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Towards Greener Homes: An Integrated Software Solution for PV System Sizing and Heat Pump Adoption

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Nomenclature

Acronyms

APE Attestato di Prestazione Energetica

API Application Programming Interface

ARERA Regulatory Authority for Energy, Networks, and the Environment

BATT Battery

CAPEX Capital expenditures

CCF Cumulated Cash Flows

CDCF Cumulative Discounted Cash Flow

CF Cash Flow

COP Coeffienct Of Performance

DCF Discounted Cash Flow

DOD Depth Of Discharge

GSE Gestore Servizi Energetici

GUI Graphical User Interface

GWP Global Warming Potential

HP Heat Pump

IEA International Energy Agency

IRPEF Imposta sul reddito delle persone fisiche

IRR Internal Rate of Return

IT Information Technology

IVA Imposta sul Valore Aggiunto

LFP Lithium Ferro-phosphate

MPPT Maximum Power Point Tracker

NOCT Nominal Operating Cell Temperature

NPV Net Present Value

OC Open Circuit

ODP Ozone Depletion Potential

ODS Ozone Depleting Substances

OPEX Operational expenditure

PBT Pay Back Time

PMG Guaranteed Minimum Price

PNIEC National Integrated Plan for Energy and Climate

PNRR National Recovery and Resilience Plan

PO Hourly Zonal Price

PUN Prezzo Unico Nazionale

PV Photovoltaics

PVGIS Photovoltaic Geographical Information System

RID Ritiro Dedicato

SC Shot Circuit

SCOP Seasonal Coeffienct Of Performance

SOC State Of Charge

SSP Scambio Sul Posto

STC Standard Test Condition

TMY Typical Meteorological Year

TOE Tons of Oil Equivalent

UNFCCC United Nations Framework Convention on Climate Change

USSP Utente dello scambio sul posto

Symbols

α Temperature coefficient of current

β Temperature coefficient of voltage

Abstract

This study explores the development and application of software for feasibility analysis and photovoltaic plant optimization in the electrification of heating systems. It focuses on replacing gas boilers with heat pumps and integrating the best photovoltaic systems size with or without electrochemical storage. Given the energy cost volatility due to recent geopolitical events, a sensitivity analysis complements the economic study to understand investment profitability in the future. The software aims to promote low-impact environmental technologies, contributing to a more sustainable future.

An analytical and observational approach was employed, utilizing data from major energy management entities in Italy and analyzing Equa S.r.l.'s customer data. Results indicate that heat pump technology is evolving, requiring government incentives for adoption. Despite this, tax deductions make installations cost-effective, yielding profit over their lifespan. Integrating a photovoltaic system enhances investment profitability with higher Internal Rate of Return (IRR) and lower Payback Time (PBT). However, adding storage to a photovoltaic system is not yet cost-effective due to high initial costs.

Consideration of two applicable incentives in Italy, *Scambio Sul Posto* (SSP) and *Ritiro Dedicato* (RID), reveals SSP as the preferred solution. Sensitivity analysis on electricity and gas costs emphasizes differences between the two incentives, showing varied economic feasibility among clients. This underscores the need for an efficient calculation system.

In conclusion, the study provides insights into the feasibility of environmentally friendly technologies, highlighting the importance of ongoing government support. The software developed offers a valuable tool for future decision-making in the transition to sustainable energy solutions.

1 Introduction

Climate change is one of the most widely discussed global issues. Starting from the Paris Agreement, which came into force on November 4, 2016, world leaders committed to limit global warming to below two degrees Celsius compared to pre-industrial levels, with an ambition to keep it well below 1.5 degrees. All EU member states have ratified the agreement, setting new energy and climate targets through the European Green Deal. To achieve these goals, the Fit for 55 package has been introduced, including a series of economic and social reforms and regulations aligned with the Energy Transition Strategy. The primary objectives include reducing greenhouse gas emissions by 55 percent by 2030 and achieving climate neutrality by 2050.

Italy can be considered one of the leading proponents of decarbonization policies due to the introduction of initiatives such as the National Recovery and Resilience Plan (PNRR), a comprehensive plan for economic recovery and resilience in the aftermath of the COVID-19 pandemic, which comprises investments in various sectors, including sustainability. Italy has also introduced initiatives like the National Integrated Plan for Energy and Climate (PNIEC), which is more specific to energy and climate with respect to the PNRR. These initiatives aim to define measures and strategies for reducing greenhouse gas emissions, increasing energy efficiency, and promoting renewable energy sources. [1]

In light of what has been presented, the purpose of this study is to analyze the techno-economic feasibility of adopting high-efficiency energy systems as replacements for outdated devices. Specifically, different configurations will be analysed, starting with the integration of a heat pump as a substitution for conventional boilers, reducing both energy consumption and emissions; the integration of a photovoltaic system will then be considered, harnessing solar energy to meet power demands efficiently; finally, the analysis will consider the addition of an energy storage through the use of batteries, opening up opportunities for peak shaving and energy self-sufficiency.

The technologies employed represent a compelling solution to tackle climate change and enhance energy security. Their use results in increased electrification within a system, leading to higher efficiencies and a reduced carbon footprint. The environmental impact will be addressed following the technical-economic analysis, with a focus on avoided CO2 emissions and the equivalent of trees planted during the lifetime of the energy system.

The discussion of these topics was carried out by creating an optimization software designed to address the intricate challenges faced by the energy engineering field, encompassing both technical and economic aspects. The software developed for this thesis is not just another tool; it is a multifunctional solution that offers a comprehensive approach to energy system analysis. It marries technical and economic evaluation while being adaptable to various future scenarios. This versatility makes it an invaluable asset for consultants and professionals working in the energy sector.
More precisely, this software suggests the best photovoltaic and battery size for the investment, performs several sensitivity analyses on cost variables such as electricity and gas costs on the bill and allows for an analysis on the cost-effectiveness of the installations not only in the current price situation but also in future scenarios with different economic framework.

In the following chapters, we will delve into the software's architecture, its technical underpinnings, and the methodologies it employs. By the end of this thesis, it is my hope that the reader will not only comprehend the inner workings of this versatile tool but also appreciate the significant impact it can have on shaping a more sustainable and economically viable energy future.

2 Tax Deduction and Energy Exchange Mechanisms

This section is dedicated to the current Italian regulations for the investment, installation, and operation of the technologies under consideration, which include: heat pumps, photovoltaic systems, and batteries.

2.1 Heat Pump and Photovoltaic Systems Deduction

Thanks to the 2023 Budget Law and the Fourth Aid Decree (D.L. November 18, 2022, no. 176), it is possible to take advantage of the heat pump bonus for energy renovation interventions in buildings, particularly for the replacement of outdated air conditioning systems with state-of-the-art heating and cooling devices.

The tax deduction granted for installing a heat pump is as follows:

- 50% renovation bonus, if the purchase of the device is part of a building renovation project or of an extraordinary maintenance, governed by Article 16-bis of Presidential Decree 917/86.
- 65% eco-bonus, if the introduction of the heat pump does not involve renovation but relates solely to the replacement of lower energy class winter air conditioning systems. In this case, the maximum deductible expense is €46,154 and the reference body for documentation is Enea. The deduction must be spread over ten annual installments of equal amounts for ten years and the tax deduction can be converted into an invoice discount or tax credit. [2]
- "conto termico", which allows for a direct refund provided by GSE (without tax deductions) ranging from 40% to 65% of the expenses incurred for replacing existing heating systems with new high-efficiency devices. The incentive amount depends on the climate zone and the technical specifications of the system.[3]
- eco-bonus 90%, granted in the case of purchasing a heat pump device in combination with a leading intervention aimed at energy efficiency. The bonus can only be issued following the issuance of the Attestato di Prestazione Energetica (APE) by a qualified technician, certifying an improvement of at least two energy classes or reaching the highest energy class of the building. [4]

In this study, the analysis is focused on the application of the 65% eco-bonus or conto termico, as they represent the most requested incentive for the selected clientele.

The installation of a photovoltaic system, with or without a battery, falls under the definition of extraordinary maintenance and can, therefore, take advantage of the 50% restructuring bonus. This incentive has a maximum ceiling of €96,000 and can be claimed as an IRPEF deduction, spread over ten years.
It can also be applied in the case when the battery is bought after the installation of the photovoltaic plant.

In addition to the aforementioned incentives, there is also a reduction in the IVA rate from 22% to 10%.

2.2 Mechanisms for valorising self-produced electricity

2.2.1 Scambio Sul Posto

Scambio Sul Posto (SSP) is a mechanism that allows any excess energy produced by a photovoltaic system to be fed into the electrical grid, which can then be used during periods of higher demand but lower production. In SSP, the electrical system serves as a virtual storage for the electricity generated but not immediately consumed, partially solving the issue of dispatchability. SSP also provides economic compensation for the overproduction of electricity: when the energy produced and fed into the grid exceeds the energy consumed, the excess is considered 'surplus'.[5]

The technical rules for determining SSP compensation, as defined in Article 12 of the Annex A to Resolution 570/2012/R/efr and subsequent amendments, are outlined in the document [6]. The specific technical report indicates that SSP requires the valuation of two components:

1. balance settlement contribution (C_S) on an annual basis;
2. surpluses.

Regarding the contribution C_S, the formula to be adopted is as follows:

$$C_S = min[O_E; C_{EI}] + CU_{Sf} * E_S \tag{1}$$

Where:

- O_E is the annual cost incurred for the purchase of electricity drawn, calculated as the product between the quantity of electricity drawn E_{PR} and the Prezzo Unico Nazionale (PUN) and measured in euros.
- C_{EI} is the equivalent value of electricity annually produced and injected into the grid by the plant, calculated using hourly zonal market prices and measured in euros.
- CU_{Sf} is the annual unitary flat-rate exchange fee for each kWh. It represents the sum of distribution costs, dispatching, and items on the bill, usually expressed in cents of euros. It consists of two components:
  1. Unitary exchange fee related to the networks, which can be approximated to 20% of the cost per kWh on the bill.[7]
  2. Unitary exchange fee related to general system charges, which can be approximated to 20% of the cost per kWh on the bill. This component mainly comprises incentives for renewable sources (77%), the promotion of energy efficiency (9%), and benefits for manufacturing companies with high electricity consumption (6.7%).[8]
- E_S is the amount of electricity exchanged with the grid expressed in kWh. Defined by the expression:

  $$E_S = min(E_I; E_{PR}) \tag{2}$$

  where E_I is the energy fed into the grid and E_{PR} is the energy taken from the grid.

The surplus can be utilized either 'as credit' or 'in liquidation' of excess energy. If the User of the energy exchange (USSP), for a specific year, decides to opt for 'credit' management, any excess, starting from that year, is carried forward as credit. The cumulated credit in a specific year can be utilized only if C_{EI} is less than O_E. However, if the user prefers the settlement of excess with bank transfer from GSE, the settlement of the contribution in exchange and surplus will occur separately. In fact, the liquidable credit is given by:

$$C_R = max[0; C_{EI} - O_E] \tag{3}$$

An important consideration relates to taxation. The economic benefit derived from self-consumption is not subject to taxes, as it stems from the reduction in energy withdrawals from the national grid. However, the income generated from selling excess energy to the electrical grid is subject to taxation. The excess energy profit must be declared for tax purposes because the surplus energy supplied to the grid through On-Site Exchange is treated as an actual energy sale. This means that the surplus is added to the total revenue under the category of 'Other Income' for the calculation of income tax (IRPEF). Since it is subject to the highest tax rate, their benefit is significantly reduced.

2.2.2 Ritiro Dedicato

The Ritiro Dedicato (RID) is a simplified mechanism available to owners of photovoltaic systems, starting in January 2008. It allows them to receive monetary compensation for excess electricity produced and fed into the grid. The entity responsible for managing the excess withdrawal and issuing the corresponding compensation is the GSE, which establishes a price for each kWh fed into the grid.[9]

The pricing regime for RID involves two contractual options:

- Hourly Zonal Price (PO), which is the price determined by the electricity market. It varies depending on the time at which the electricity is fed into the grid and the market zone where the system is located.
- Guaranteed Minimum Price (PMG), which is a basic minimum price set annually by ARERA (Regulatory Authority for Energy, Networks, and the Environment). The minimum price typically varies based on the renewable source on which the systems requesting access to RID are based, as well as the quantity of energy withdrawn annually.[10]

For the subsequent analysis, an average RID price was considered. This was obtained by processing the average monthly prices for hourly periods and market zones provided by GSE. [11]

Taking into account the distribution of hourly periods during the days of the week:

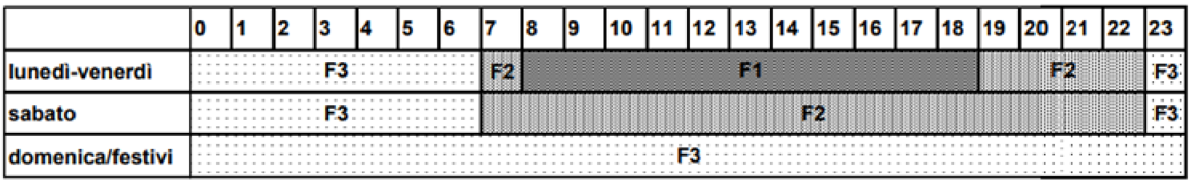


Figure 1: Hourly periods F1, F2, F3

The percentage weight of the various hourly periods has been calculated for each month of the year. The obtained results are as follows:

	F1 Weight	F2 Weight	F3 Weight
January	0.331	0.260	0.408
February	0.323	0.264	0.413
March	0.300	0.273	0.427
April	0.237	0.237	0.425
May	0.408	0.260	0.408
June	0.295	0.275	0.429
July	0.331	0.260	0.408
August	0.314	0.280	0.405
September	0.312	0.255	0.432
October	0.331	0.260	0.408
November	0.310	0.282	0.408
December	0.317	0.254	0.429

Table 1: F1, F2 and F3 Weights

These values have been combined with the 2023 price data for the different time slots, released by the GSE in the previously mentioned document. The area considered is the Northern Italy, composed by the regions of Valle D'Aosta, Piemonte, Liguria, Lombardia, Trentino, Veneto, Friuli Venezia Giulia, and Emilia Romagna.

Prezzi 2023 (Euro/MWh)

Fascia	F1											
Zona	gen.	feb.	mar.	apr.	mag.	giu.	lug.	ago.	set.	ott.	nov.	dic.
Centro Nord	193,64	166,49	140,10	124,65	104,89	107,07	112,83	105,01				
Centro Sud	185,91	162,69	105,14	120,66	102,99	103,95	112,66	104,88				
Nord	192,06	165,32	139,05	124,07	104,82	106,26	112,87	104,57				
Sardegna	179,82	164,68	84,46	121,75	100,12	105,48	113,23	95,54				
Sicilia	163,32	158,39	98,44	116,43	94,85	106,11	112,91	102,52				
Sud	171,47	161,73	99,68	117,90	103,63	104,60	112,57	102,40				
Calabria	166,06	161,40	101,12	117,92	94,68	104,61	112,28	102,76				

Fascia	F2											
Zona	gen.	feb.	mar.	apr.	mag.	giu.	lug.	ago.	set.	ott.	nov.	dic.
Centro Nord	176,18	156,58	119,47	112,98	93,71	97,18	100,96	97,60				
Centro Sud	173,49	151,31	110,16	109,26	89,85	96,40	99,58	95,94				
Nord	174,03	153,41	114,48	110,50	95,45	99,40	100,84	99,51				
Sardegna	170,17	160,97	94,58	107,76	95,49	106,70	117,34	116,91				
Sicilia	141,97	148,65	99,75	109,53	85,27	95,70	100,93	112,30				
Sud	171,83	151,98	112,40	114,14	91,21	96,25	100,03	98,18				
Calabria	162,85	158,42	121,30	121,04	101,22	102,07	103,26	113,72				

Fascia	F3											
Zona	gen.	feb.	mar.	apr.	mag.	giu.	lug.	ago.	set.	ott.	nov.	dic.
Centro Nord	157,63	140,72	112,81	117,68	71,50	79,68	91,66	86,63				
Centro Sud	151,54	130,86	100,55	113,64	70,12	77,22	90,07	86,16				
Nord	156,74	139,83	111,49	115,67	76,07	83,31	92,18	87,05				
Sardegna	146,32	135,55	87,80	111,43	74,50	86,77	100,28	94,30				
Sicilia	151,29	111,77	91,71	110,30	84,56	74,69	89,49	92,51				
Sud	145,86	125,01	100,71	113,35	72,10	77,73	90,30	87,08				
Calabria	148,44	129,48	105,90	116,85	81,49	82,25	93,21	95,68				

Figure 2: RID prices for 2023

The resulting average monthly prices are reported in the table below:

Month	**Monthly Price [€/MWh]**
January	172.94
February	151.64
March	120.59
April	104.66
May	90.64
June	94.51
July	101.29
August	96.05

Table 2: Monthly Prices

Hence, an average price for 2023 of approximately €116.54/MWh is obtained.

Additionally, as with the SSP surplus, energy fed into the grid through the RID is also considered as the sale of electricity. Therefore, the resulting income must be added to the income declaration and is subject to taxation.

3 Technologies overview

This section aims to provide some general technical information about the technologies that will be used in the calculation model. In particular, we will consider heat pumps, photovoltaic systems, and batteries.

3.1 Heat Pumps

This study considers air-source heat pumps that have better performance with respect to the more traditional systems which rely on an energy conversion (for example from electricity to heat or from fossil fuels to heat).
The use of such technology introduces both advantages and disadvantages.
Considering the secondary fluid which is the outdoor air, the main benefit is given by its high availability, while the main drawbacks are related to the strong variation of temperature, the low heat transfer performance compared to other fluids, the frost formation in colder climate and the high value of the pumping power required when using fans to create the proper flow rate. [12]
Other considerations must be done on the refrigerants used as primary fluids [3.1.2]

3.1.1 Working principle

The working principle of a heat pump can be explained with the vapour compression cycle that is schematized as follows:

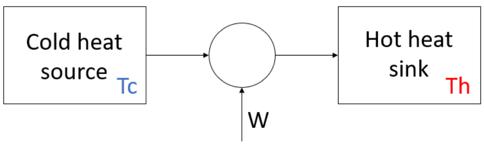


Figure 3: Vapor compression cycle

The heat is transferred from the cold heat source to the hot heat sink by providing electrical work to the system. In fact, according to the second law of thermodynamics, heat flows spontaneously just when it goes from a hotter area to a colder one, thus external work must be provided to move in the opposite direction.
A vapour compression cycle is made up of a compressor, an expansion valve and two heat exchangers: the condenser and the evaporator.

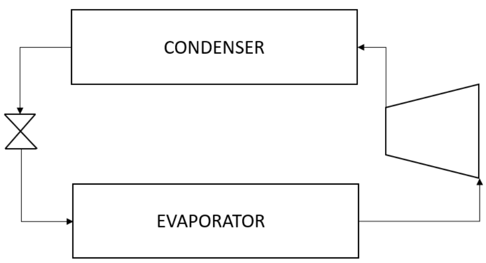


Figure 4: Vapor compression cycle components

At the beginning, the low temperature low pressure vapour enters the compressor that increases the fluid pressure by bringing it from the evaporating pressure to the condensing pressure. At the compressor discharge the fluid is at high temperature and high pressure and it flows inside the condenser where it rejects the heat to the hot heat sink. The liquid, then, undergoes an expansion process thanks to the expansion valve and its pressure is decreased again till the evaporating pressure. The last step of the cycle consists of the fluid entering the evaporator, where an evaporation heat extraction process from the cold heat source takes place.

3.1.2 Refrigerants

Every vapour compression system relies on a working fluid to perform heat transfer.
There exist different classifications; they can be natural or synthetic, can be characterized depending on the molecular composition or the environmental impact or the kind of mixture they are made of. Due to climate change concern, nowadays, the refrigerants choice highly depends on the effect of those fluids in the ambient, together with their safety level.
The main parameters used to measure the environmental impact are:

- Ozone Depletion Potential (ODP) which is a measure of the ozone-depleting substances' (ODS) impact on the ozone layer in the Earth's stratosphere
- Global Warming Potential (GWP) assesses the ability of a greenhouse gas to trap heat in the Earth's atmosphere over a specific period of time, usually 100 years, relative to carbon dioxide

Currently, the market offers various heat pump solutions that operate with different refrigerants. In general, synthetic refrigerants can be classified based on their chemical composition:

- CFCs (Chlorofluorocarbons): Hydrocarbons where hydrogen atoms have been removed. They have high values of Ozone Depletion Potential (ODP) and Global Warming Potential (GWP), are stable, and non-flammable. They were widely used in the past but were internationally phased out through the Montreal Protocol, adopted in 1987 and effective from January 1, 1989. [13]
- HCFCs (Hydrochlorofluorocarbons): Hydrocarbons containing hydrogen, chlorine, and fluorine atoms. While their ODP is lower than that of CFCs, the GWP remains high. They were introduced as a temporary solution to replace CFCs but are now being phased out.
- HFCs (Hydrofluorocarbons): Hydrocarbons characterized by the absence of chlorine. They are the nowadays most common refrigerants on the market, introduced to replace CFCs and HCFCs, which are now considered environmentally unsuitable due to their high environmental impact.

A fourth group that can be introduced is that of HFOs (Hydrofluoroolefins), a family of refrigerants derived from propane. Like HFCs, they consist of hydrogen, fluorine, and carbon, but they belong to the category of alkenes, characterized by a double bond between carbon atoms. Due to their chemical structure, they are substances that become unstable once released into the atmosphere and therefore decompose rapidly. Unlike HFC refrigerants, they do not accumulate in the atmosphere and have a very low greenhouse effect. Because they do not contain chlorine, they also do not harm the ozone layer, making them environmentally friendly refrigerants. [14]

The most commonly used refrigerants for residential systems are hydrofluorocarbons. Among the most used are:

- R410A: A mixture of R32 and R125, each present at 50%. It is particularly suitable for high-temperature conditions but has a very high GWP, equal to 2088. Many countries, including those in the EU, are regulating the use of this refrigerant in favor of more environmentally friendly alternatives. For example, the European Regulation No. 517/2014 on F-Gases imposes a list of obligations, including the adoption of refrigerants with a GWP below 750 starting from 2025.
- R32 (Difluoromethane): Adopted for both residential and commercial solutions and widely used in air conditioning systems. This refrigerant represents a compromise between efficiency and environmental concerns. It has a GWP value of 675, 68% lower than R410A, and offers higher energy efficiency of about 5%. Another advantage of this refrigerant is its ease of recharging, which greatly simplifies the maintenance of systems using it. However, R32 is classified as flammable and therefore requires appropriate handling during its use. [15]

There are also other natural solutions, including:

- R290 (Propane) and R-600a (Isobutane): These do not contain ozone-damaging CFC or HCFC substances. However, they are flammable and require specific safety precautions.
- Carbon Dioxide (R744): Widely available and has a zero GWP. Nevertheless, it requires specialized compression systems and presents some operational challenges. It is more commonly used in highly efficient geothermal heat pumps.

