.704	1129.94	1557.42	1878.8	2129.94	2348.1	2508.18	2617.53	2646.22	2662.3	2671.33	2663.99	2642.92	2613.39	2579.83
15	-3954.885	-1996.88	-424.137	363.855	789.081	1111.34	1361.6	1582.01	1744.34	1853.69	1882.38	1898.46	1905.24	1897.9	1874.58	1844.77	1809.25
18.4	-6138.203	-4180.2	-2591.6	-1810.4	-1387.87	-1065.61	-815.346	-594.623	-422.586	-315.45	-281.83	-270.027	-265.345	-274.748	-305.037	-338.548	-374.072
20	-7165.647	-5207.65	-3613.05	-2834.85	-2412.32	-2090.06	-1839.79	-1619.07	-1444.04	-1336.9	-1300.45	-1291.48	-1286.8	-1300.87	-1332.48	-1365.99	-1401.52
23	-9092.104	-7134.1	-5534.28	-4755.68	-4333.15	-4010.9	-3760.63	-3539.91	-3359.26	-3252.12	-3215.67	-3206.7	-3202.45	-3227.33	-3258.94	-3292.45	-3327.97

Table 8: NPV for different configurations of Battery Capacity and size installaion

4. Final Recommendation

Based on the comprehensive analysis presented in the thesis, the following final recommendation is made for residential solar panel installations in Padova, Italy:

For a system without battery storage, the best decision is to purchase 12 solar panels. This configuration leads to a NPV of €7070 , with a payback period of approximately 13.39 years. This recommendation is grounded in the data-driven analysis which shows that this number of panels optimizes the balance between cost, savings, and energy efficiency.

In contrast, for a system equipped with a battery, the optimal configuration changes. It is advisable to purchase 13 solar panels coupled with a battery capacity of 4.6 kWh, which maximizes the NPV to €7264. This setup not only increases the household’s energy self-sufficiency significantly but also offers an even stronger financial incentive.

These recommendations are robust, taking into account current government subsidies, the cost of capital, and the market and energy conditions specific to Padova. . The detailed analysis ensures these findings are both reliable and pertinent to potential solar panel adopters in the region, providing a solid foundation for making informed decisions about investing in solar energy.

Moreover the impact of changes in electricity costs, potential fluctuations in consumption levels, and variations in the selling price of excess energy were thoroughly analyzed. This scenario analysis ensures that the recommendations are not only optimal under current conditions but also resilient to future market uncertainties.

Comparative Analysis

The paper also encompasses a comparative analysis exploring the divergent economic landscapes of installations in Padua versus Ravello. This offers valuable insights into the interplay of geographical, economic and environmental factors influencing the financial viability of solar energy projects in distinct regional contexts. We now delve into the financial benchmarks of the two distinct scenarios, each structured with a 75% debt and 25% equity funding arrangement. In Ravello, the installation reaches an optimal NPV of €10,297 with 15 panels, corresponding to a nominal power of 6.525 kW. On the other hand, Padua's NPV peaks at €7,070, with 12 panels delivering a nominal power of 5.160 kW. Further, Ravello boasts a shorter payback period of 10.72 years and a higher IRR at 11.31%, versus Padua's longer payback of 13.39 years and lower IRR of 9.94%. This variance can be attributed to a mix of geographical and economic factors intrinsic to the areas where these installations have been developed. Starting from electricity annual consumption, in the 14 former it is assumed to be 2,700 kWh, while a standard household in Padua is expected to consume 3,970 kWh annually. Firstly, we tend to explain this because Ravello is located in Southern Italy, enjoying a milder climate compared to Padua, which is situated in the Northern part of the country. The warmer summers and colder winters in the region of Veneto likely contribute to higher energy consumption (e.g. for heating and cooling purposes) compared to the Amalfi Coast-based town. Additionally, cultural factors may also play a role. Padua can indeed be considered a more progressive city with a greater openness to innovation. As a result, households are more inclined to use electric stoves and electric water heating systems, rather than gas-powered solutions that are more common in Southern Italy. Another difference we encountered stands at LCOE level: Ravello's figure is €0.05, whereas in Padua it stands at €0.07. Since the LCOE captures both capital and operational expenses over the system's lifetime against total energy produced, examining such factors can explain the disparity. Indeed, we note a not negligible difference in installation expenses: the comprehensive cost, for five panels of similar characteristics, in Padua amounts to €4,354, while in Ravello is €3,739. We tend to attribute this to substantial variations in regional GDP per capita. In Campania, GDP per capita is around €20,000 (Regione Campania, 2022), whereas in Veneto, it stands at €34,000 (Regione Veneto, 2022). Higher GDP per capita often correlates with higher average income levels, which can translate into more elevated labor costs, demand for goods and services, thus higher prices. Moving to energy production, a significant discrepancy between the two towns is that Ravello experiences more sunny days throughout the year compared to Padua. This is directly reflected in the global irradiance on the inclined plane, a measure of the amount of solar energy available for conversion into electricity by the PV system, mounted at an optimal angle. According to data from the Photovoltaic Geographical Information System website, accessed from the PVGIS-SARAH2 database and based on a three-year average (2018, 2019, 2020), the global irradiance in Padua is recorded at 1739 kW/m^2, while in Ravello it stands at 1988 kW/m^2 per year. This difference implies that, ceteris paribus, PVs installed in Ravello have a higher potential for power production, meaning higher energy density efficiency (i.e. energy output generated per m^2). In numbers, this translates to a higher NPV per m^2 for Ravello (€332.48) compared to Padua (€297.14). This, coupled with the lower installation and maintenance costs, makes the financial benefit of installing greater for households living in Ravello.

References

European Joint Research Center (2024). *Photovoltaic Geographical Information System (PVGIS).* https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis_en

Enerdata (2023). *Italy energy report*. https://www.enerdata.net/estore/country-profiles/italy.html

Gestore Servizi Energetici (2024). *Ritiro Dedicato*. https://www.gse.it/servizi-per-te/fotovoltaico/ritiro-dedicato

Gestore Servizi Energetici (2024). *Scambio sul posto*. https://www.gse.it/servizi-per-te/fotovoltaico/scambio-sul-posto/

Agenzia Entrate (2024). *Agevolazioni per le ristrutturazioni edilizie* https://www.agenziaentrate.gov.it/portale/web/guest/aree-tematiche/casa/agevolazioni/agevolazioni-per-le-ristrutturazioni-edilizie

Solar Energy Point (2024). *PV Panels Details*. https://www.solarenergypoint.it/shop/longi-solar-hi-mo-6m-lr5-54hth-430m-modulo-fotovoltaico-monocristallino-430w

Geo Green Power (2023). *Solar Servicing and Maintenance*. https://www.geogreenpower.com/solar-panels/maintenance/

Chatham Financial (2024). *European Market Rates.* https://www.chathamfinancial.com/technology/european-market-rates

Regen Power (2023). *Lifespan of Home Energy Storage System*. https://regenpower.com/life-span-of-home-storage-system/

Ufficio di Statistica della Regione Campania. (2023). *Bollettino Mezzogiorno. Regione Campania*. https://www.regione.campania.it/assets/documents/campania-ottobre.pdf

Ufficio di Statistica della Regione del Veneto (2023). *La resilienza agli shock ripetuti. Regione Veneto.* https://statistica.regione.veneto.it