3.1.3 Defrosting

During cold climate, it's possible for the heat pump to experience a malfunction due to ice formation on the heat exchange surfaces. This phenomenon occurs when the evaporation temperature falls below the dew point temperature and below 0°C. The combination of these two conditions freezes the water droplets present in the air, which accumulate on the heat exchanger's surface, causing several issues, including a reduction in the cross-sectional area of air, an increase in air pressure drop, a decrease in air volumetric flow rate, a decrease in air velocity, and a reduction in the air's heat transfer coefficient, which is already low compared to other fluids.

Ice is a porous medium and thus represents an additional thermal resistance that lowers the overall heat transfer. Considering that heat exchange is directly proportional to the heat transfer coefficient, to the air's heat exchange, and to the temperature difference between the air and the evaporation temperature, it follows that ice formation further reduces the evaporation temperature, significantly decreasing the heat pump's performance.

Therefore, a defrosting cycle becomes necessary, temporarily interrupting the system's normal operation. There are various methods to carry out a defrosting process:

- Through a reverse cycle using a four-way valve: the condenser is used as an evaporator, extracting warm air from the room to be heated and sending it to the heat exchanger to melt the ice. In this way, the opposite effect is achieved, temporarily cooling the environment that should be heated.
- Through a hot gas by-pass: when ice forms, the by-pass valve is opened, and a portion of the high-pressure, high-temperature gas from the compressor's discharge is injected at the evaporator's inlet.

3.1.4 Heat pumps performance

The main index used to analyse heat pumps performances in stardard conditions is the Coefficient of Perfomance (COP) that is given by the ratio:

$$COP = Q/W \tag{4}$$

where Q is the heat transferred from the lower-temperature reservoir to the higher-temperature reservoir and W is the work required by the device to extract heat from the low temperature reservoir.
The COP value is always greater than one, meaning that the work required to operate the heat extraction is lower than the useful effect. This makes heat pumps heating more efficient than heating from other devices like the electric resistances. However, the higher the temperature of the heat sink, the lower is the COP, so, the amount of work required for unit of heat increases.

Another parameter to consider for the performance of the heat pump is the Seasonal Coefficient of Performance (SCOP), which is more precise than COP as it takes into account the system's operation at varying temperatures. SCOP is defined as the ratio of the time integral of the heat required by the building during the winter season to the time integral of the electric consumption of the heat pump during the winter season, as also defined by the formula:

$$SCOP = \frac{\int^{heating\_season} Q_{building}\,dt}{\int^{heating\_season} W_{heat\_pump}\,dt} \tag{5}$$

3.2 Photovoltaic System

Photovoltaic systems are a widely adopted and well-known technology in the field of renewable energy, therefore just few lines will be dedicated to this topic.
In particular, this chapter will briefly discuss PV production and all the aspects and parameters that characterize it. Many arguments will be discussed later during the definition of the analytical model.

Photovoltaic systems encompass a range of technologies, including monocrystalline silicon, which is the most used solution for building PV modules. The efficiency and output of photovoltaic systems are influenced by several factors, such as the tilt and azimuth angle of the solar panels, which optimize their alignment with the sun's path. Additionally, the presence of energy storage solutions, like batteries, can enhance the system's overall performance by enabling energy storage for later use. External elements, such as shading from nearby structures or vegetation, can impact energy production and must be considered in system design. Key aspects of photovoltaic system analysis involve sizing, determining the number of modules, inverter capacity, and overall energy production. The interaction of these factors within the context of residential applications is a focal point of this study, as will be explained later.

4 Analytical Model Definition

The purpose of the model is to analyze the economic feasibility of a heat pump in various system configurations:

1. Heat Pump Integration: heating system with only a heat pump replacing the boiler.
2. Heat Pump Integration with Photovoltaic: heating system with a heat pump replacing the boiler and the installation of a photovoltaic system.
3. Heat Pump, Photovoltaic, and Battery Synergy: heating system with a heat pump replacing the boiler and the installation of a photovoltaic system with a battery.

Particular attention will be given to points 2 and 3, where optimization will be performed on the optimal photovoltaic system size within a power range from 3 kW to 15 kW and optimization on the battery size, choosing from 5 kWh, 10 kWh, 15 kWh, and 20 kWh.

Additionally, an environmental analysis will be conducted in terms of avoided CO2 emissions and equivalent planted trees in all the cases presented above.

4.1 Heat Pump Integration

This model was developed in Excel and considering the annual values for thermal and electric consumption. The goal was to create an analytical tool that could help understand the economic feasibility related to the adoption of an heat pump for different customers, as the costs of gas and electricity on the bill are very different case by case. Since the study requires to analyse the cash flow during the whole lifetime and considering the high difficulty of predicting the development of gas and electricity costs in the future, several scenarios were considered.

4.1.1 Variables and Parameters

The parameters considered in this part of the model are:

- The methane conversion factor, which allows converting cubic meters of gas to thermal kWh and depends on the chemical composition. The value used is 9.94 kWh_{th}/m^3.[16]
- Consumption percentage in the month of January, considered the most critical month from a temperature perspective in northern Italy. A value of 35% of total annual consumption has been assumed.
- Operating hours of the heat pump per day set at 10.
- SCOP, which, although variable, has been considered constant at 4. Modern technologies can easily reach a value of 5, but a more conservative case was chosen, hence a SCOP of 4.[17]
- Discount rate, used to calculate the present value of future cash flows. The discount rate can vary depending on the contexts in which it is applied. For low-risk project investments, such as those in question, it can range from 3% to 6%. Therefore, a fixed value of 5% was chosen.
- The lifetime of the heat pump is considered equal to 20 years. This is also the time range considered for the economic analysis.

The independent variables used are:

- Annual thermal requirement taken from Law 10 and measured in [m^3/year].
- Cost of methane gas on the bill [€/m^3].
- Cost of electricity on the bill [€/kWh].
- Heat pump deduction equal to 65%, as also specified in the chapter [2.1]. This value was chosen as an independent variable to analyze the convenience of the heat pump both in the case in which the incentive is applied and in the case in which it is not adopted.
- Capital expenditures (CAPEX) depend on the size of the heat pump. At this purpose, three different approximated range of sizes have been considered:

Size	**Power range**	**Cost**
S	$P \leq 10\,\text{kW}$	21000€
M	$11 \leq P \leq 17\,\text{kW}$	25000€ - 27000€
L	17 kW < P ≤ 25 kW	30000€

Table 3: Table: Heat Pump CAPEX

Actually, the sizing of a heat pump is much more complex than this, since it requires to consider the thermal inertia of the building, the kind of terminals present inside rooms, the presence or absence of a thermal accumulation and the morphology and all the components of the thermal circuit. Nonetheless, it's important to remember the aim of the study, which is not to properly size an heat pump. Therefore, an approximate investment cost represents a good solution.

Finally, the output variables are:

- Pay Back Time (PBT), representing the time it takes to recoup the investment.
- Internal Rate of Return (IRR), which is a percentage value indicating how much an investment can yield in one year.
- Net Present Value (NPV) that defines the present value of a series of cash flows that are summed up and discounted.

4.1.2 Scenarios

For the configuration with a heat pump only, the following scenarios have been considered:

- Base case with constant electricity and gas prices over time.
- Decreasing electricity prices and constant gas prices. According to the IEA [18], renewable energy generation has increased over the years in Italy:

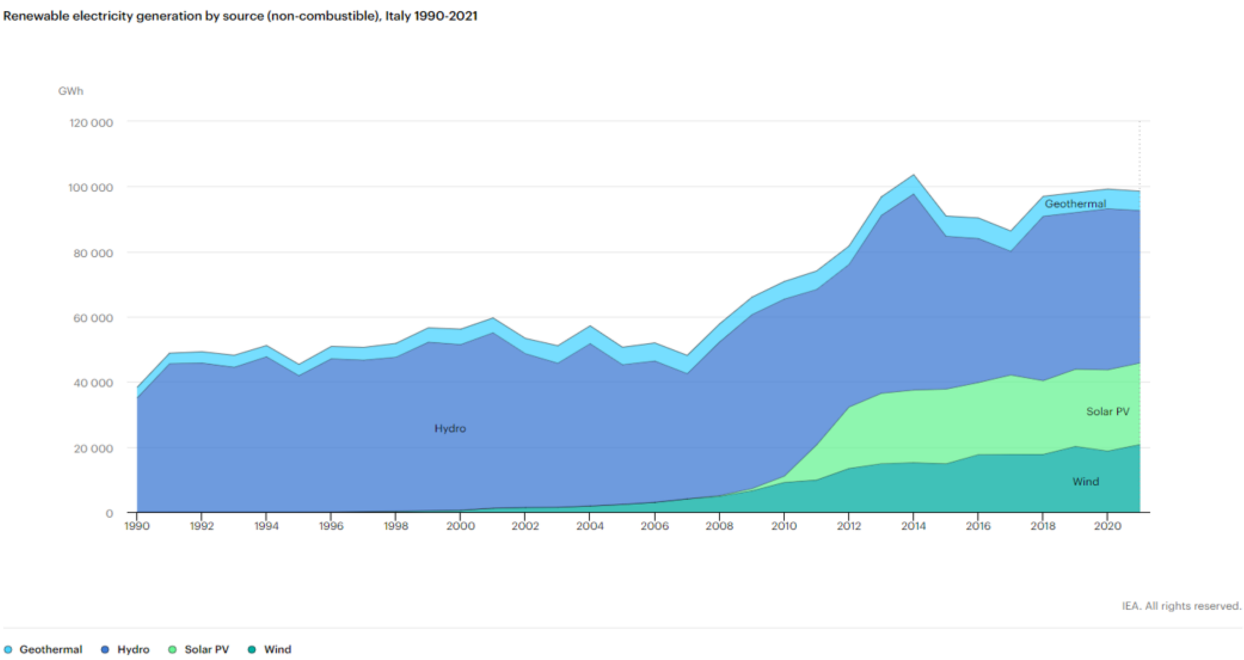


Figure 5: Renewable Penetration in Italy

Assuming that the increase in renewable energy penetration in the Italian energy mix continues in the future and exceeds the increase in electricity demand, it is possible to hypothesize that the cost of electricity will decrease over time. Analyzing the overall price of electricity as shown in the ARERA graph [19]:

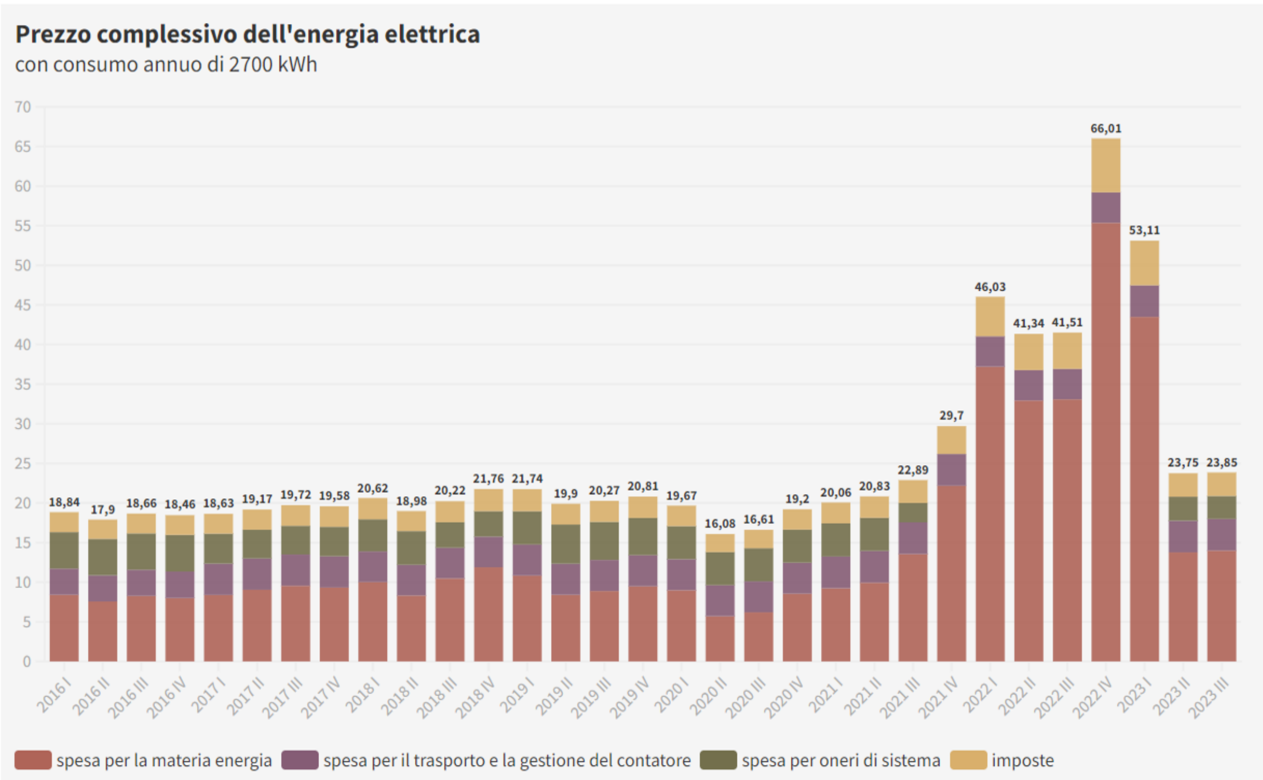


Figure 6: Electricity Price in time

It is possible to observe that the minimum value reached is approximately €0.16/kWh.

In the case study, this value was used as the minimum achievable cost, starting from the bill cost. For simplicity, a time range of price decrease equal to 7 years was assumed, making it possible to define the decrease in the cost per kWh during the system's useful life. Through an analysis of gas costs over the years (values taken from ARERA), it was observed that the cost of the raw material, excluding the period of crisis due to the COVID-19 pandemic, does not exhibit a significant upward or downward trend:

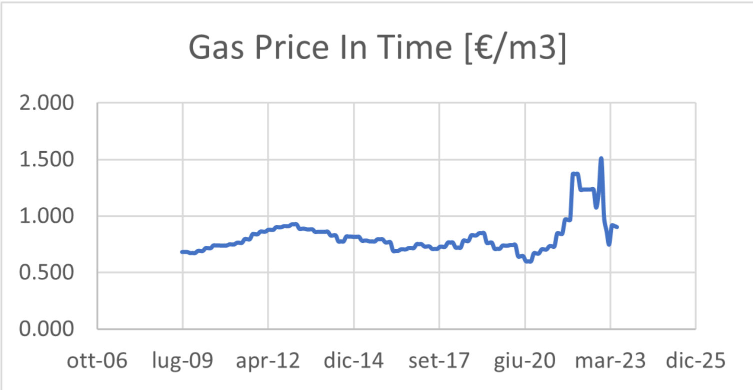


Figure 7: Gas Price in time

Assuming that expenses for transportation and meter management, system charges, and taxes do not change significantly, it is possible to consider the gas cost as constant over the years.

- Increasing electricity prices with a constant gas cost. This scenario involves an annual increase of 2% in electricity costs, under the assumption that electricity demand is increasing more rapidly than the rate of electricity production from renewable sources. The assumption of a constant gas price is connected to the explanation of the previous scenario.
- Decreasing electricity prices with increasing gas prices. The decreasing trend in electricity follows the rules defined in the second scenario, while the increase in gas costs can be justified by the need to enhance the country's energy security and reduce the use of this energy source within the country. To predict future gas prices, a linear regression was performed on gas costs released by ARERA. By calculating the annual percentage change, it was possible to determine the cost of gas from 2023 to 2042 starting from the gas cost on the bill.

4.1.3 Mathematical Analysis

Regarding the mathematical treatment, the first step in defining the model is sizing the heat pump based on the thermal consumption obtained from the gas bill or, for a more precise calculation, from Legislative Decree 10.

Starting from the annual gas consumption in cubic meters $Req_{gas,y}$ and utilizing the conversion factor for methane, it is possible to calculate the thermal energy (En_{th}) required by the building in kW_{th}/yr:

$$En_{th} = Req_{gas,y} * 9.94 \tag{6}$$

The heat pump must be capable of meeting this heat demand. Using the Seasonal Coefficient of Performance (SCOP), it is then possible to determine the electrical energy required by the heat pump throughout the year:

$$En_{el} = En_{th}/SCOP \tag{7}$$

This value will be required for the analysis of operating costs during the system's lifetime.

We can now delve further into the heat pump sizing, calculating its capacity, and consequently determining the investment cost, which complies with the values presented in [Table 3]. These values include the materials needed to create the system, labor, regular maintenance, and administrative procedures.

Assuming that January is the most critical month of the year and that its consumption accounts for approximately 35% of the total annual consumption, we can find the thermal demand for the entire month, for a single day in January, and the power of the heat pump in kW, considering its daily operation of 10 hours:

$$Cons_{Jan} = 0.35 * En_{th} \tag{8}$$

$$Cons_{day} = Cons_{Jan}/31 \tag{9}$$

$$P_{heat\_pump} = Cons_{day}/10 \tag{10}$$

Once the size of the heat pump and the respective investment cost have been selected, potentially deducted if the eco-bonus is requested, it is necessary to set the values for the cost of gas and electricity on the bill, which will vary from one system to another.

We can now find the annual cost of electricity and gas by multiplying the cost per cubic meter and kWh by the annual consumption. The difference between these two terms represents the annual savings R_y in €/year:

$$C_{tot,gas} = C_{gas} * Req_{gas,y} \tag{11}$$

$$C_{tot,el} = C_{el} * En_{el,hp} \tag{12}$$

$$R_y = C_{tot,gas} - C_{tot,el} \tag{13}$$

For each year of the system's useful life, the cash flows are defined as follows:

$$CF = R_y - CAPEX \tag{14}$$

It is also assumed that the system's investment is made at year 0 and that the annual savings at the same year are null. For a detailed analysis, it is necessary to discount future cash flows using the discount rate, as shown in the formula:

$$DCF = CF/((1 + disc)^y) \tag{15}$$

Where "disc" is the discount rate, and "y" represents the considered year. From the series of values obtained by calculating the DCF for each year of the system's life, the IRR can be found. Meanwhile, the NPV is calculated as the cumulative value of DCF at the last year of the system's lifetime. Finally, the PBT is the payback year of the investment, which can be identified as the year when the CDCF, initially negative, becomes positive. Alternatively, the PBT can be identified as the year when the graph of CDCF, where the x-axis represents the years of useful life, intersects the horizontal axis. This analysis should be applied to all scenarios presented earlier.

4.1.4 Primary Energy Saved

A short chapter has been dedicated to the primary energy saved by using the heat pump in place of the boiler. To address this analysis, it is necessary to consider the Tons of Oil Equivalent (TOE) required by the boiler and the heat pump. The TOE is a unit of measurement for primary energy, equivalent to 11,630 kWh_{th} and 6.84 barrels. Considering the conversion factor for methane of 9.94 kWh/m^3, 1 TOE corresponds to:

11,630 [kWh_{th}] / 9.94 [kWh/m^3] = 1,170.02 [m^3] of gas.

By dividing the building's thermal demand given by Law 10 by this value, it's possible to find the TOE required for the operation of the boiler.

Similarly, by utilizing the equation [7] and starting with the electrical consumption of the heat pump, considering a national grid efficiency for electricity of 0.46 [20], the value of primary energy in kWh for the heat pump can be calculated. This value can then be converted to TOE by dividing it by 11,630 kWh_{th} per TOE.

Finally, the difference in primary energy in TOE in the two cases is calculated. A positive value indicates energy savings, while a negative value suggests a more energetically disadvantageous system.

A further step can be taken by converting the TOE into thermal energy and monetary value.

Once obtained the difference in primary energy between the two different generation systems, it's possible to multiply the result in TOE by 11,630 kWh_{th} to calculate the thermal savings or multiply the result by the cost in euros per TOE. This latter value is obtained by multiplying the barrels per TOE for the cost of oil in dollars and for the euro-to-dollar conversion.

4.2 Heat Pump Integration with Photovoltaic

Unlike the first configuration, in order to conduct a proper economic analysis, it is necessary to work with hourly photovoltaic production values and hourly electricity consumption values. An annual value, in fact, would not allow a correct estimation of self-consumption, which is closely dependent on the consumption profile of the user and the hours of renewable energy production.

Therefore, the use of an analysis tool that allows for easy handling of a larger volume of data is required. For this purpose, Python has been chosen as the programming language, PyCharm as the working environment and Sourcetree as the code development management software.

4.2.1 Variables and Parameters

As will be explained later, this calculation model has been divided into blocks to simplify its implementation. In this subsection, the global variables and parameters will be presented, encompassing all the blocks.

The independent variables used in this part of the model are:

- Location of the installation site for the photovoltaic system and heat pump. This input requires the initialization of latitude, longitude, and altitude.
- Tilt angle, which is required for calculating the hourly photovoltaic production over the year.

- Annual electrical consumption prior to the introduction of the heat pump.
- Electrical consumption profile.
- PUN and PO, which will be necessary for the contribution calculation.
- Tax deductions for the heat pump and photovoltaic system. The input required in this case is different from that of the Heat Pump Integration configuration. In the previous case, the input represented the actual percentage of incentives, but now the process has been automated: it is sufficient to indicate "yes" if the incentive is present, and the code automatically inserts the correct incentive.
- Similar to the Heat Pump Integration configuration, it is necessary to provide the values of annual thermal demand and the cost of gas and electricity on the bill.
- The kind of Contribution adopted must be specified as "SSP" or "RID".

The dependent variables obtained as output are:

- Electricity production
- Energy fed into the grid and energy drawn from the grid
- Electricity bill
- Economic contribution
- In common with the Heat Pump Integration configuration, heat pump size, IRR, NPV, and PBT.

As for the parameters used, reference is made to those in the subsection [4.1.1] as they remain unchanged from the previous case.

4.2.2 Code and Mathematical Analysis

Within the calculation software, there are several sections, each with a specific purpose. To have a better understanding of the steps followed, this paragraph will be further divided into Blocks:

- Block 1: Photovoltaic Production
- Block 2: Electrical Consumption
- Block 3: Production and Consumption Reprocessing
- Block 4: Contribution
- Block 5: Economic Dataframes
- Block 6: Main Code (in common to both the *Heat Pump Integration with Photovoltaic* and the *Heat Pump, Photovoltaic and Battery Synergy* configurations. It will be treated after the *Heat Pump, Photovoltaic and Battery Synergy* introduction).

4.2.2.1 Block 1: Photovoltaic Production The first step is to calculate the hourly photovoltaic production. This will be done through a PVGIS API. Considering the need to optimize the photovoltaic system for optimal economic return, it is required to define a *PV_Characteristics* class that contains the main characteristics of the installation, including:

- Plant name
- Peak power
- Number of modules
- Number of strings
- Inverter model
- Latitude, Longitude and Altitude
- Tilt

Within this class, it will be possible to define a *pv_production* method that utilizes the pvlib library. *pv_production* downloads hourly radiation data from PVGIS, taking as input: latitude, longitude, tilt, start and end data collection, azimuth, shading model from pvlib, module type, and tracking system (set to zero for this study because just rooftop installations are considered). From the downloaded data, it is then possible to calculate the hourly values of total diffuse radiation as the sum of ground diffuse radiation and sky diffuse radiation. Finally, global radiation is calculated by adding total diffuse radiation and direct radiation.

Subsequently, the system is built by defining the location, a library of modules and inverters (using the CEC database), temperatures, the number of modules per string, the module model to be used (in this case study, the Jinko JKM410M_72HL model with 410 Wp is considered [A.1]), and the inverter model. This last variable will be defined in the main code so that the optimal inverter model is applied for each photovoltaic system power. The creation of the system model is performed using the *PVSystem* class from pvlib, which takes all the previous parameters as input but the location and the library. Meanwhile, the simulation model is created using the *ModelChain* class, which involves using the *.results.ac* function to calculate the alternating current hourly production throughout the year.

At the end of this code, it is possible to print the results graphically, with time on the x axis and the power produced in [W] on the ordinate axis. In the following figure it is reported the PV production related to a 15kW plant (blue), 10kW plant (orange) and 5kW plant (green):

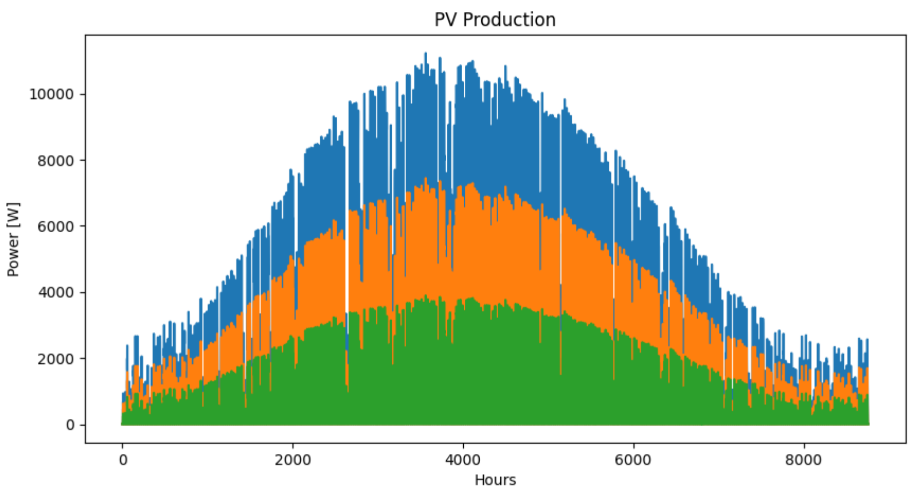
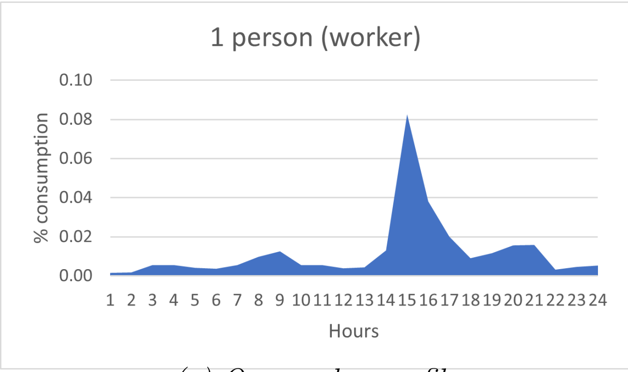


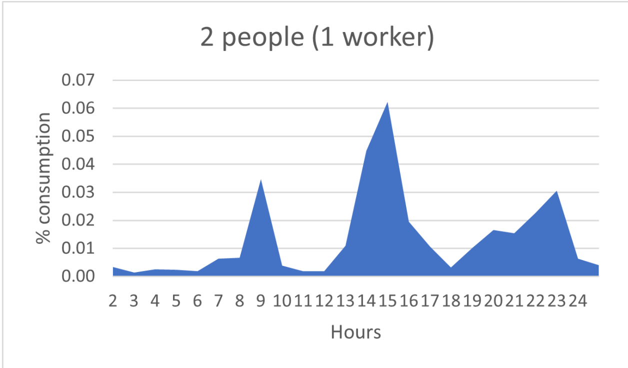
Figure 8: PV Production

The time on the graph is related to 2020 since PVGIS most updated data are the ones of year 2020.

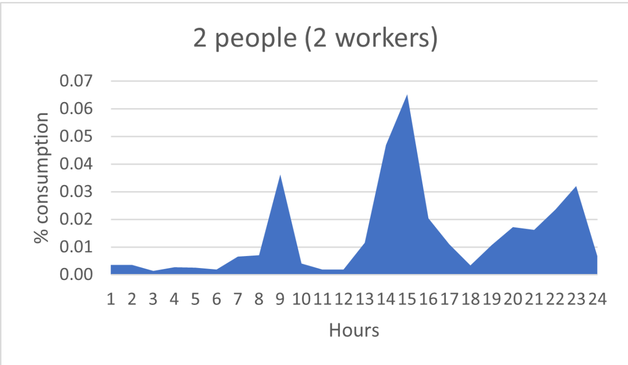
4.2.2.2 Block 2: Electrical Consumption The purpose of this block is to define the total hourly consumption for the entire year. The first step is to apply an hourly consumption profile that reflects the user's behavior. To do this, the following predefined profiles released by the EMIM course at Politecnico di Milano were used:



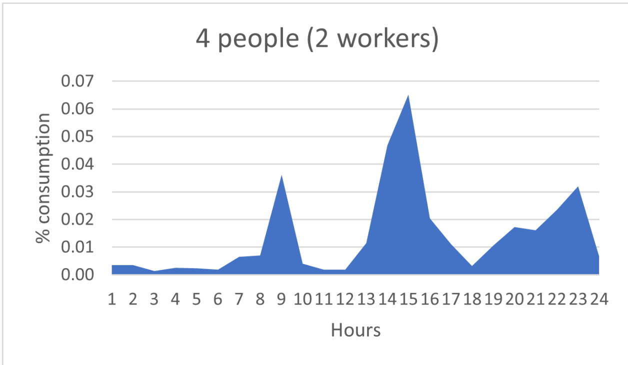
(a) One worker profile



(b) Two people, one worker profile



(c) Two people, two workers profile



(d) Four people, two workers profile

Figure 9: Percentage Consumption Profiles

After uploading the data from Excel to Python, the profiles were processed to obtain the percentage values of hourly consumption relative to the total annual consumption. The normalization of values allows their application to a generic customer's electricity bill, providing an estimate of their hourly consumption behaviour. However, it's important to note that in this initial phase, electric consumption does not yet include the use of the heat pump.

The next step is to determine the required electrical current of the heat pump. As previously seen, the annual electrical requirement of a heat pump can be calculated by multiplying the annual thermal demand in cubic meters by the methane conversion factor (9.94 kWh/m^3) and dividing it by the machine's SCOP, which is still assumed to be 4. However, consumption patterns will vary based on day-to-day temperatures. Since the model is not using a well-defined heat pump model and doesn't have daily consumption values for typical profiles to analyze, the decision is to approximate the heat pump's consumption on a monthly basis. With access to the monthly consumption data of a typical customer, a data analysis in Excel was conducted on these values to allocate the heat pump's consumption across the various months of the year, with reference to Northern Italy.

Commencing with the monthly consumption data solely pertaining to the heat pump for the years 2020, 2021, and 2022, the hourly consumption values per each month were derived by dividing them by the respective month's day count and the number of hours related to the heap pump daily operation (value set to 10 hours per day). In order to obtain an hourly consumption

estimate suitable for diverse scenarios, the monthly consumption averages were calculated for each individual month across the three years of analysis. The summation of all these values yielded an annual average electrical demand for the heat pump. This value was then utilized to divide the hourly average number of each month by the overall average annual consumption value, resulting in a percentage profile applicable to the model.
The results are presented in the table:

Month	Average hourly heat pump consumption [%]
January	0.061
February	0.046
March	0.037
April	0.023
May	0.011
June	0.010
July	0.009
August	0.010
September	0.010
October	0.017
November	0.034
December	0.062

Table 4: Table: Percentage Profile

Back to the Python code, the next steps were to apply the consumption profile obtained in the previous part to the annual consumption of the heat pump, resulting in hourly electrical consumption for each month. This part was developed by initially creating a list for each month that contained all the hours of the month with the consumption pattern: corresponding hourly heat pump consumption during the ten central hours of the day, when the pv production is greater, and consumption set to zero during the remaining 14 hours. Subsequently, all the lists were merged in order to get the entire year heap pump consumption.
The final step involved the calculation the total electricity consumption hour by hour by summing the existing consumption before the addition of the heat pump and the electrical demand of the machine.

4.2.2.3 Block 3: Production and Consumption Reprocessing This section operates as if it was an exchanged energy meter: by taking hourly input data for production and consumption throughout the year and the annual energy production, it estimates the values of injected energy, withdrawn energy, self-consumed energy and the annual bill.

The excess energy produced and injected into the grid is calculated as the difference between the energy produced and the energy consumed, with negative values set to zero.

$$En_{entered} = En_{produced} - En_{consumed} \tag{16}$$

Similarly, the energy withdrawn from the grid is determined by the difference between consumption and production, with values less than zero being nullified.

$$En_{taken} = En_{consumed} - En_{produced} \tag{17}$$

Both calculation methods yield the total annual energy value and the hourly values for the entire year. However, the function related to the injected energy also returns the annual self-consumption, since it is defined as:

$$En_{self\_consumed} = En_{produced} - En_{entered} \tag{18}$$

Finally, the electric bill in €/year is obtained by multiplying the cost of electricity in €/kWh by the annually withdrawn energy.

$$En_{bill} = En_{taken} * C_{el} \tag{19}$$

4.2.2.4 Block 4: Contribution The need to handle both the SSP Contribution and RID Contribution has led to the definition, concerning the code implementation, of two derived classes. From an IT point of view, this favors the implementation of various future incentive solutions, should today's ones need to be changed.

For the calculation of the SSP Contribution, the input data required for the analysis are as follows:

1. PUN
2. PO
3. Injected Energy
4. Withdrawn Energy
5. Electricity bill

As can be observed, variables 3, 4, and 5 represent the output of the *Production and Consumption Reprocessing* [4.2.2.3] code section. Referring to Chapter [2.2.1], the energy cost is calculated as the product of PUN and the withdrawn energy, while the value of injected energy is obtained by multiplying PO by the injected energy.

At this point, the next step involves calculating CU_{sf} as follows:

$CU_{sf} = 0.2 * (El_{bill}/En_{withdrawn,year}) + 0.2 * (El_{bill}/En_{withdrawn,year})$

Finally, by utilizing the formula [1], it is possible to obtain the SSP Contribution result. Additionally, one must not overlook the share of surpluses, defined as in formula [3] and subject to taxation. The income tax rates for different income brackets to be applied are as follows:

Taxable Income	**Rate**
15000€ - 28000€	27%
28000€ - 55000€	38%
55000€ - 75000€	41%
Over 75000€	43%

Table 5: Rates for Taxable Income

As for the RID Contribution, it is determined by the product of the average RID price in 2023 [2.2.2] and the injected energy. For this value as well, the appropriate tax for the income bracket must be applied.

4.2.2.5 Block 5: Economic Dataframes The economic analysis is carried out inside Dataframes in a similar way to the one used for the *Heat Pump Integration* configuration.

The required input variables for the economic calculations are as follows:

- Cost of electricity per kWh
- Cost of gas per m^3
- Heat pump deduction and photovoltaic deduction
- Investment cost of the heat pump
- Investment cost for the photovoltaic system
- Investment cost for the replacement of the inverter in the twelfth year
- Annual electrical energy required for the operation of the heat pump
- Annual thermal demand
- SSP/RID Contribution

Subsequently, a function is defined to construct the economic dataframe. The first calculation performed is to determine the total investment cost, inclusive of the photovoltaic system and heat pump. Through deduction variables, it is possible to decide whether the incentive bonus should be applied. In cases where this needs to be considered, we have:

$$CAPEX = CAPEX_{hp} * 0.35 + CAPEX_{pv} * 0.5$$

It is assumed that the investment cost is paid in full in the first year of the system's useful lifetime, when, as seen also in the previous configuration, the revenues of the system are null.

The dataframe is constructed as follows:

- In the first column, the analysis years from 2023 to 2042 are listed.
- The second column contains the capital expenditures, and at the 11th year, the inverter replacement cost is included.
  For the investment cost it was considered that prices have a linear behaviour with respect to the plant size. Considering sizes from 3kW to 15kW and drawing a line between their respective prices, the following regression trend has been obtained:

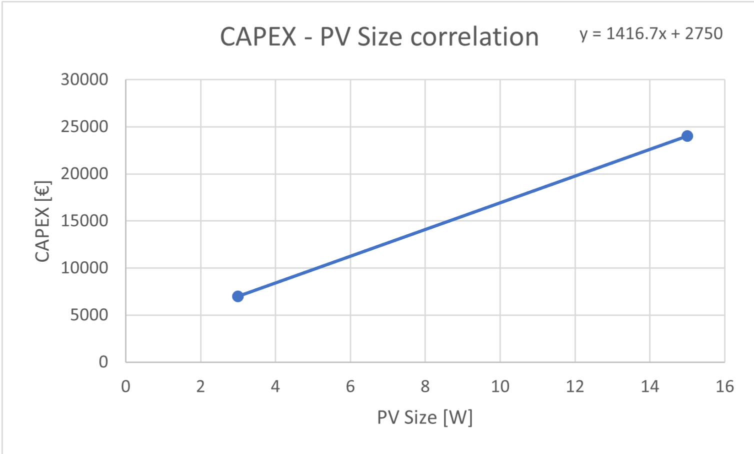


Figure 10: PV Investment Cost

This analysis allows for a better generalization on prices since their volatility is very high. In fact, it depends on the economic context, the installation company and the market period. Without a well-defined price behaviour, it would be impossible to highlight the best economic solution in a consistent way since results would be too variable. Moreover, the linear approximation represents a good estimation for CAPEX in a photovoltaic system since they are mainly given by the modules and structures prices. The larger the plant, the higher the investment cost is, thus the economy of scale is not applicable for this plant solution.
The replacement of the converter has been estimated in economic terms, considering the market base cost of the machine, an increase of approximately 30%, and installation costs. The results obtained are presented in the following table, together with the photovoltaic investment cost:

Size[kW]	**CAPEX[€]**	**Inverter Substitution[€]**
3	7000.1	566.5
4	8416.8	612.1
5	9833.5	724.9
6	11250.2	794.7
7	12666.9	873.9
8	14083.6	953.6
9	15500.3	1033.3
10	16917	1113.1
11	18333.7	1192.8
12	19750.4	1272.5
13	21167.1	1352.2
14	22583.8	1431.9
15	24000.5	1511.7

Table 6: Photovoltaic System Costs

For inverter replacement, the possibility of deducting 50% of the cost has also been included.

- The third column contains the cost of electricity. For the *Heat Pump Integration with Photovoltaic* configuration, it was decided to apply a decreasing cost of electricity, for the reasons explained in the second scenario of the *Heat Pump Integration* configuration. [4.1.2]

- Column four is the product of the electricity cost for each year and the respective grid electricity consumption, representing the operating costs of the system (OPEX).
- The fifth column calculates the cost of unused gas. This allows for a direct comparison between a system with a heat pump and one with a boiler that satisfies the same thermal demand. The values in this part of the dataframe are derived from the difference between the annual gas cost and the operating costs of the heat pump system and represent a gain.
- The sixth column includes the contribution values obtained from SSP each year. All the values are equal to zero when the RID is applied.
- Column number seven contains the surplus values given by the SSP formulas. Again, every time the RID is selected, these values are null.
- In column number eight there are the savings on the bill that are the difference between the old bill value and the new one. In case the SSP contribution is adopted, the new bill is given by the cost of the energy taken from the grid minus the contribution and the surplus values. While, if the RID is considered, it is equal to the difference between the cost of the energy taken and the cost of all the energy entered into the grid (evaluated with the mean RID price value of 2023).
- This leads to the analysis of cash flows. Proceeding step by step, the undiscounted cash flows are firstly defined:

  $$CF = Cost_{gas\_unused} + Contribution - CAPEX$$

- The application of the formula [15] with a discount rate of 5% allows for the calculation of discounted cash flow values.
- Finally, the last column of the dataframe analyzes the cumulative cash flows (CDCF).

4.3 Heat Pump, Photovoltaic, and Battery Synergy

In this section, we will discuss the differences introduced in the model for the addition of a battery to the photovoltaic system. In particular, sizes of 5kWh, 10kWh, 15kWh, and 20kWh were considered. The integration of energy storage brings about a significant change in the management of injected and drawn energy, but not in electricity production, consumption, or contribution calculation. Therefore, the Python code has been modified in only a few blocks, which are Block 3 and Block 5.
The different battery sizes have been applied indiscriminately to all solar power system sizes, with the aim of highlighting not only the optimal storage capacity but also emphasizing the impracticality of large batteries for small-scale photovoltaic installations.

4.3.1 Variables and Parameters

The input and output variables, as well as the parameters used in this configuration, are the same as those in the *Heat Pump Integration with Photovoltaic* configuration but with some additions, as outlined below.

Regarding the independent variables, the following have been added:

- Presence of the battery. In the case of storage, this input variable should be set to "yes." This enables the model to automate the calculation processes: if the battery is present, the code will perform all calculations considering storage integration; otherwise, the software will operate as in the previous configuration with the heat pump and the photovoltaic system. This type of structure allows for code optimization, including computational speed, by avoiding the need to process information related to energy storage when it is not adopted. At the same time, it enables a concise code capable of analyzing various system configurations.
- Tax deduction for the battery. Similar to the deduction for the heat pump and photovoltaic system, the input command simply requires specifying "yes" if the deduction is in place. The discount percentage is applied directly within the code.

The dependent variables remain the same as in the *Heat Pump Integration with Photovoltaic* case.
As for the global parameters, the value of DOD has been added, always set at 80%.

4.3.2 Code and Mathematical Analysis

4.3.2.1 Block 3: Production and Consumption Reprocessing Within this code block, battery management has been introduced with the aim of optimizing the system's self-consumption. To operate the storage system, however, it is necessary to first create an instance of the storage system. For this purpose, a *battery_system* class has been constructed, defined solely by the constructor method with the attributes: size, state of charge (SOC), depth of discharge (DOD).

In code Block 3, two methods were defined, one to set the battery attributes (*set_battery*) and the other for charge management (*batt_operation*).
The *set_battery* function is essential to call the *battery_system* class inside the *energy_meter* class.
Instead, the ultimate purpose of *batt_operation* is to return the values of energy injected and withdrawn for the system with storage integration, starting from photovoltaic production and user consumption.
The first command in the function is purely for control:

```
if self.battery is None:
    print("Battery not initialized. Please set the battery first.")
    return
```

It notifies the operator that the battery instance has not been initialized yet, even though the code for its operation has already been initiated. If this condition occurs, this command prints the message "Battery not initialized. Please set the battery first."

After changing the indices of the production and consumption dataframes to make them more suitable for data processing and after accessing the attributes of the Battery instance, two empty dataframes can be created, which will be populated with the values of injected energy and withdrawn energy.

The logic implemented for the operation of energy storage is as follows:

- If electricity production exceeds user consumption, there is surplus energy available. If the battery's SOC is not 100%, this surplus can be used to meet the energy demand and to store electricity in the battery until it is fully charged. If the overproduction is greater than the energy that can be used to charge the battery, the remaining portion will be fed back into the grid. In this scenario, energy withdrawn is therefore zero, while the energy injected is positive. Conversely, energy injected into the grid will be zero if the surplus is entirely used to satisfy consumption and increase the battery's charge. Finally, if the battery is already fully charged, then all surplus energy must be fed back into the grid.

- If consumption exceeds photovoltaic production, and the battery has enough charge to satisfy the entire additional consumption, there will be no energy withdrawn from or injected into the grid. In cases where the storage charge is insufficient, the maximum possible charge will be utilized (respecting the DOD, which is considered to be 80% in this model, taking Huawei batteries as an example), and the additional energy demand will be met by drawing from the grid. Finally, if the battery is already completely discharged, all additional consumption must be met by purchasing electricity from the grid.

Similar to the Heat Pump Integration with Photovoltaic configuration, the values of injected and withdrawn energy returned by the function will be annual values, resulting from the summation of all hourly values contained in the dataframes.

4.3.2.2 Block 5: Economic Dataframes The input variables for economic calculation have been extended to include:

- Economic deduction for the battery
- Battery investment cost
- Replacement cost for the battery in the twelfth year

For the analysis of the investment cost of the entire system, it is necessary to include the investment cost of storage in year zero, which, in the case of a 50% deduction, must be halved. The CAPEX related to the considered batteries and the replacement costs in the twelfth year are as follows:

Size[kWh]	CAPEX[€]
5	6000
10	8800
15	12000
20	14933

Table 7: Battery Costs

The entire procedure described has been integrated into Block 5 of the previous configuration, with an automation system that nullifies the parameters of storage in case it is not adopted. This allows for a more effective utilization of the model, even for operators with different roles from that of computer scientists.

4.3.2.3 Block 6: Main Code The Main code's purpose is to call all the classes and functions defined in the previous blocks, concatenate their outputs, or pass them as inputs to other functions.

In the **initial code segment**, the parameters required for the creation of the **photovoltaic system** are defined, which include power, the number of modules, the number of strings, and the inverter model. The number of modules to be installed for different photovoltaic powers is determined as follows:

$$N_{modules} = P_{PV} * P_{modules} \tag{20}$$

where P_{PV} is the power of the peak photovoltaic field and $P_{modules}$ is the peak power of the modules.
The value is approximated to the nearest whole number.

The inverter model is then selected from the list of *cec_inverters* created from *pvlib*. The choice is based on inverters with equal or slightly lower power than the size of the photovoltaic field and the most commonly used brands in Italy, including SolarEdge, SMA, and Huawei.

Once the technical specifications of the modules (obtained from the datasheet provided in the Appendix [A.1]) and the inverters (from the *pvlib* inverter list) are known, the number of strings for the system can be defined using the following correlations:

- Verification on the maximum voltage:

$$N_{mod\_per\_string} < \frac{V_{max\_in\_inv}}{V_{OC\_mod}} \tag{21}$$

  $N_{mod\_per\_string} \rightarrow$ number of modules per each array

  $V_{max\_in\_inv} \rightarrow$ inverter maximum input voltage [V]

  $V_{oc\_mod} \rightarrow$ modules open circuit (OC) voltage [V]

- Verification on the minimum activation voltage:

$$N_{mod} > \frac{V_{mppt\_inv\_min}}{V_{worst\_cond}} \tag{22}$$

  where:

$$V_{worst\_cond} = V_{oc@Tamb,min} = V_{oc\_STC} + \beta * V_{oc\_STC} * \Delta T \tag{23}$$

  $N_{mod} \rightarrow$ number of modules

  $V_{MPPT\_inv\_min} \rightarrow$ inverter minimum MPPT (Maximum Power Point Tracker) voltage [V]

  $V_{oc@Tamb,min} \rightarrow$ inverter open circuit voltage at minimum ambient temperature [V]

  $V_{oc\_STC} \rightarrow$ inverter open circuit voltage at STC [V]

  $\beta \rightarrow$ temperature coefficient of voltage [%/°C]

- Verification on the maximum current:

$$N_{array} < \frac{I_{max\_in\_inv}}{I_{worst\_cond}} \tag{24}$$

  where:

$$I_{worst\_cond} = I_{SC\_ref} * \frac{G}{G_{ref}} * (1 + \alpha * (T_{cell} - T_{ref})) \tag{25}$$

and

$$T_{cell} = T_{amb} + \frac{NOCT - T_{NOCT}}{G_{NOCT}} * G \tag{26}$$

$N_{array} \rightarrow$ number of strings

$I_{max\_in\_inv} \rightarrow$ inverter maximum input current [A]

$I_{SC\_ref} \rightarrow$ reference short circuit (SC) current [A]

$G \rightarrow$ irradiance for the location considered [W/m^2]

$G_{ref} \rightarrow$ irradiance in STC [W/m^2]. For the selected photovoltaic modules this value is equal to 1000 W/m^2

$\alpha \rightarrow$ temperature coefficient of current [%/°C]

$T_{ref} \rightarrow$ temperature in STC condition equal to 25°C

$NOCT \rightarrow$ Nominal Operating Cell Temperature considered equal to 45°C from the modules datasheet

$T_{NOCT} \rightarrow$ ambient temperature in NOCT conditions equal to 20°C from the modules datasheet

$G_{NOCT} \rightarrow$ irradiance in NOCT conditions equal to 800W/m^2 from the modules datasheet

It is important to remind that the model's purpose is to provide an initial feasibility analysis with an associated optimization of the photovoltaic system's size, rather than a tailored system design. Therefore, V_{worst_cond} and I_{worst_cond} are approximated to the voltage and current values at STC for the modules.
The results of this analysis are presented in the table:

Power[kW]	Number of modules	Number of strings	Inverter model
3	8	1	SE3000H
4	10	1	SE4000H
5	13	1	SE5000H
6	15	1	SE6000H
7	17	1	SE7000H
8	20	2	SPR_8000f
9	22	2	SUN2000_9KTL
10	25	1	SE1000H
11	27	3	SB11000TL
12	30	3	STP12000TL
13	32	3	STP12000TL
14	36	3	CPS_SC14KTL_DO
15	38	3	STP15000TL

Table 8: PV Data

As it can be seen, all the plants with a Solaredge inverter (from 3kW to 7kW and 10kW) are composed by just one photovoltaic string. In fact, in this case, it is required to use Solaredge optimizers and for these specific cases, considering that the modules power is lower tan 440W, it is possible to use the S440 optimizers for which a single string can be made up of 8 to 25 modules. The related datasheet is attached in the Appendix [A.2].

The subsequent steps include creating a dataframe with the table data, entering the necessary input data for photovoltaic production calculation (project name, latitude, longitude, tilt, altitude), and creating an array containing all the photovoltaic instances, one for each power from 3kW to 15kW.
After creating all the photovoltaic instances, it becomes possible to call the *pv_production* function for each of them and store the results in a production dataframe.
The *pv_production* function from *pvlib* generates a timestamp index starting from 00:10:00 on January 1st. For the subsequent analyses, it is necessary to change the index to start from 00:00:00, which is achieved with the following line of code:

```
df_production.index = df_production.index.floor('H')
```

where *df_production* is the production dataframe.

Additionally, the result of the ModelChain is the PV production for a leap year. To consider a conservative case, only non-leap years are analyzed, requiring the removal of rows in the dataframe corresponding to February 29th:

```
df_production = df_production[~((df_production.index.month == 2) &
                (df_production.index.day == 29))]
```

The production results sometimes contain negative values close to zero, likely associated with the consumption of electronic devices when photovoltaic production is insufficient. These negative values should not be considered in photovoltaic production calculations and are set to zero.

In the **second part** of the code, the user's consumption is generated hour by hour throughout the year based on the selected consumption profile. The initial step involves taking input values related to the electricity demand from the bill, the thermal requirement from the bill or law 10, and the most suitable demand profile for the case study. Subsequently, a consumption instance is created, to which the actual profile can be applied, and from which the total annual request can be generated using the *tot_consumption* method. The obtained data is then stored in a dataframe for easier and subsequent processing.

In the **third part** of the code, the only required input data are the cost of electricity per kWh and the presence/absence of the battery. The output values at the end of this code section are the annual values of injected energy, withdrawn energy, self-consumed energy and the annual electricity bill in the case of a heat pump installation and a photovoltaic system with or without a battery. If energy storage is present, the *batt_operation* function is applied to calculate injected and withdrawn energy. Otherwise, the methods described in Chapter [4.2.2.3] are used.

The **fourth part** of the code pertains to the calculation of the contribution and is therefore very brief. It solely includes the call to the derived contribution class to be applied, either RID or SSP, and the call to the method for calculating the economic contribution. Again, this portion of code is automated so that the right method is called depending on the kind of contribution set in the data input.

In the **fifth part** of the code, the economic viability of the considered systems is analyzed. Capital expenditures related to the photovoltaic system, battery, inverter replacement, and other independent model variables (gas cost, financial deductions for the heat pump, photovoltaic, and battery) are set. The code is then called to generate economic dataframes for all photovoltaic system sizes, and the IRR and NPV values are ultimately calculated.

4.3.2.4 Data Backup Data saving was performed through the logger, which is a component for recording messages or information related to the execution of a program or application. Logs are files or text outputs containing this information. The main purpose of a logger is to provide a detailed and structured record of software execution, which is extremely useful for diagnostic, debugging, and monitoring purposes.

The logger is characterized by different severity levels for each message. The most common severity levels include:

- DEBUG: Debug messages for diagnostic purposes.
- INFO: Informational messages about program execution.
- WARNING: Messages signaling potential issues.
- ERROR: Messages indicating non-fatal errors.
- CRITICAL: Messages indicating critical errors that interrupt program execution.

After importing the *logging* module, it is possible to configure the logger using *basicConfig*: specifying the log file, the minimum logging level (which is set to INFO in the model), and the log message format.

Within the calculation software, the saved information includes:

- Annual photovoltaic energy production.
- Total annual electricity consumption, including the heat pump.

- Values of electricity taken from the grid and injected, along with corresponding bills for all photovoltaic system sizes.
- The contribution provided by the tax deduction for each photovoltaic system size.
- The size of the heat pump and its respective investment cost.
- NPV (Net Present Value) and IRR (Internal Rate of Return) for each analyzed solution.

4.4 Graphical User Interface

To further facilitate the use of the software by personnel outside the IT department, a graphical user interface (GUI) has been created for inputting values and viewing output results. The GUI was developed using the Tkinter library, which is well-suited for small-scale applications. Tkinter supports all major operating systems, including Windows, macOS, and Linux, which is its primary advantage. [21]
The user interface was primarily designed for practical usability rather than focusing on aesthetic appeal.

To avoid launching the software through PyCharm, it is possible to create a desktop icon that performs the same function as the 'RUN' button in the development environment. To achieve this, it's needed to create a batch file that contains the run command, the directory for activating the correct Python environment, and the name of the Python file to be executed. Since the software developed uses a Miniconda environment, it is required to first provide the directory to activate Conda using the activate.bat script within the Miniconda installation.
In the context of this thesis, the icon was created using Canva.

The Input Collection window is as follows:

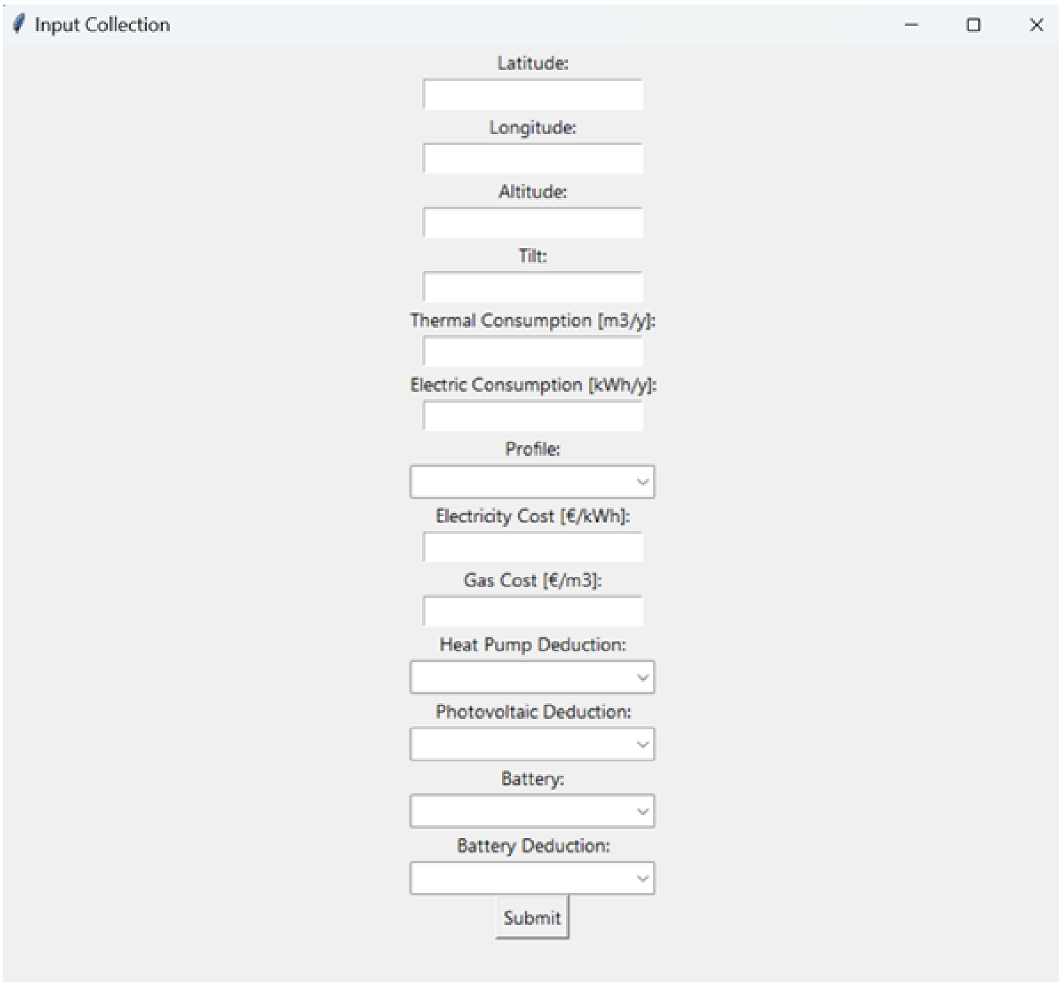


Figure 11: GUI Interface

The required inputs are the global ones for configurations 2 and 3. Once the requested data has been entered, it can be submitted through the designated 'Submit' button. To facilitate the data input, a drop down list widget is used for the available consumption profiles and the "yes" or "no" option for deductions and for the battery adoption.

The GUI related to the results has been structured to provide the main output data of the software:

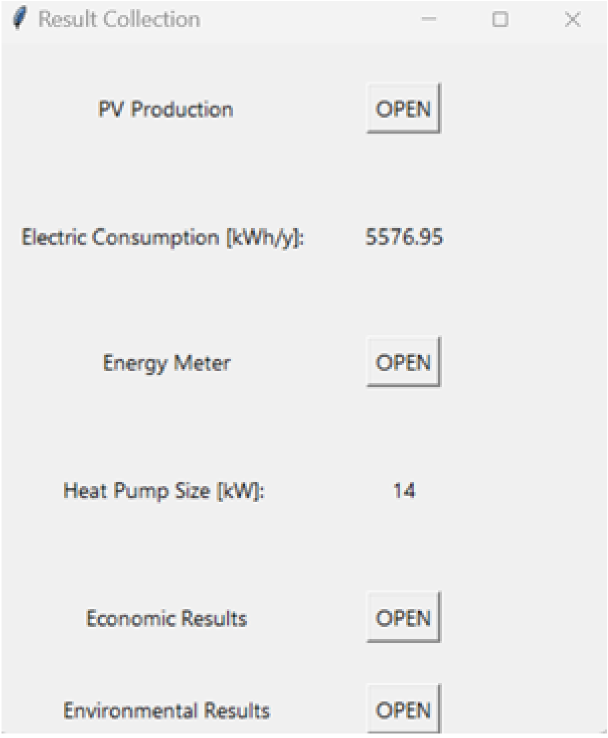


Figure 12: GUI Results

By clicking on the 'OPEN' button associated with PV Production, a new window is generated, allowing to view the production chart for each photovoltaic size:

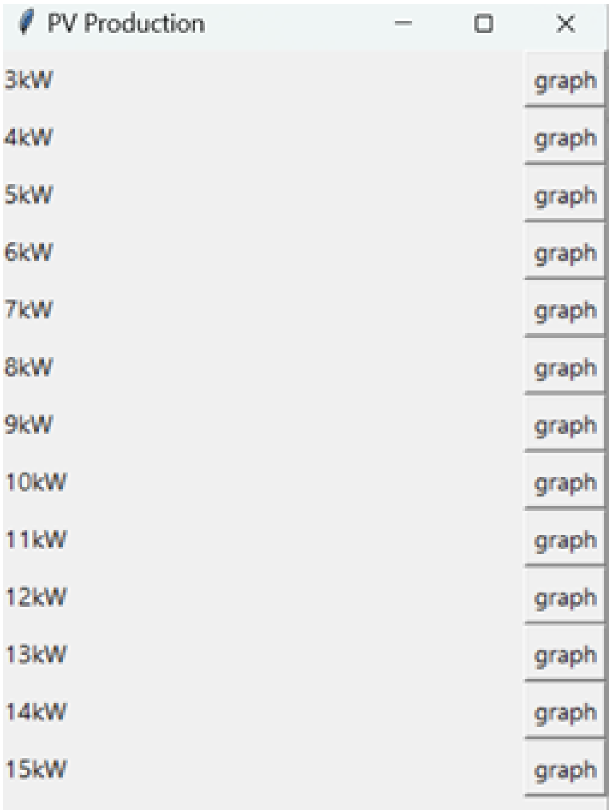


Figure 13: GUI PV Production

For example, clicking on the 'graph' button for the 5kW system generates the following chart:

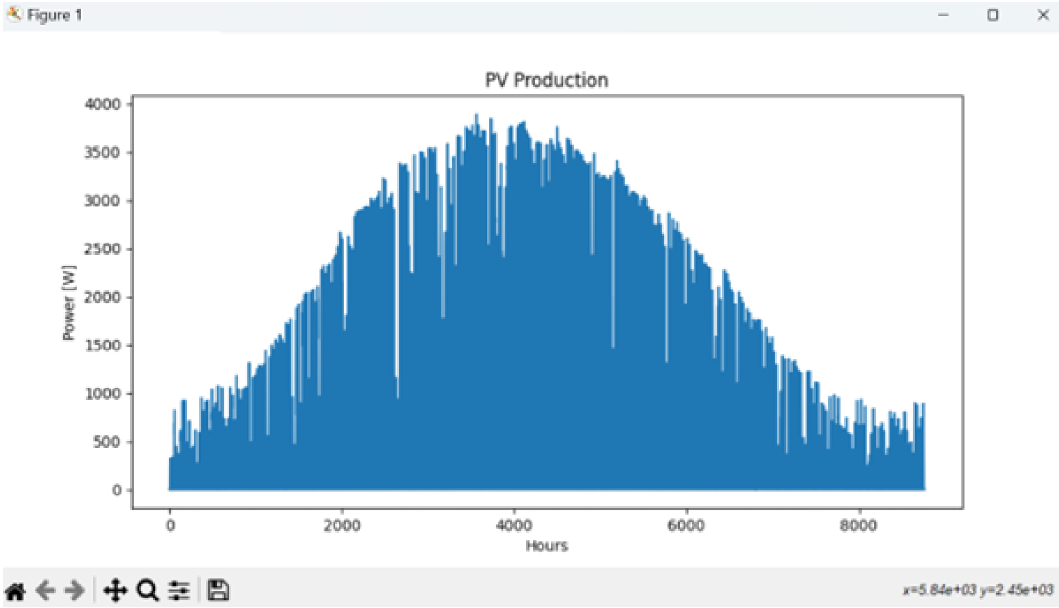


Figure 14: GUI PV Production graph

Next, the annual electricity consumption values in [kWh/yr] and the size of the heat pump in [kW] are displayed. By pressing the 'OPEN' button for Energy Meter, the following window appears:

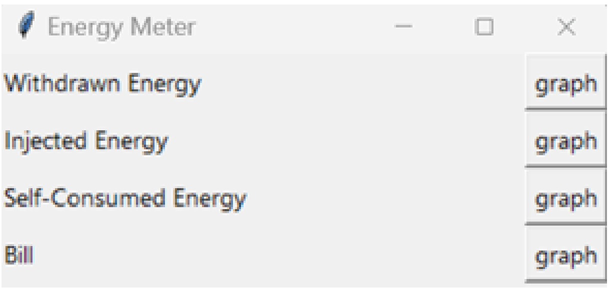
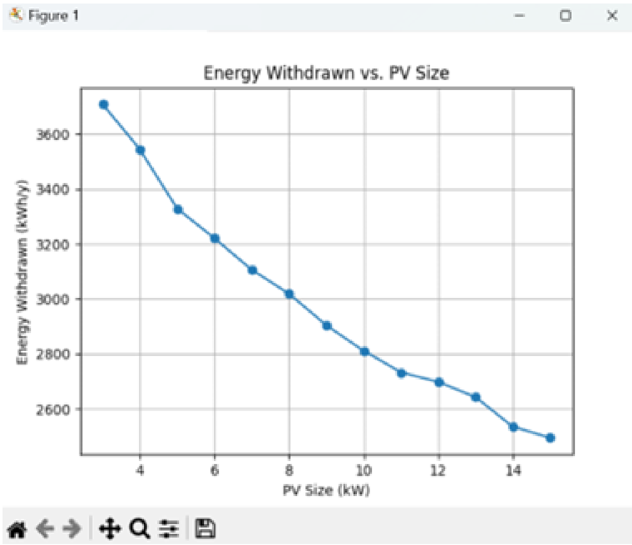
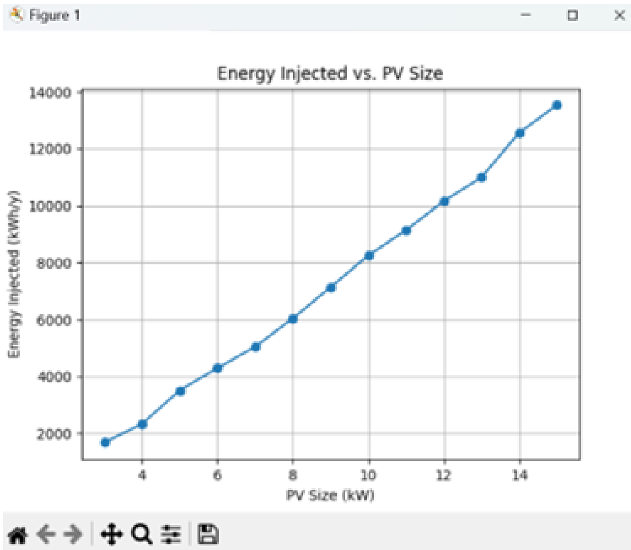


Figure 15: GUI Energy Meter

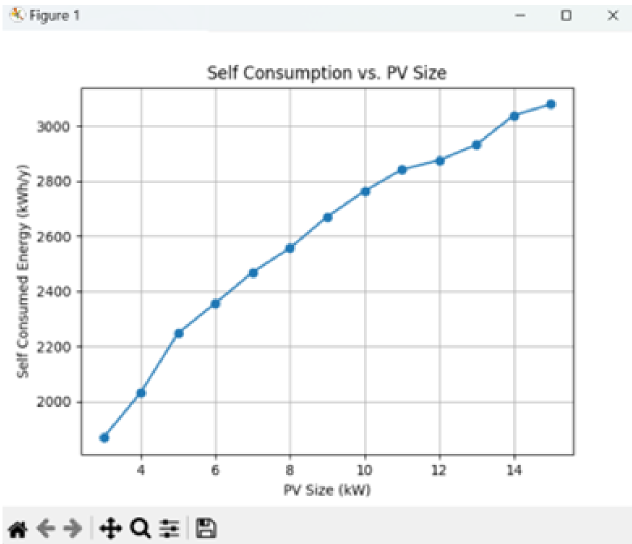
It is therefore possible to view the charts for the energy drawn, energy fed back, self-consumed energy, and the bill for each size of photovoltaic system:



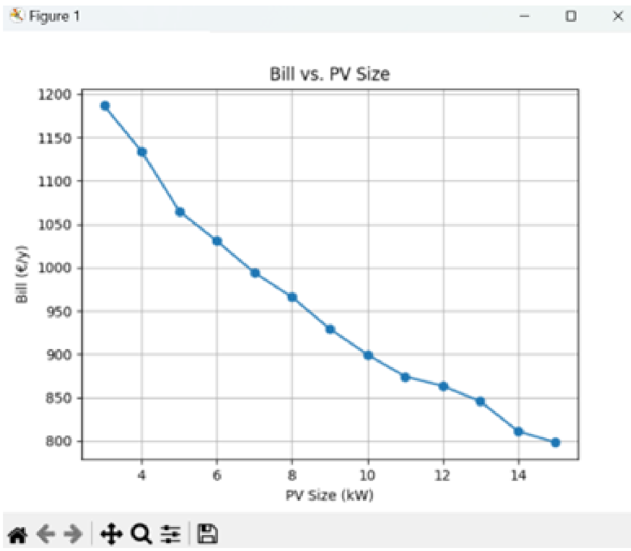
(a) *Withdrawn Energy*



(b) *Injected Energy*



(c) *Self-Consumption*



(d) *Bill*

Figure 16: Energy Meter graphs

By clicking the 'OPEN' button for Economic Results, it is possible to view the cash flow bar chart for each photovoltaic size and the IRR-PV Size chart to quickly determine the most cost-effective photovoltaic solution:

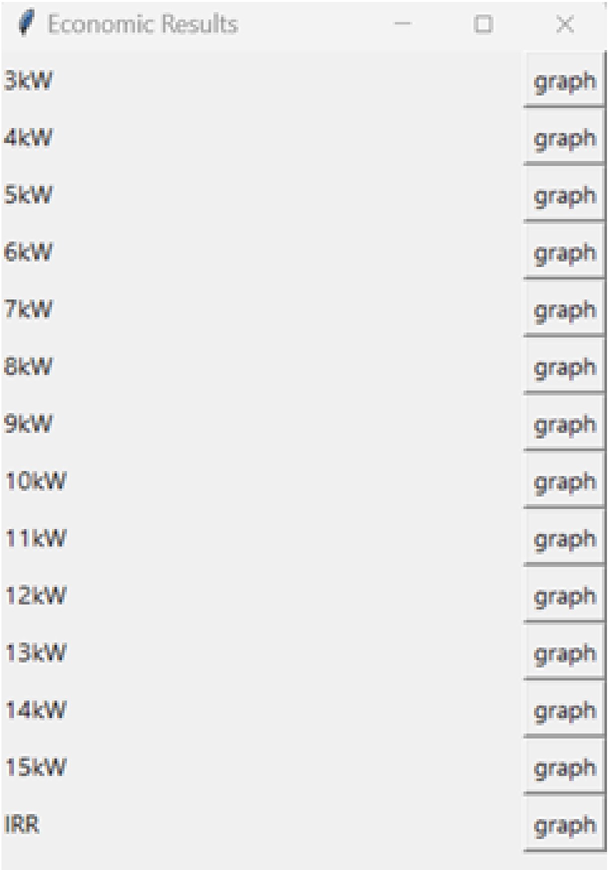


Figure 17: GUI Economic Results

For instance, the 5kW system exhibits a cash flow over its lifespan as shown in the chart:

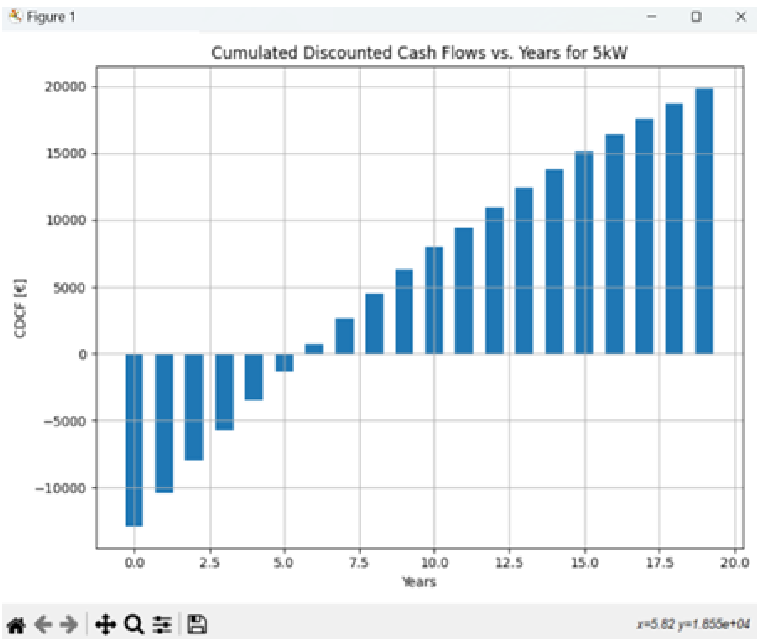


Figure 18: Cash Flows

While the IRR chart reveals that the best solution in terms of the internal rate of return is the 5kW system. A more in-depth analysis will be conducted in the results chapter [6].

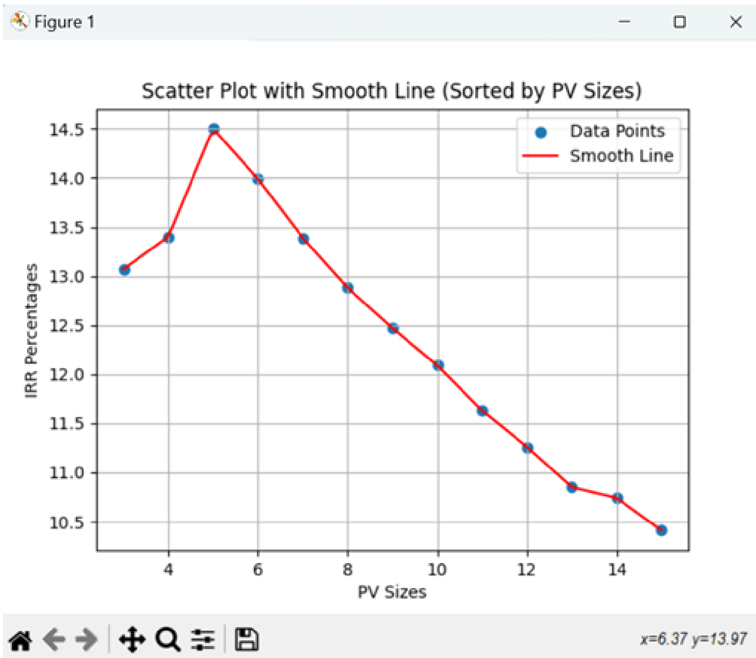


Figure 19: IRR

Finally, by using the 'OPEN' button in the Environmental Results section, it is possible to access charts related to avoided CO_2 emissions and equivalent planted trees:

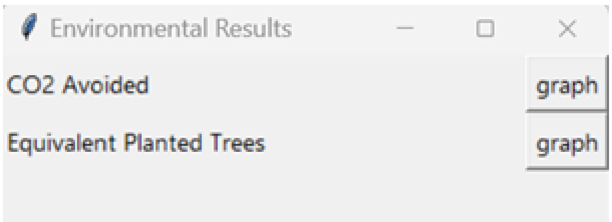
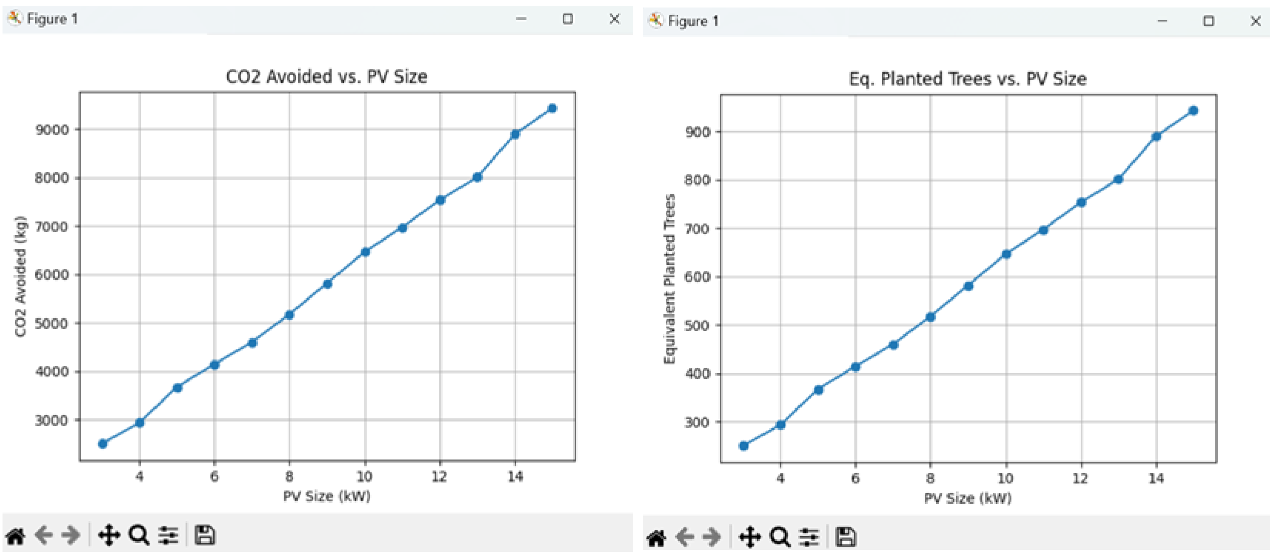


Figure 20: GUI Environmental Results



(a) CO2 Avoided *(b) Equivalent Planted Trees*

Figure 21: Energy Meter graphs

All the GUI windows presented till this point are the ones related to the *Heat Pump Integration with Photovoltaics* configuration. Concerning the addition of the chemical battery, the Economic Results window was structured differently, in order to show all the results related to the various combinations given by PV size and storage capacity. Thus, this results window appears as follows:

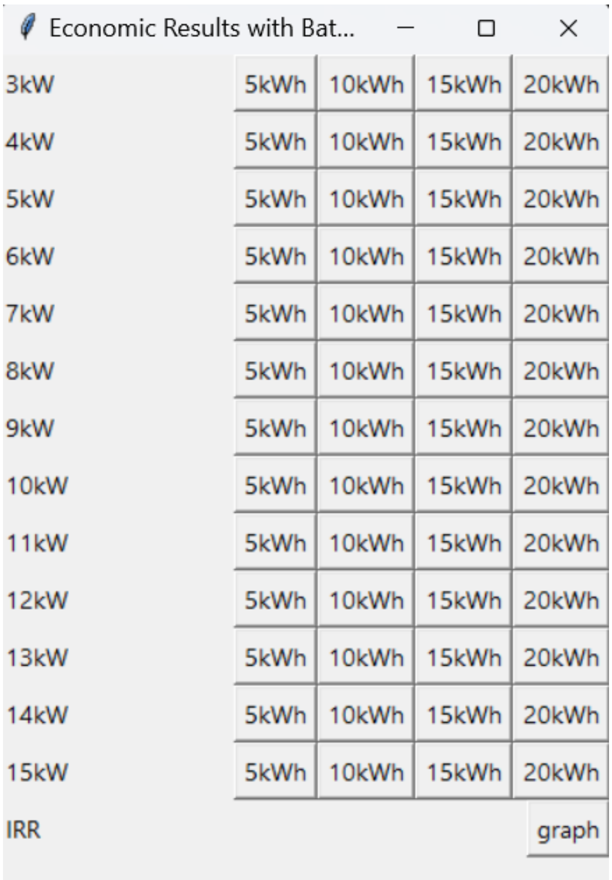


Figure 22: GUI Economical Results with Battery

Although this interface is designed to assist the operator in using the software, some improvement modifications could be added. For example, utilizing a Google Maps API to directly input the customer's address instead of their latitude, longitude, and altitude or incorporating a loading window during the code execution.

4.5 Python Libraries

The development of the analysis and optimization software involves the use of several libraries. For a more comprehensive description of the model, the following list provides the libraries used and their functions within the code.

- **Pandas** is an open-source Python library specialized in data manipulation and analysis. It is widely employed in fields where the management of structured data is essential. The DataFrame is the primary data structure in Pandas, representing data in a tabular form with rows and columns. This structure resembles a spreadsheet or a database table and offers a high degree of flexibility for data manipulation. Pandas facilitates data importation from a wide array of sources, including CSV files, Excel files, databases, and more. Additionally, data can be exported in various formats. This library is utilized in all of the code blocks described.

- **Matplotlib** is a widely used Python library for creating graphics, such as line plots, scatter plots, bar charts, histograms, and more. It is a powerful tool for data visualization and is commonly used in scientific and data analysis projects. This library is used for a better visualization of results, that will be presented in the next chapters.
- **Openpyxl** is a Python library for reading and writing Excel files. It provides a powerful and flexible way to create, modify, or extract data from Excel workbooks. This module is used at the end of the code in order to save the economic dataframes into an Excel file, this allows to perform the final data processing also with Excel worksheets.
- **Numpy-financial** The numpy-financial package contains a collection of elementary financial functions like the calculation of the future value, the internal rate of return, the interest portion of a payment, the net present value of a cash flow series and the rate of interest per period. In this study, this module was used to calculate the IRR after the creation of the economic dataframes.
- **Logging** As already mentioned previously in the Chapter [4.3.2.4], this library was used for saving data throughout the code.
- **Pvlib** Pvlib (or Photovoltaic Library) python is a community supported tool that provides a set of functions and classes for simulating the performance of photovoltaic energy systems. It provides a wide range of tools and functions for modeling and analyzing the behavior of photovoltaic systems. This library is used for the analysis of the photovoltaic plant production and, in particular, the following packages were used:
  1. **ModelChain** The ModelChain class provides a standardized, high-level interface for all of the modeling steps necessary for calculating PV power from a time series of weather inputs. It include various methods but the one used for the model analysis is *ModelChain().run_model_from_poa(data)* that runs the model starting with broadband irradiance in the plane of array. The useful results are given by *ModelChain().results.ac*
  2. **Location** Location objects are convenient containers for latitude, longitude, timezone, and altitude data associated with a particular geographic location. It is required to define the location of the photovoltaic system that is required as input by the ModelChain.
  3. **PVSystem** The PVSystem is a fundamental class used for modeling a photovoltaic system. It represents a photovoltaic system, including the photovoltaic modules, inverters, and associated parameters that affect its performance. PVSystem objects are used for simulating and analyzing the behavior of PV systems in various environmental conditions.
  4. **TEMPERATURE_MODEL_PARAMETERS** The temperature module contains functions for modeling temperature of PV modules and cells. The output obtain is then used as an input for the PVSystem class.
- **Tkinter** The tkinter package ("Tk interface") is the standard Python interface to the Tk GUI toolkit, which is used for building graphical user interfaces. More specifically, a GUI is a type of interface that allows users to interact with a computer or software application using graphical elements such as windows, icons, buttons, and menus, rather than solely relying on text-based commands. The GUI is called at the beginning of the code, in order

to display the input data window and to collect the independent variables. This library was used to model the GUI described in Chapter [4.4].

5 Model Validation

The validation of the developed calculation model allows us to verify the correctness of the results generated by the software. To ensure the objectivity of this process and considering the absence of calculation models with a similar function in the market, it was decided to use an analysis platform that closely resembles the one developed in the course of this thesis. The chosen solution involves the use of Solaredge Designer, a free online tool that enables the complete design of any photovoltaic system.

As it can be inferred, the Designer tool does not perform the same calculation functions as the developed software. Therefore, the initial step involves studying the operation of the online tool and subsequently adapting the software to its specific features values. This adaptation enables a comparison between the two calculation solutions.

To facilitate the treatment of this chapter, particularly the comparisons between the two tools, the thesis sotware will be indicated with the acronym TGH (Towards Greener Homes) while Solaredge Designer with the acronym SED.

5.1 Solaredge Designer

As the focus of this thesis is not centered on the use of this online platform, it is recommended to refer to the official Solaredge website for information on how to use the Designer [22].

However, the following features of SED are listed below to facilitate the understanding of how TGH was temporarily adapted for the subsequent comparisons.

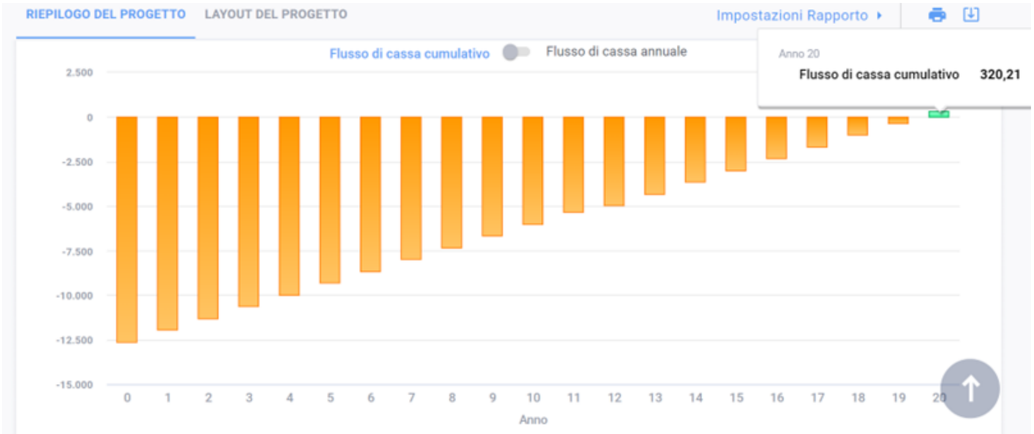
The first noteworthy feature is related to the type of contribution used by SED. Since the Designer is a tool available to all Solaredge users worldwide, the choice of remuneration for exchanged energy is based on RID, as it is a more widespread contribution type than SSP. Therefore, SED serves as a suitable validation tool for RID but not for SSP. For the latter, a better economic return is expected, as it includes not only excess payment but also the Cs contribution.

Secondly, in the "Summary and Report" section of SED, it is essential to note that the cash flows presented in the bar chart are not discounted. This statement can be easily verified by changing the discount rate percentage in the "Financial Analysis" section. For instance, by varying the discount rate from 0% to 5%, one can observe that the cash flow remains the same, while the following elements change:

- Maintenance cost (NPV)
- Lifetime bill savings (NPV)
- System benefits (NPV)
- Return on investment (ROI)
- Levelized cost of energy (LCOE)

Thus the comparison between the cash flows in SED and TGH must be done on the Cumulated Cash Flows (CCF), without the application of the discount rate.
For completeness, the following two images show Solaredge reports created with two different discount rates:

(a) Economic parameters



(b) Cumulated Cash Flow

Figure 23: Solaredge Report - 0% discount rate

(a) Economic parameters

(b) Cumulated Cash Flow

Figure 24: Solaredge Report - 5% discount rate

5.2 Data Details

To validate the model, it was necessary to define the calculation parameters and settings used.

Regarding the cost of electricity, it was set to €0.308/kWh in both SED and TGH with a scenario of constant price for all the 20 years of operation.

Electricity production should be the same for both models. An initial analysis on Solaredge revealed a discrepancy in photovoltaic production estimates compared to TGH: a 3kWp system with the same modules (Jinko 410W) and the same inverter (SE3000H) produces approximately 4000kWh/yr on SED, while the calculation model yields around 3375kWh/yr.
According to the European Commission [23], the average annual photovoltaic production in northern Italy is approximately 1100kWh/kWp. For a 3kWp system, this results in an estimated production of 3300kWh per year, much closer to the TGH value than SED. Therefore, the value obtained from TGH can be considered correct, and the model validation proceeds by adjusting the system's power in Solaredge to achieve an annual production as close as possible to 3375kWh/yr. Thus, for the PV design in SED, 6 modules are used instead of 8, obtaining a peak photovolatic power of 2.46kWp. With this PV configuration, the production is 3000kWh/yr.

Next, the annual consumption values need to be entered. Both calculation tools used a consumption of 4281kWh/yr, including the electrical demand of standard appliances (e.g., refrigerator, computer, television, lighting, etc.) and the energy requirement by the heat pump.

Another parameter to consider is the location, which must be the same for both analyses.

Finally, it's important to set the correct consumption profile. In this regard, the decision was made to adapt the Solaredge consumption profile in the initial "Consumption" section to that of TGH . This choice was made to simplify the data adjustment process. TGH applies an hourly consumption profile throughout the year, while SED uses consumption percentages for different time slots. It is, therefore, easier to pass from more specific data to approximate data rather than the opposite. Once the "Custom Consumption Profile" is selected in SED, consumption data can be loaded at intervals, which were obtained through Excel reprocessing. The consumption profile used in the TGH simulation (2 people, of which 1 is a worker) and adapted to the input requirements for SED is as follows:

Time Slot	**Percentage [%]**
00:00 - 06:00	5
06:00 - 10:00	16
10:00 - 14:00	18
14:00 - 18:00	30
18:00 - 00:00	31

Table 9: Solaredge Custom Profile

It is also important to emphasize that Solaredge is not capable of performing a comprehensive economic analysis that includes the gains from not using natural gas. Its purpose is indeed to consider only the photovoltaic system. Therefore, the validation of the TGH model was carried out by excluding the costs related to the non-use of natural gas resulting from the adoption of the heat pump in place of the boiler.

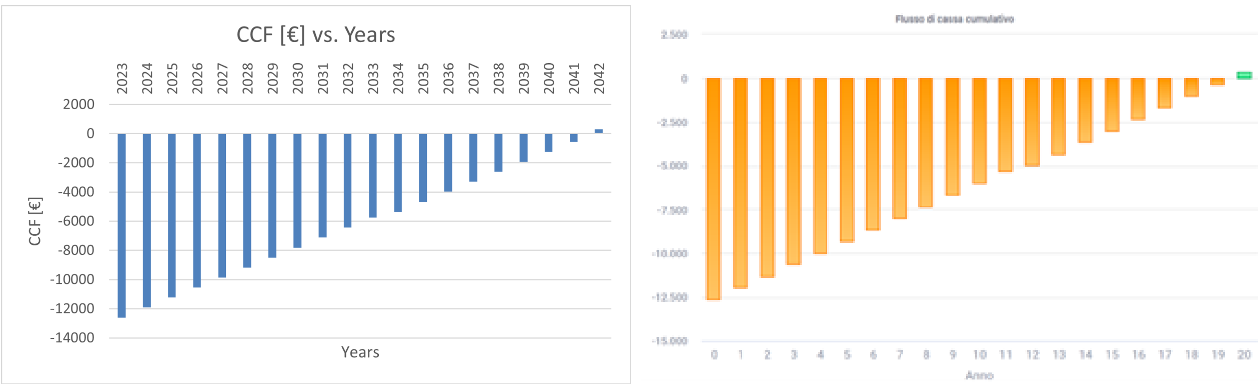
5.3 Results

The use of TGH with a RID contribution resulted in the following outcomes:

Years	CAPEX [€]	El. Cost [€/kWh]	Bill Saving [€/yr]	CF [€/yr]	CCF [€]
2023	12600	0.308	0	-12600	-12600
2024	0	0.308	684.97	684.97	-11915
2025	0	0.308	684.97	684.97	-11230
2026	0	0.308	684.97	684.97	-10545
2027	0	0.308	684.97	684.97	-9860
2028	0	0.308	684.97	684.97	-9175
2029	0	0.308	684.97	684.97	-8490
2030	0	0.308	684.97	684.97	-7805
2031	0	0.308	684.97	684.97	-7120
2032	0	0.308	684.97	684.97	-6435
2033	0	0.308	684.97	684.97	-5750
2034	283	0.308	684.97	684.97	-5348
2035	0	0.308	684.97	684.97	-4663
2036	0	0.308	684.97	684.97	-3978
2037	0	0.308	684.97	684.97	-3293
2038	0	0.308	684.97	684.97	2608
2039	0	0.308	684.97	684.97	1923
2040	0	0.308	684.97	684.97	1238
2041	0	0.308	684.97	684.97	-553
2042	0	0.308	684.97	684.97	131

Table 10: TGH RID validation results

The results from SED are presented in the Solaredge Designer report in the appendix [A.3].



(a) CCF TGH *(b) CCF SED*

Figure 25: Comparison CCF - TGH vs. SED

After comparing the results from both software tools, it is possible to proceed with the data analysis, comparing the two solutions.

Comparing the results of TGH with those of SED:

- The system cost is €12,600 and it is the same in both scenarios. It is inclusive of the photovoltaic system and the heat pump, with a 50% deduction for the former and a 65% deduction for the latter.
- The inverter substitution cost is €283 for TGH and €285 for SED, thus they are quite equal.
- The electricity cost is €0.308/kWh in both cases.
- The annual bill savings amount to approximately €680 for TGH and €660 for SED. The results differ by only 3%, confirming the accuracy of the TGH calculation.
- The CCF value for the last year of the system's life is approximately €130 for TGH and €320 for SED. This value also attests to the model's reliability, indicating that the PBT is the same in both calculation systems, with a gain difference of only about €190.

Regarding the comparison of the software with the SSP contribution, as mentioned earlier, a direct comparison between the models is not feasible. However, it is expected that the TGH's SSP solution will offer a more favorable economic evaluation compared to SED's RID solution. From the analysis results, it is evident that, for TGH and SSP, the IRR is higher, the NPV has increased, and the PBT in the SSP has decreased, transitioning from the last year of the system's life to the sixteenth year. This confirms the expectations, demonstrating the accuracy of the SSP calculation model.

To avoid misunderstandings, it should be noted that, for the RID solutions of TGH and SED, the investment payback time only occurs in the final year of the system's life. For an investor, this result serves as a warning sign for an unprofitable investment. However, it should be acknowledged that these results are not intended for the final economic analysis of the *Heat Pump Integration with Photovoltaic*, but are solely designed for model validation. In this section, the photovoltaic investment cost is artificially inflated, as it also includes the installation of the heat pump, but it does not account for the gains related to the non-use of gas, which cannot be included in the analysis using Solaredge Designer.
In the following section, the results will be presented, and the gas savings component will be included, as it is a significant factor in the economic analysis.

6 Results Analysis

In this section, some results and considerations obtained from the use of the model in the three different configurations will be presented.

Given the need to compare the solutions obtained from the different configurations, it was decided to adopt a single case study to which to apply the calculation model. The chosen case study is characterized by:

- latitude = 45.73037830851841
- longitude = 9.155297727573705
- altitude = 354
- tilt = 20°
- thermal consumption = 1291 m^3/yr
- electric consumption = 2364 kWh/yr
- consumption profile = ”2 people (of which 1 worker) percentage”
- electricity cost = €0.32/kWh
- gas cost = €1.68/m^3
- PUN = €0.12875/kWh
- PO = €0.09/kWh
- tax for income declaration = 30%

The findings outlined in the following subsections shed light on key aspects, such as cost-effectiveness.
Furthermore, we will talk about a convenient investment for IRR values greater than or equal to 5%. However, keep in mind that the convenience of an investment depends on various factors, such as the hurdle rate, risk tolerance, PBT and investment objectives.

6.1 Heat Pump Integration

For this initial configuration, the only data relevant to the analysis include the cost of natural gas, the cost of electricity, and the annual thermal consumption. The remaining data listed above are useful just for the other two configuration, where the photovoltaic production is taken into consideration.

Based on the heat pump sizing, it was necessary to install a 15kW unit to meet the entire thermal demand. The selected capacity corresponds to an investment cost of €26,000.

As explained in Chapter [4.1.2], various scenarios were adopted for the economic analysis in different potential future situations.

Regarding the scenario with constant gas and electricity costs, the Excel calculation model predicts a PBT in the eleventh year, an IRR of 5%, and a NPV of €4,704.78. Graphically:

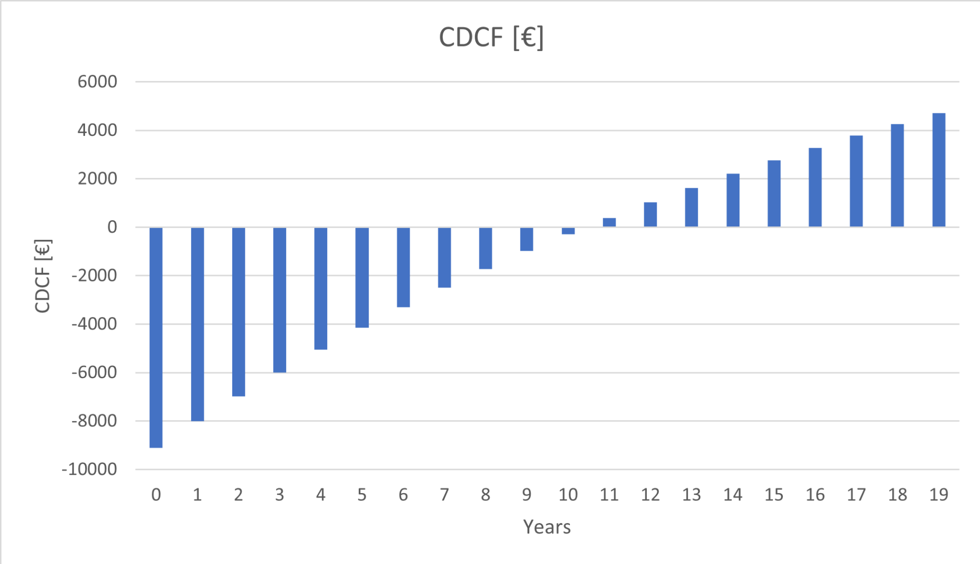


Figure 26: CDCF - Heat Pump Integration - Scenario 1

The second scenario presented is the one with constant gas cost and decreasing electricity cost. If the price per kWh decreases over the years, the replacement of the boiler with a heat pump becomes even more cost-effective since the heat pump helps reduce gas consumption while increasing electrical consumption. In line with the reasoning just explained, the model demonstrates a three-year improvement in Payback Time compared to the previous case, an IRR value doubled (10%), and a Net Present Value of €9,552.63:

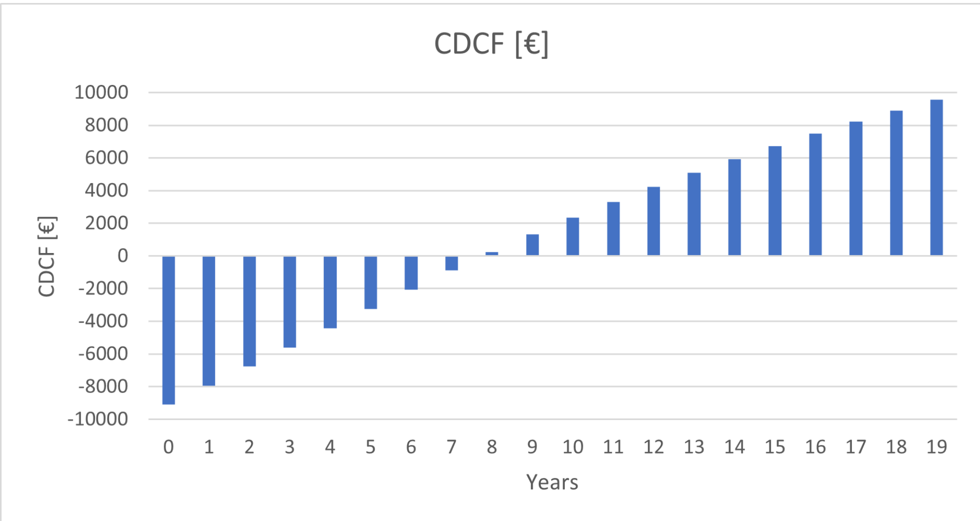


Figure 27: CDCF - Heat Pump Integration - Scenario 2

In the case where electricity prices follow an increasing trend over the years, with constant gas costs, the economic parameters would deteriorate compared to those of the first scenario. However, the solution obtained would still be cost-effective compared to maintaining the boiler. This is justified by the higher gas cost, which electricity would not even match in the last year of the system's useful life, a year in which the cost of electricity would have reached its highest value. Through numerical analysis, a PBT of 13 years, an Internal Rate of Return of 3%, and an equal NPV of €2,329.89 were obtained:

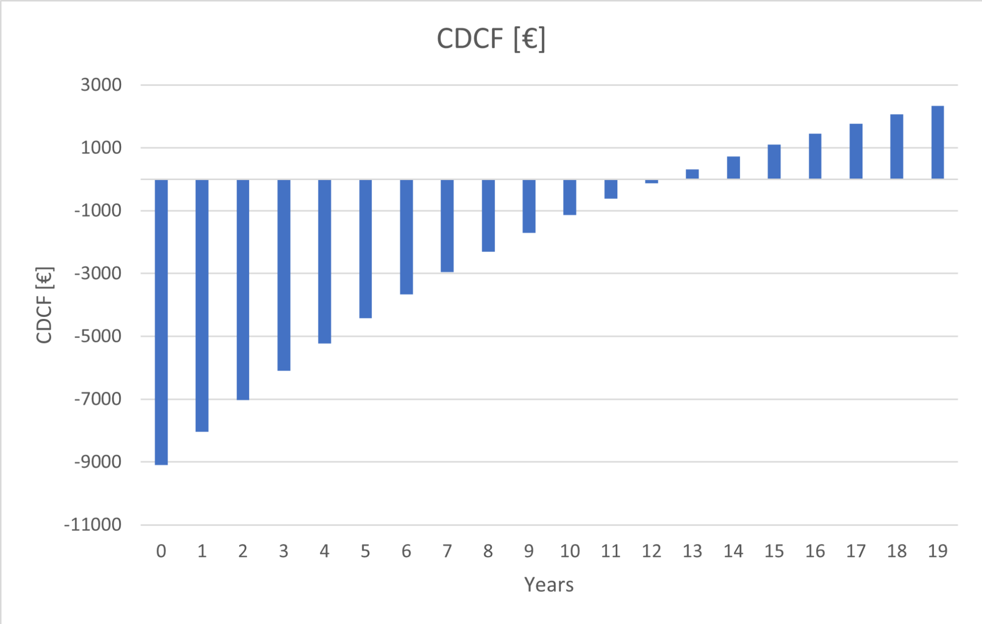


Figure 28: CDCF - Heat Pump Integration - Scenario 3

Finally, the last scenario with decreasing electricity prices and increasing gas costs is the most profitable, with an IRR of 11%, a PBT in the eighth year, and an NPV of €11,408.6:

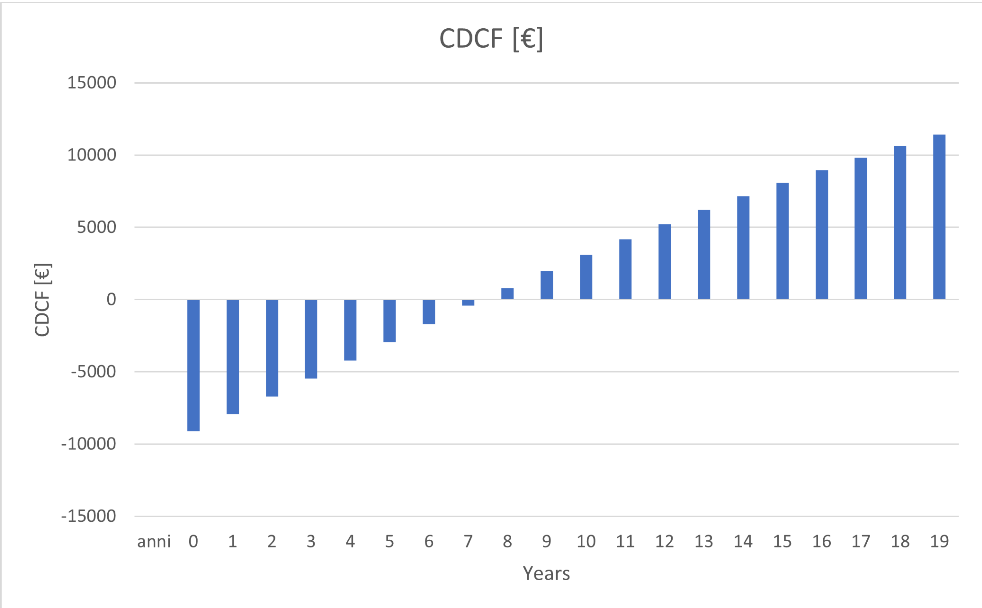


Figure 29: CDCF - Heat Pump Integration - Scenario 4

An additional scenario, which represents the worst-case scenario, could be considered: increasing electricity prices and decreasing gas costs. However, this scenario was not included in the analysis as it is presumed to be unlikely to occur. A reduction in gas costs in the face of a continuously increasing global energy demand would strongly promote its adoption, contradicting the policies aimed at combating climate change, enhancing European energy security, and increasing electrification of systems.

Finally, it may be interesting to understand what happens if the heat pump deduction is absent. This case is studied with reference to constant gas cost and electricity cost during the lifetime. The results show that the investment convenience is lost due to the high investment costs:

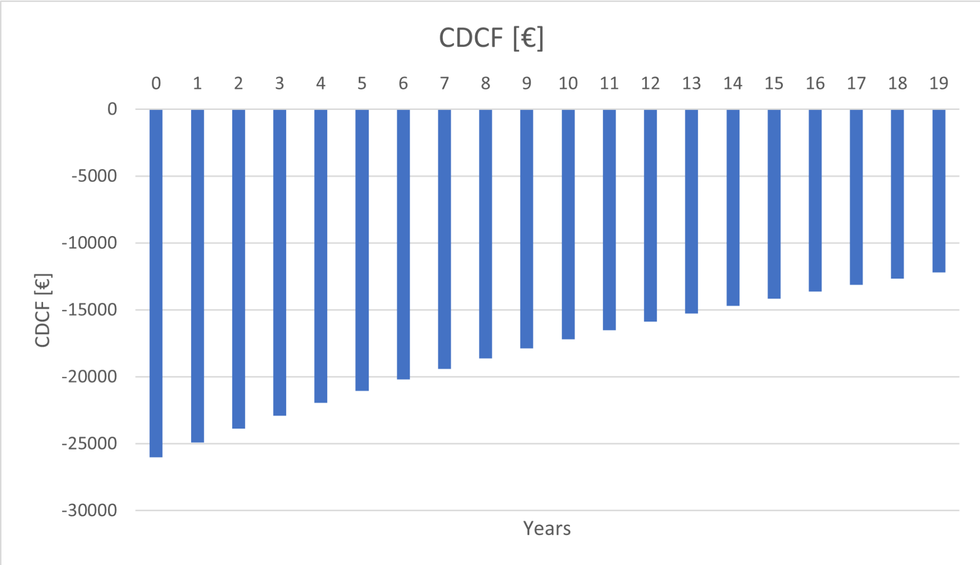


Figure 30: CDCF - Heat Pump Integration - No Deduction

Analyzing all the obtained results, it can be observed that the scenario with constant gas and electricity costs represents a kind of baseline case, from which we deviate positively or negatively at different severity levels with the other scenarios.
Furthermore, it is evident that replacing the boiler with a heat pump in the studied case is always cost-effective if the deduction is present. Even in the worst-case scenario (28), there is a positive internal rate of return, although the cost-effectiveness in this case is not high. It is essential to remember that the benefits are not only financial but also ecological, thanks to the reduction in avoided CO2 emissions and this analysis is carried out in chapter 7.
However, the investment is no more feasible if the deduction is absent. Thus suggesting that the heat pump is a technology that is not yet mature and, therefore, requires government interventions for its adoption.

6.2 Heat Pump Integration with Photovoltaic

The results of the *Heat Pump Integration with Photovoltaic* configuration have been analyzed considering a decreasing cost of electricity and a constant gas price. The following scenarios were derived:

1. With a 50% tax deduction for the photovoltaic system and a 65% deduction for the heat pump.
2. With a 50% tax deduction for the photovoltaic system but no deduction for the heat pump.
3. With no tax deduction for the photovoltaic system but a 65% deduction for the heat pump.
4. With no tax deduction at all.

In contrast to the previous section, for this configuration, there are various system sizes (ranging from 3kW to 15kW) for which the optimal solution is evaluated.

The study of the first case with deductions for both technologies shows a high level of cost-effectiveness for all photovoltaic system sizes. As observed in the following figure, the lowest IRR value is still above 10%.

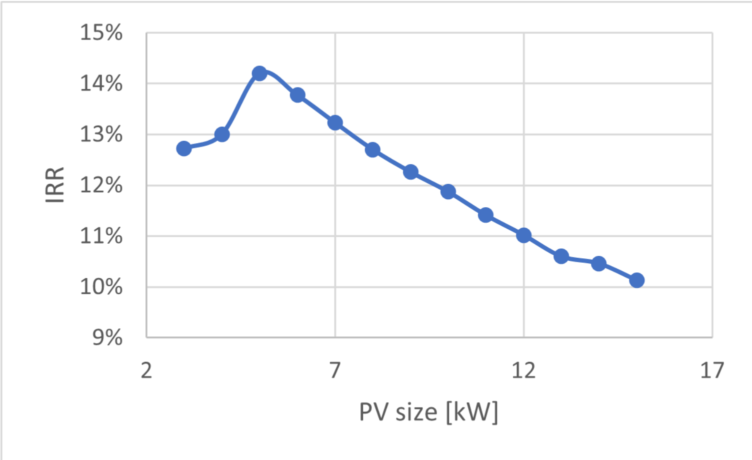


Figure 31: Size-IRR comparison

However, the aim of this thesis is to highlight the best solution, which in this case is represented by the 5kW system, with an IRR of 14.20% and a PBT of 7 years. Regarding NPV, the best solution is instead the 15kW system.

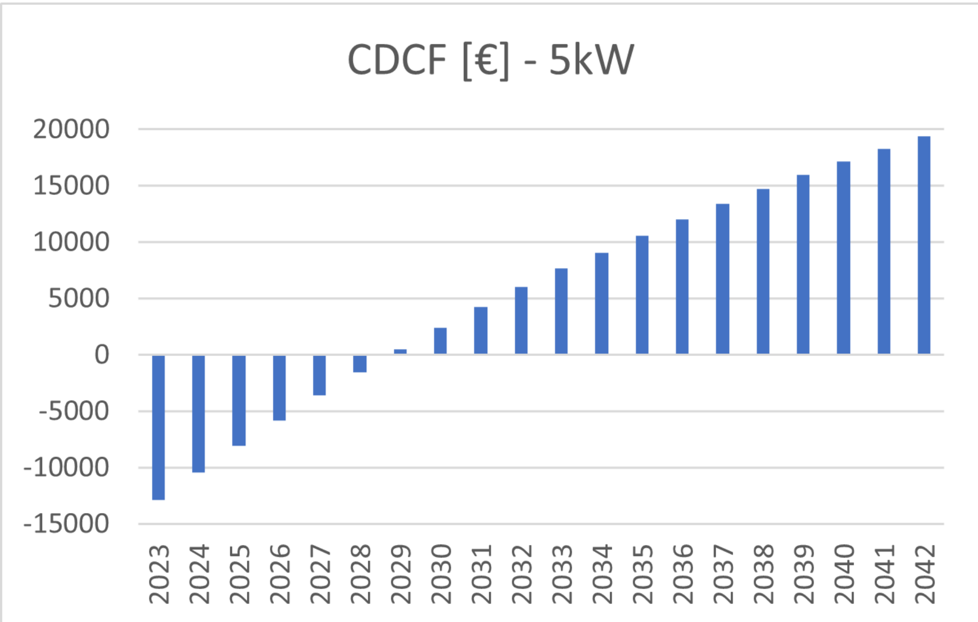


Figure 32: CDCF - HP + PV - Case 1

In the second scenario, the 5kW system becomes profitable only in the second-to-last year of the system's life, but it is no longer the best solution. Without the possibility of deducting the investment cost of the heat pump, the economic optimum shifts to larger photovoltaic systems, allowing the exploitation of the gain from electricity overproduction. However, the profit achievable in this case is very low, with an IRR not exceeding 1%, making it an unprofitable and high-risk investment with an extended PBT.

Removing the 50% deduction for photovoltaic CAPEX in the third scenario leads to the same conclusions as the second scenario. In this case, the optimal system size is 5kW. This size not only provides the best IRR and PBT compared to other system configurations but also boasts the highest NPV. It's worth noting that in this scenario, as the entire investment cost of the photovoltaic system needs to be amortized, the PBT extends by 3 years compared to the second scenario, and the IRR decreases to 8.11%.

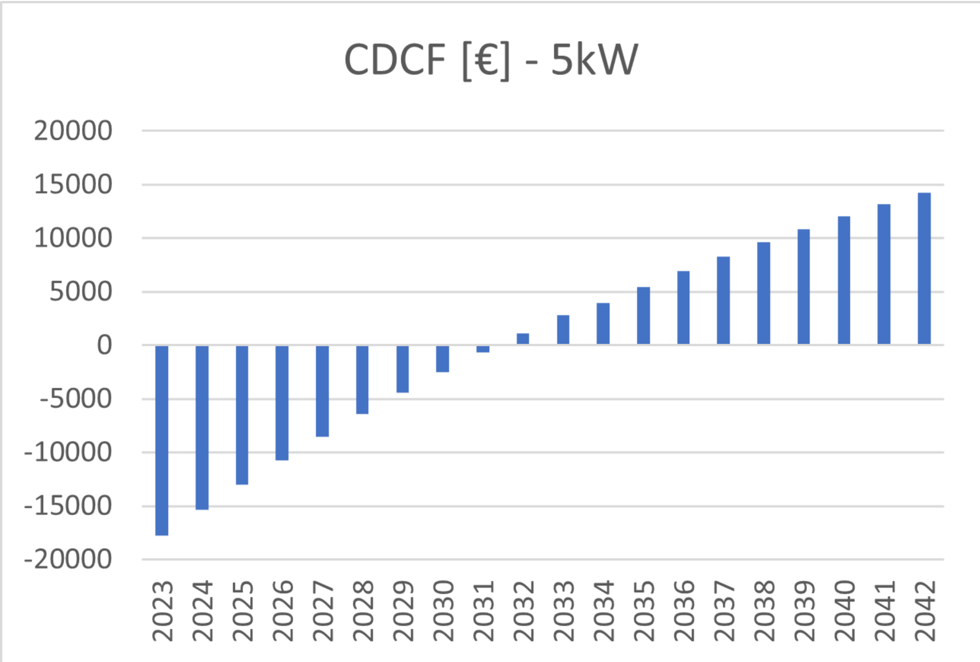


Figure 33: CDCF - HP + PV - Case 2

Lastly, in scenario number 4, it's not possible to recover the investment for any photovoltaic system size. The investment cost is too high to be recouped before the heat pump system along with the photovoltaic system is retired. The best solution in terms of IRR is the 5kW system, yet it still exhibits a negative internal rate of return, indicating an unprofitable investment.

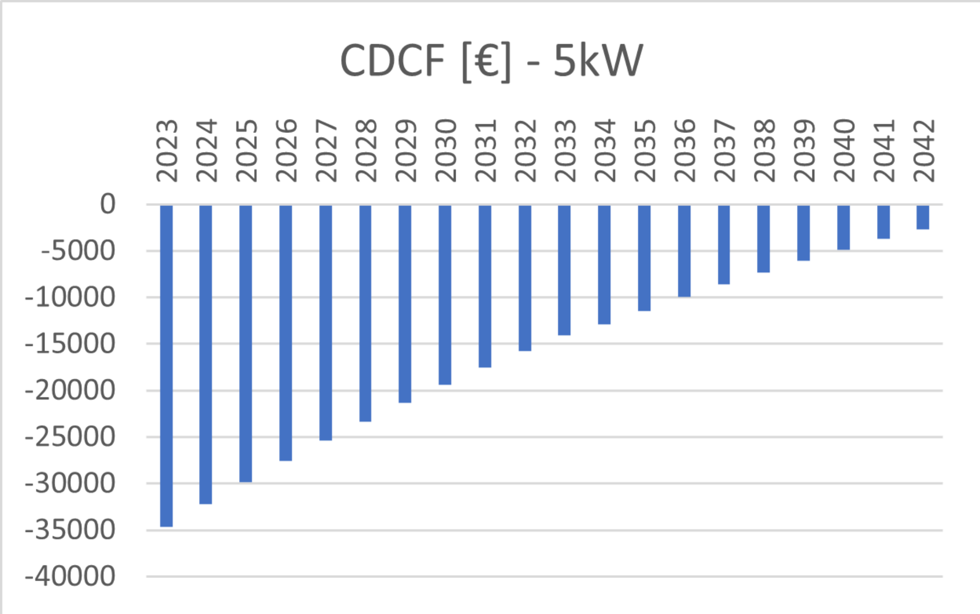


Figure 34: CDCF - HP + PV - Case 3

All the results presented in this section were obtained considering an SSP contribution. For the sake of completeness, an analysis is also conducted where the RID contribution is applied, allowing for a comparison with the previous case. This study is performed only on scenario number 1 and analyzing the 5kW plant, including all deductions.

The solution with RID and 5kW is characterized by the following economic return:

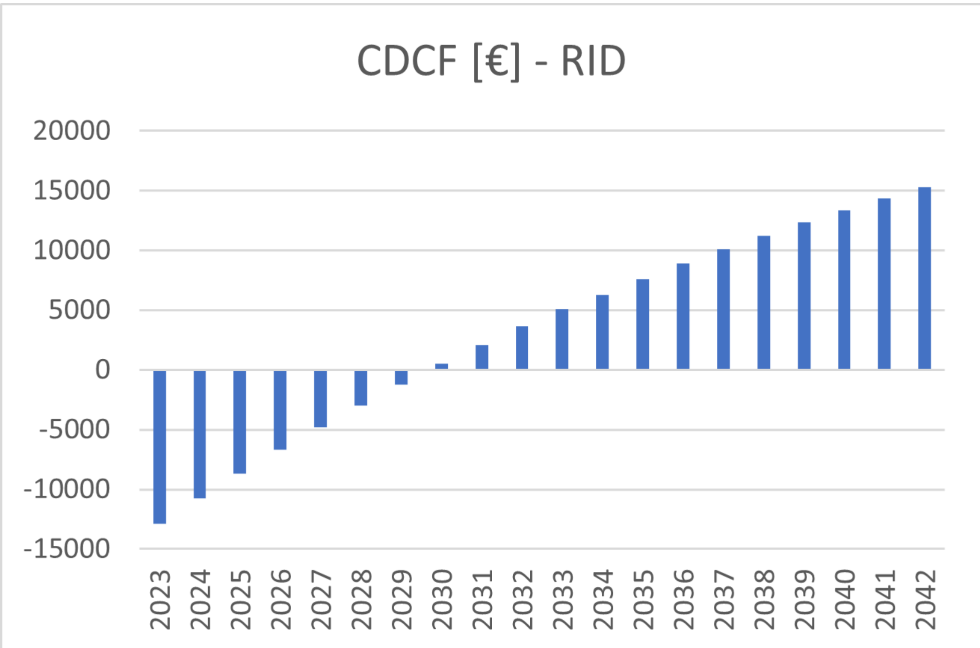


Figure 35: CDCF - HP + PV - Case RID

With an IRR of 12%, it is evident that the investment with the option of Ritiro Dedicato is still profitable, but less lucrative than in the case with the SSP. This consideration was expected, considering that the SSP compensates for the energy fed into the grid at a higher value compared to the RID option.

It can be concluded that the optimal size of the photovoltaic system is the one that covers the electrical consumption of the user and that, with the actual available deductions, the SSP contribution is the best solution. Regarding the application of tax deductions, it is always profitable to install a system with a heat pump and photovoltaics if it is possible to deduct 65% and 50% of their respective capital costs. Profitability is not lost in the case where the deduction related to the photovoltaic system is not applied, but it is no longer advantageous when the heat pump cannot benefit from the CAPEX deduction. As in the *Heat Pump Integration* configuration, this suggests that, unlike photovoltaics, heat pumps are still an emerging technology, requiring state intervention to promote their adoption as a replacement for more common gas boilers.

6.3 Heat Pump, Photovoltaic, and Battery Synergy

In the *Heat Pump, Photovoltaic, and Battery Synergy* configuration, three scenarios were analyzed, again considering a decreasing electricity price and a constant gas cost:

1. Installation of a battery with a 50% tax deduction in addition to the photovoltaic system with a heat pump, both with tax deductions.
2. Installation of a battery without a tax deduction in addition to the photovoltaic system with a heat pump, both with tax deductions.
3. Installation of a battery in addition to the photovoltaic system with a heat pump without any tax deductions.

The initial observation pertains to the battery. For any size of the photovoltaic system, the economic output variables (NPV, PBT, and IRR) deteriorate as the battery size exceeds 5 kWh. It can thus be concluded that the optimal battery size is 5 kWh.
Once the optimal battery size is determined, the analysis proceeds to assess the optimal photovoltaic power. Similar to the *Heat Pump Integration with Photovoltaic* configuration, the analysis for the best configuration in the first scenario was conducted considering the graph that relates the photovoltaic size to the IRR:

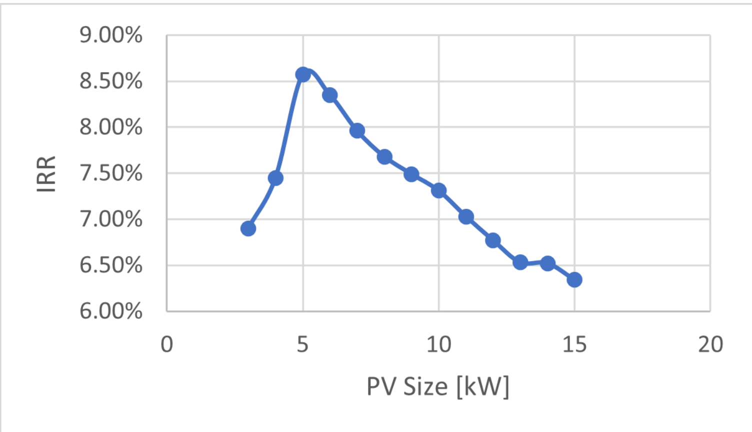


Figure 36: Size-IRR comparison

Compared to the scenario without a battery, the internal rate of return is lower. While previously the minimum value remained above 10%, now the maximum value is below 10%. However, these results are still favorable, considering that the lowest IRR is above 6%. Once again, the optimal photovoltaic solution is the one with a power of 5 kW, which corresponds to an IRR of 9.21% and a payback time of 9 years.

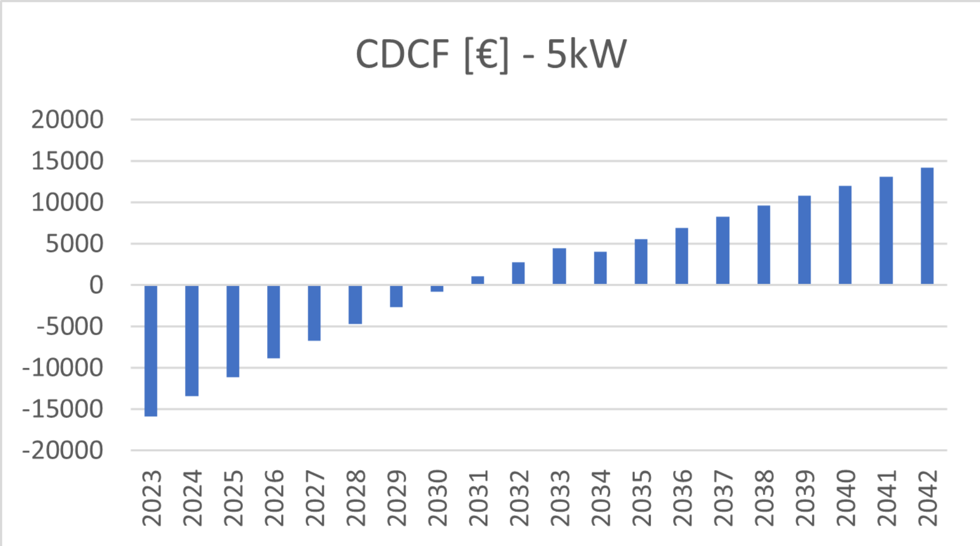


Figure 37: CDCF - HP, PV + BATT - Case1

Now, considering that there is already a system with a heat pump and a photovoltaic system in place, we analyze the scenario in which a battery is added without any tax deductions. The best solution has an IRR of 5.55% and a payback time of 13 years.

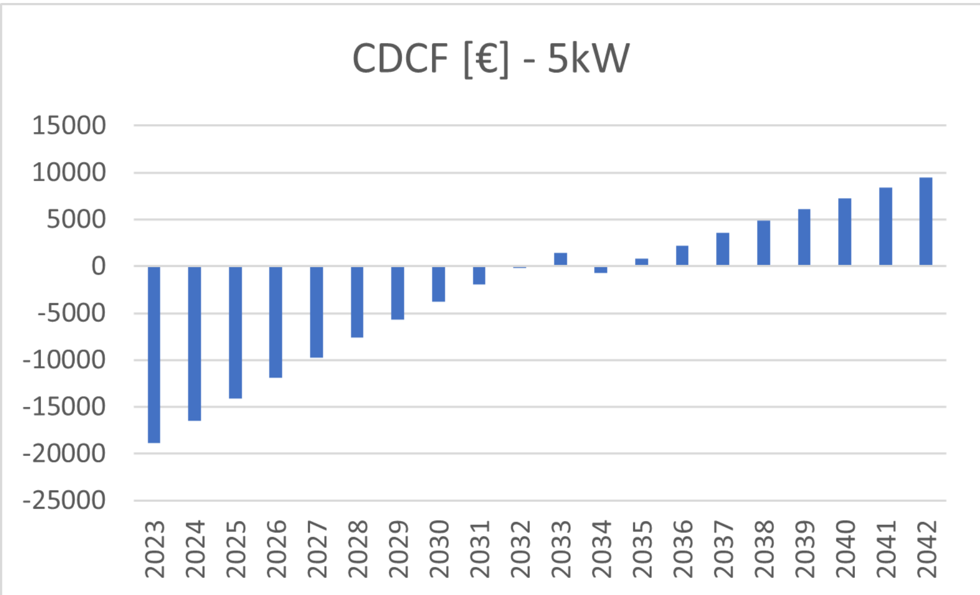


Figure 38: CDCF - HP, PV + BATT - Case2

In conclusion, the last scenario with the absence of tax deductions for all the adopted technologies leads to a predictable outcome. In the *Heat Pump Integration with Photovoltaic* configuration and scenario four (no tax deductions), the investment in the installations was not financially viable, with no economic return within the system's useful life. It can be inferred that adding a non-deductible battery to the system can only worsen the economic analysis. Indeed, the obtained result is as follows:

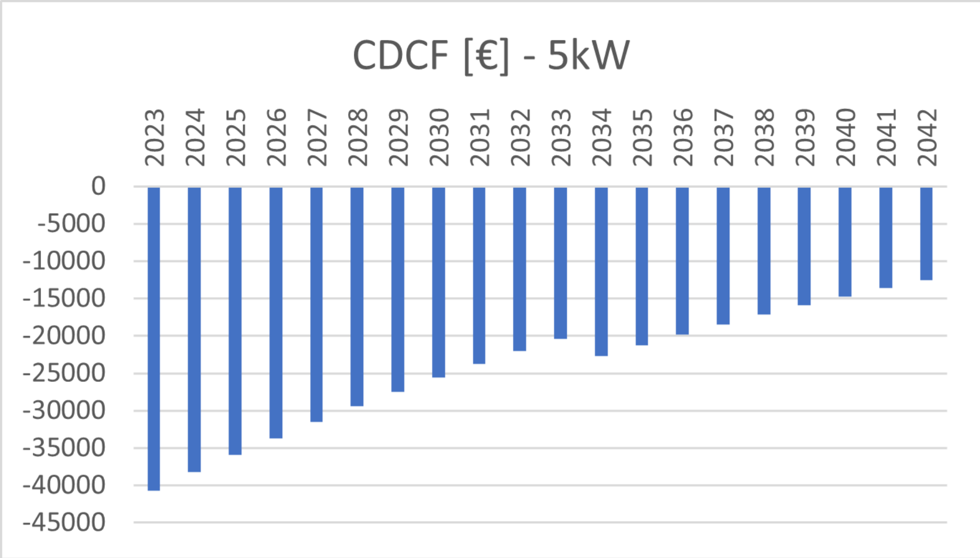


Figure 39: CDCF - HP, PV + BATT - Case3

As in the previous configuration, it could be of interest to analyse the case with the RID contribution instead of the SSP. The result obtained for the 5kW plant is a PBT of 10 years and an IRR of 7%, which is less feasible than the SSP solution:

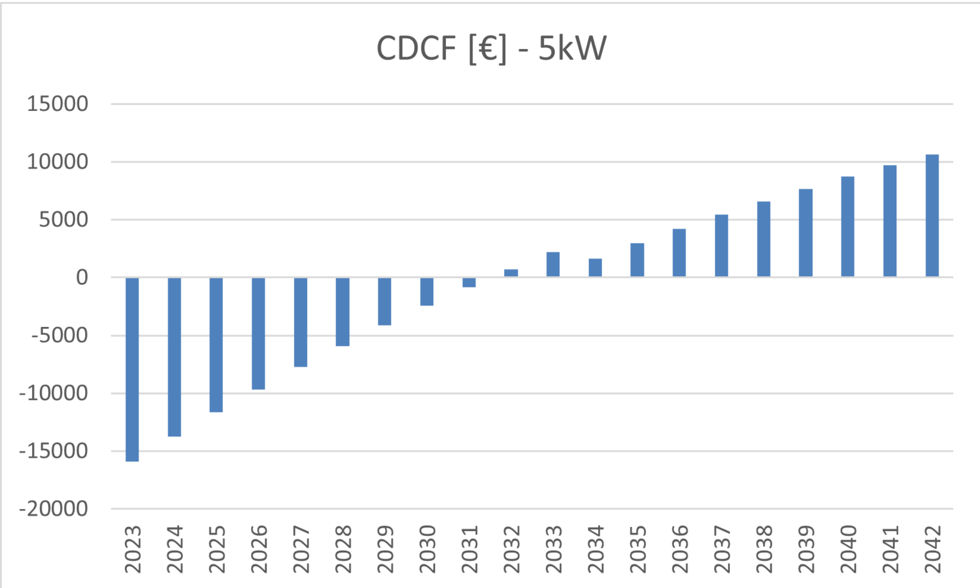


Figure 40: CDCF - HP, PV + BATT - RID

We can now draw some further conclusions from the results obtained in the various scenarios and for all the configurations.

It is evident that as long as the replacement at the eleventh year concerns only the inverter, the replacement cost is immediately offset by the system's gains. However, when the cost of battery replacement is also added, there is a temporary reversal in the trend in the graphs. This behavior is much more pronounced when the battery is not subject to tax deductions: the high investment cost requires more years to be recovered, and it causes positive cash flows to intersect the x-axis again, resulting in cash flows below zero in some cases.

Furthermore, when comparing the scenarios with and without a battery, considering the tax deductions in place, it is much more cost-effective to install a system without storage. This is valid both for the SSP and the RID contribution. Another comparison can be made between the RID solution with and without the battery: considering the recent information about the possible expiration of the SSP starting from year 2024, it is of interest to understand if the RID contribution favours or not the adoption of a battery. From the results obtained, the battery costs are still too high, bringing to a less profitable investment. However, considering the necessity to have a storage to increase the self-consumed electricity (that, as already said, for the SSP was the grid itself) it may be that the Italian state will promote battery adoption with new incentives.
A brief table with the results with and without the battery is reported below:

	WITH STORAGE	**NO STORAGE**
IRR	14.20%	8.57%
PBT	7 years	9 years
NPV	>0	>0

Table 11: Results table

7 Environmental Analysis

The environmental assessment focuses on quantifying the reduction in carbon dioxide emissions resulting from the *Heat Pump Integration*, *Heat Pump Integration with Photovoltaic* and *Heat Pump, Photovoltaic and Battery Synergy* system's operation, thereby contributing to the global effort to combat climate change. In addition, the environmental benefits are calculated by equating them to the number of trees that would need to be planted to offset the same amount of CO_2 emissions.

It is important to notice that the emissions in the two configurations *Heat Pump Integration with Photovoltaic* and *Heat Pump, Photovoltaic and Battery Synergy* are the same if only the lifetime emissions are considered. Thus, what counts is the photovoltaic production, that decreases the national electricity production from fossil sources. The differences between the two cases would be outlined only if the technologies embedded CO_2 is considered.

The primary objectives of this chapter are to define the variable and parameters used, to introduce the Python code and to present the results.

7.1 Variables and Parameters

The independent variables used in the Python code for environmental analysis are as follows:

- Annual electricity consumption of the heat pump in kWh
- Annual gas consumption in m^3
- Annual electricity production from the photovoltaic system

Regarding the dependent variables, the software provides the following outputs:

- Avoided CO_2 emissions
- Equivalent trees planted

Lastly, the parameters adopted in this section of the calculation model are as follows:

- Carbon dioxide emissions from the Italian national energy mix for electricity production. The value to consider, as provided by the Ministry of the Environment, is 0.53 kg_{CO_2}/kWh [24].
- CO_2 generation from the combustion of methane, emitting 1.8 kg_{CO_2}/m^3 [25].

7.2 Code and Mathematical Analysis

Starting from the calculation of the avoided CO_2 emissions thanks to the use of a heat pump replacing a natural gas boiler, it is assumed that all the electricity used to power the heat pump is drawn from the national grid.
Therefore, the carbon dioxide emissions resulting from the heat pump's operation are given by:

$$HP_{CO_2} < 0.53 * Cons_{el,HP} \tag{27}$$

This value is then compared with the emissions that would occur if the gas boiler was not replaced:

$$Boiler_{CO_2} < 1.8 * Cons_{gas} \tag{28}$$

The difference between the previous terms leads to the avoided CO_2 emissions due to the increased electrification of the heating system:

$$CO_{2,difference} = Boiler_{CO_2} - HP_{CO_2} \tag{29}$$

The last term to evaluate within the code relates to photovoltaic electricity production (*En_prod*). The avoided emissions in this case are linked to the total electricity output of the system. Even if part of the electrical energy is not self-consumed, the remaining portion will still be injected into the grid and used by other consumers, thus avoiding the need to generate this portion of electricity through the national energy mix.

$$PV_{CO_2} = 0.53 * En_{prod} \tag{30}$$

$$CO_{2,avoided} = PV_{CO_2} + CO_{2,difference} \tag{31}$$

The next step involves converting the avoided CO_2 into equivalent trees planted. To perform this conversion, it must be considered that, according to the United Nations Framework Convention on Climate Change (UNFCCC) [26], an average tree absorbs 10 kg_{CO_2} per year. Therefore:

$$Eq_{trees} = CO_{2,avoided}/10 \tag{32}$$

No additional Python libraries are required for the Environmental Analysis code.

7.3 Results

The results of the environmental analysis were obtained by referring to the case study presented in Chapter [6].

7.3.1 Heat Pump Integration

The results for the *Heat Pump Integration* are simpler to get since they are given just by the CO2 avoided due to the substitution of methane with electricity. Relying just on formulas [27], [28] and [29], the avoided CO_2 is $623.49 kg_{CO_2}$/yr that corresponds to 62.3 equivalent planted trees.

7.3.2 Heat Pump Integration with Photovoltaic + Heat Pump, Photovoltaic and Battery Synergy

After inputting the data, it is possible to calculate the annual consumption of the heat pump and the annual production of the photovoltaic system. The avoided emissions are closely tied to the heat pump's consumption, which, as seen previously, is designed to meet the thermal demands of the user, and they are also linked to photovoltaic production.

Since the annual thermal demand remains constant throughout the system's lifetime, the energy required for the heat pump's operation will be the same for all PV sizes, resulting in constant emissions each year. In contrast, photovoltaic production varies from 3kW to 15kW, thus, avoided CO2 emissions and equivalent trees planted will increase with the size of the photovoltaic system. As shown by the results, the best environmental solution is the one with the maximum production of electricity from renewable sources and, therefore, coincides with the installation of a 15kW photovoltaic system.

The obtained results have been compiled in the following table:

PV Size [kW]	CO_2 **avoided [ton]**	**Eq. Trees Planted**
3	2.4	241
4	2.8	282
5	3.5	352
6	4	397
7	4.4	440
8	5	495
9	5.6	556
10	6.2	617
11	6.7	666
12	7.2	718
13	7.6	763
14	8.5	848
15	9	899

Table 12: Environmental Results table

8 Sensitivity Analysis

Sensitivity analysis was conducted in Excel for *Heat Pump Integration* and in Python for the other two configurations.

In the following subsections, the data used for the analysis is presented, along with the Python code for the study, the libraries employed, and finally, the considerations made in light of the obtained results.

This paragraph is of high importance cause it allows to understand how the results could vary in time, considering the current high volatility of prices due to wars, shortage of raw material and climate change.

8.1 Python Code Analysis and Libraries

In this section, we will describe the Python code used for the sensitivity analysis of the *Heat Pump Integration with Photovoltaic* and *Heat Pump, Photovoltaic, and Battery Synergy* configurations. The additional script is common to both scenarios; it will include a call to the previously used calculation model, which will automatically define the calculations to be executed depending on whether the battery is present or absent.
Furthermore, the additional Python libraries needed for the study will be defined.

Commencing with the description of the data-saving part, a function named *change_filename_for_filehandler* was written to take as input the logger used and the name of the new log. It allows changing the log name for each run of the calculation model with a different combination of electricity cost and gas cost. This approach facilitated the creation of an organized and automated results collection database.

The subsequent step pertains to data analysis. In this computational segment, data was inputted into a .json file containing a *Config* configuration defined by:

- *system_data* → encompassing general independent project variables (project name, latitude, longitude, altitude, tilt, thermal and electrical consumption, and the presence or absence of the battery).
- *electrical_data* → containing the type of consumption profile.
- *economical_data* → housing economic variables and parameters (PUN, PO, electricity cost on the bill, gas cost on the bill, heat pump deduction, photovoltaic deduction, battery deduction, type of contribution).

To enhance communication between different Python scripts, a new .py file was defined to facilitate communication with the .json file. Thus, through *system_configuration.py*, a class for *Config* and a class for each of its subsections (*SystemData*, *ElectricalData*, *EconomicalData*) were created. Moreover, for each class, private attributes, setters, and getters were defined. In particular, the attributes of *Config* are the classes of the subsections themselves. Additionally, a method for getters and one for setters were defined in *Config* to enable communication with the .json file.
To import the data into the main script, an instance of *Config* is created, and the method to load files from the json is applied.

Finally, the computational part can be analyzed. First, the electricity costs and gas costs

for which sensitivity analysis is to be performed are defined. Through two for loops, iteration over the just-defined values is possible, changing the value of variables in the *Config* instance. Once the gas and electricity costs are defined for each run of the calculation method described in [4], the name of the new log is defined with *change_filename_for_filehandler*, and the calculation script is called to run for the configuration defined in the instance, for the declared logger, and for the optimal photovoltaic size (5kW in this case).
The result obtained is a list of IRR where each value corresponds to a specific combination of gas cost and electricity cost. By converting the list into a matrix using Numpy, it is possible to create a heatmap in Matplotlib.

8.2 Heat Pump Integration

A study was conducted on the variation of gas cost in the range from €0.5/m^3 to €4/m^3 and electricity cost in the range from €0.1/kWh to €1/kWh, with values adjusted in the respective Excel cells. It is observed that the range of variation in the cost of natural gas is much broader than that considered for electricity. In fact, upon analyzing contracts from various clients, it has been noted that there is significantly greater variability in the gas bill cost compared to the price of electricity, maybe due to the current unstable geopolitical situation . Finally, to analyze the impact of both variables on economic feasibility, the gas cost/electricity cost ratio was considered.

The sensitivity analysis was performed for the scenario with constant electricity and gas prices during the system's lifespan. Using the calculation model, IRR values were calculated for gas costs in the range defined above, with a step of €0.5/m^3 and a fixed electricity price of €0.3/kWh. The obtained results are reported in the table and depicted in Figure [41]:

Gas Cost [€/m^3]	**IRR** [%]
0.5	-
1	-8
1.5	5
2	15
2.5	27
3	40
3.5	56
4	77

Table 13: Sensitivity on Gas Cost - HP Integration

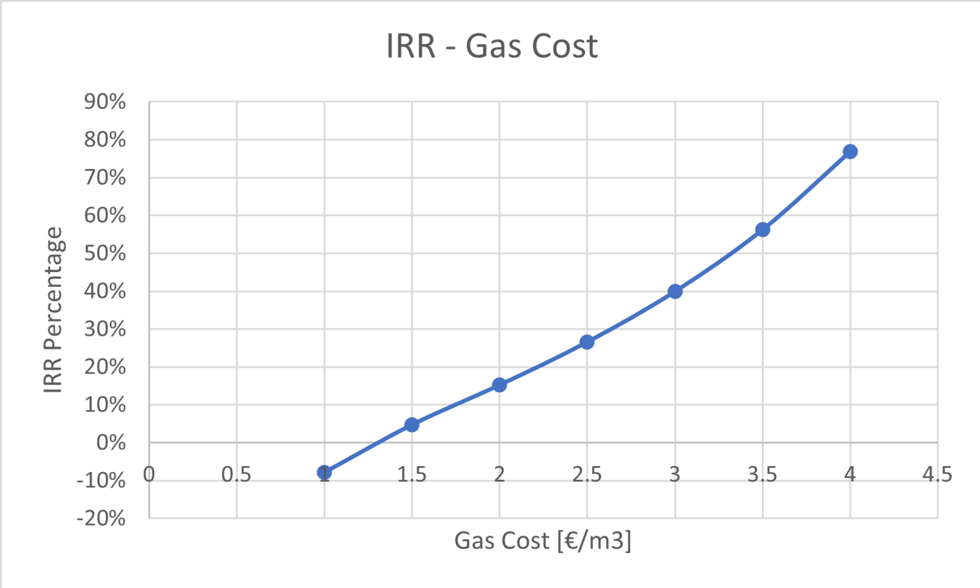


Figure 41: Sensitivity on Gas Cost - HP Integration

The cost of gas significantly influences the investment's profitability: in a system configuration where the only green technology is provided by the heat pump, the economic return is solely determined by the cost of not using gas. Therefore, with a constant electricity cost for all scenarios and a fixed thermal consumption, the higher the gas cost, the better the economic return.

Particular attention must be given to the case with a gas cost of €0.5/m^3. In this economic configuration, the operational costs due to the use of the heat pump are higher than those related to the use of the gas boiler. Although the gas cost is higher than that of electricity, due to the conversion from thermal to electrical energy, the numerical value related to the annual consumption of the heat pump exceeds the gas requirement. This results in a system that will never pay off, as highlighted in the following graph:

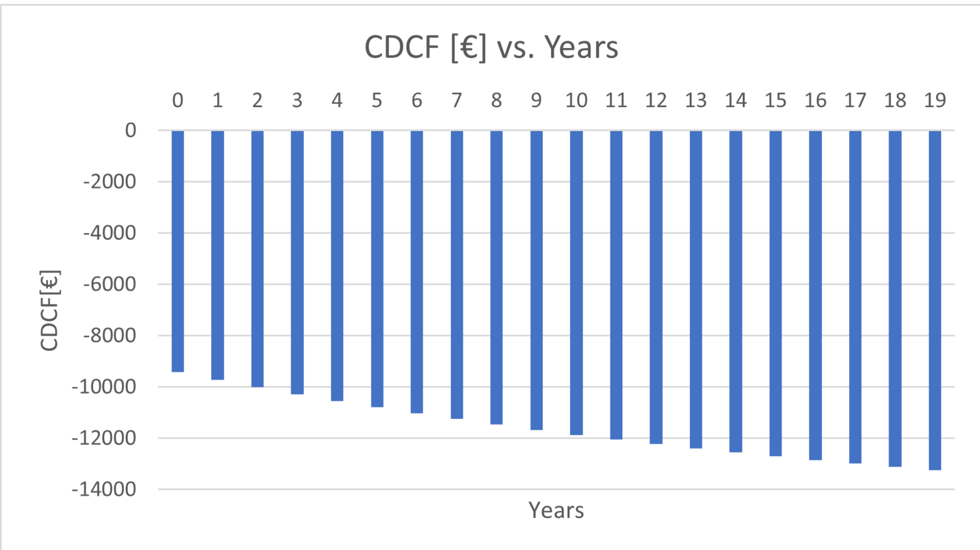


Figure 42: Sensitivity on Gas Cost - HP Integration - CF

As for the analysis of electricity costs, configurations with costs ranging from €0.1/kWh to €1/kWh were studied with a step of €0.1/kWh, and a gas cost of €1/m^3 was considered. It was observed that the only cost-effective case is with an electricity cost of €0.1/kWh, which yields an IRR of 5%. From €0.1/kWh to €0.3/kWh, the investment's economic viability deteriorates, and it no longer covers the expenses. When the electricity cost is €0.4/kWh, the 5% discount rate decreases the cash flows more than the gains increase them; this leads to progressively lower DCF values over the lifespan, although the CDCF increases. From €0.5/kWh to €1/kWh, the operational costs for the operation of the heat pump are higher compared to those that would be incurred by maintaining the operation of the gas boiler; therefore, the IRR cannot be calculated.

For the analysis of the gas cost over electricity cost ratio, the decision was to consider the ratios of 5, 10, 20, 30 and 40. The result is depicted in the graph:

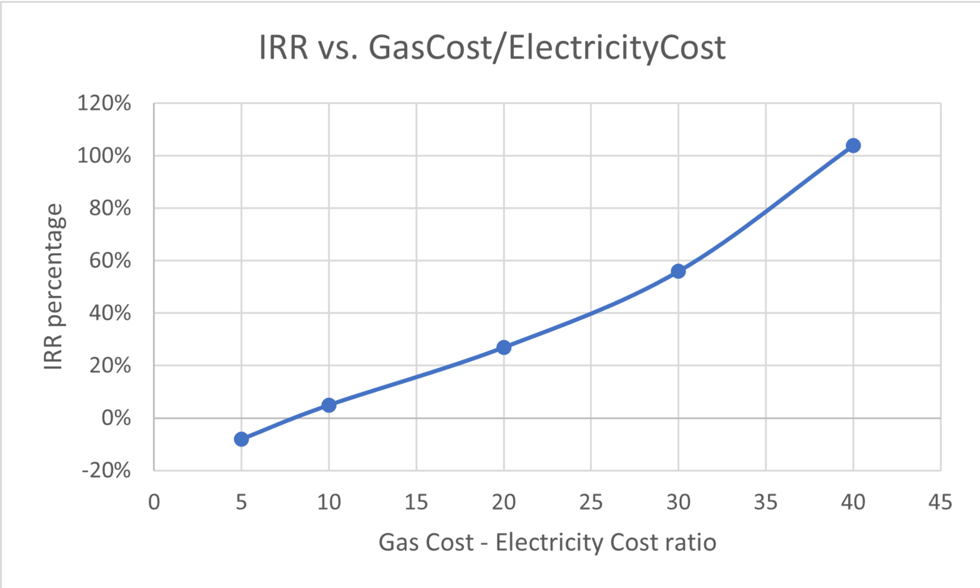


Figure 43: Sensitivity on Gas and Electricity Cost - HP Integration

It is possible to highlight that the higher the gas/electricity cost ratio, the higher the feasibility of the investment. This conclusion is justified by the fact that the convenience for the *Heat Pump Integration* solution is given by the cost of non-use of gas which is greater the lower the cost of electricity needed to operate the heat pump and the higher the cost of gas avoided. The behaviour showed in the graph is very similar to the one of picture [41], highlighting the importance of the gas cost impact.

8.3 Heat Pump Integration with Photovoltaic

Applying the Python code described earlier for sensitivity analysis, through a single for loop on gas costs, it is possible to study the behavior of the IRR. The results obtained for the optimal 5kW system with electricity price equal to €0.32/kWh and both SSP and RID are reported in the following table and graph:

Gas Cost [€/m^3]	**IRR** [%] **- RID**	**IRR** [%] **- SSP**
0.5	-4.04	-0.45
1.0	3.02	5.94
1.5	9.28	11.99
2.0	15.51	18.20
2.5	22.08	24.83
3.0	29.23	32.10
3.5	37.17	40.20
4.0	46.11	49.33
4.5	56.28	59.73
5.0	67.98	71.69

Table 14: Sensitivity on Gas Cost - HP + PV Integration

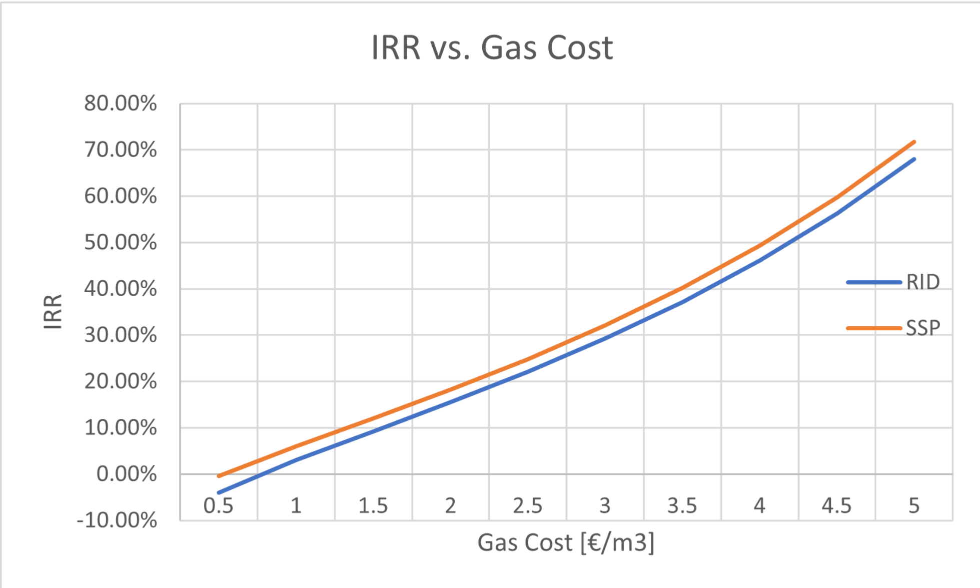


Figure 44: Sensitivity on Gas Cost - HP + PV Integration

As evident from the graph, the IRR increases with the rise in gas cost for both the SSP and the RID contribution. This behaviour suggests the gains from replacing the boiler with the heat pump play a significant role in the feasibility analysis of the investment. Even if the IRR with SSP is higher, the difference is so small that it can be overlooked.

The subsequent study concerns the sensitivity analysis on electricity cost using a fixed gas cost of €1.68/m^3. As in the previous case, the optimal 5kW photovoltaic system was considered. The results are presented below:

Electricity Cost [€/kWh]	IRR [%] - RID	IRR [%] - SSP
0.1	12.77	13.16
0.2	12.47	13.94
0.3	11.66	14.15
0.4	10.90	14.35
0.5	10.18	14.53
0.6	9.50	14.71
0.7	8.85	14.87
0.8	8.24	15.02
0.9	7.66	15.17
1.0	7.11	15.30

Table 15: Sensitivity on Electricity Cost - HP + PV Integration

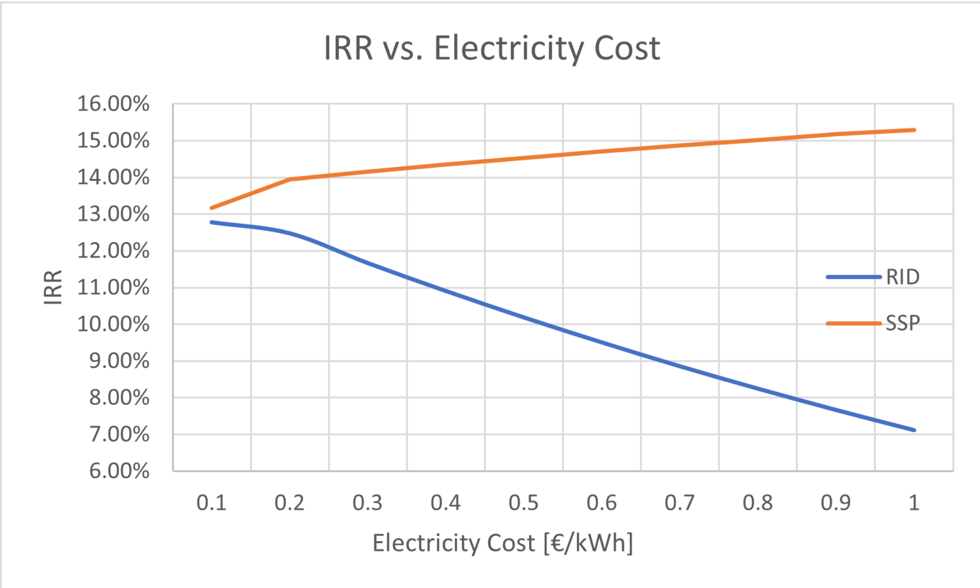


Figure 45: Sensitivity on Electricity Cost - HP + PV Integration

Regarding the RID contribution, the trend of the IRR is opposite to what was seen previously with gas cost. In this case, the investment's feasibility decreases with increasing electricity cost. This behavior can be justified by considering that, for consistently lower electricity costs, the annual bill expense is lower. Therefore, the cost for the operation of the heat pump decreases, and the gains from not using gas increase.

If, on the other hand, the trend for the SSP is analyzed, it can be observed that the internal rate of return increases with the cost of electricity. Therefore, there is an opposite behavior compared to the case with RID. The increasing development is explained by the regulation that determines the contribution calculation [2]. In fact, while in RID, profits from photovoltaic production result only from the sale of non-self-consumed energy, if SSP is adopted, an additional gain is obtained from C_s, within which CU_{sf} is present, increasing with the rise in the electricity price on the bill. This term thus improves the economic situation and consequently increases the IRR.

It is, therefore, interesting to consider the combined effects of sensitivity analysis on costs,

considering both the variation in gas prices and the variability of electricity prices. Intuitively, after the study of the separate effects, one might think that the best economic solution for RID will be obtained for the highest gas cost and the lowest electricity cost while for the SSP contribution for both the highest gas and current prices.
To directly visualize the results of a study involving the use of three different variables (gas cost, electricity cost, and IRR), a heatmap was used:

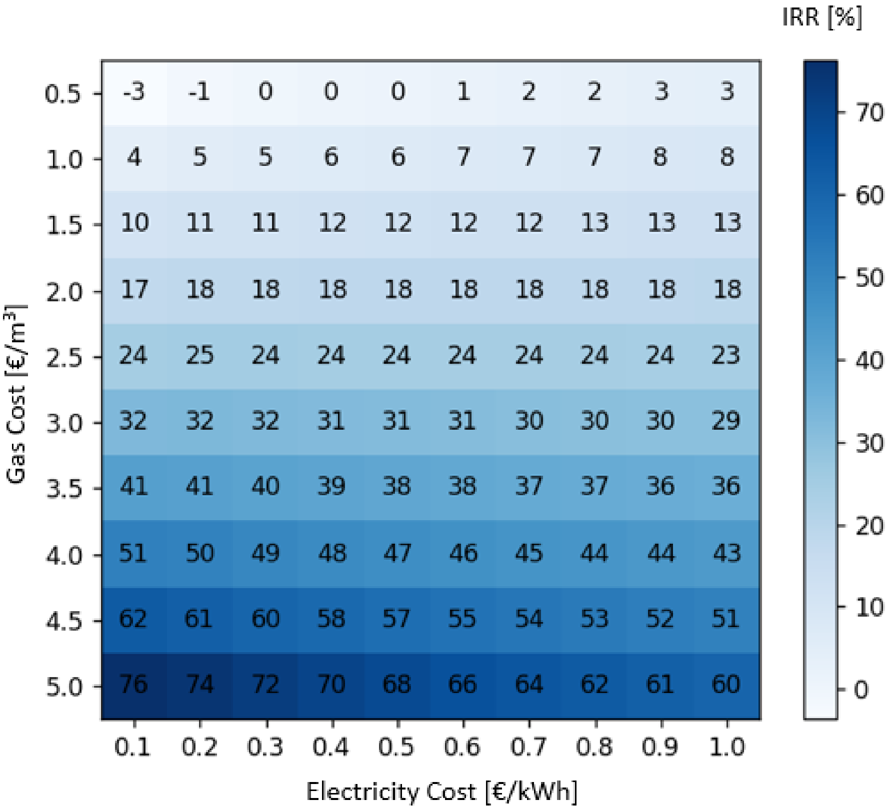
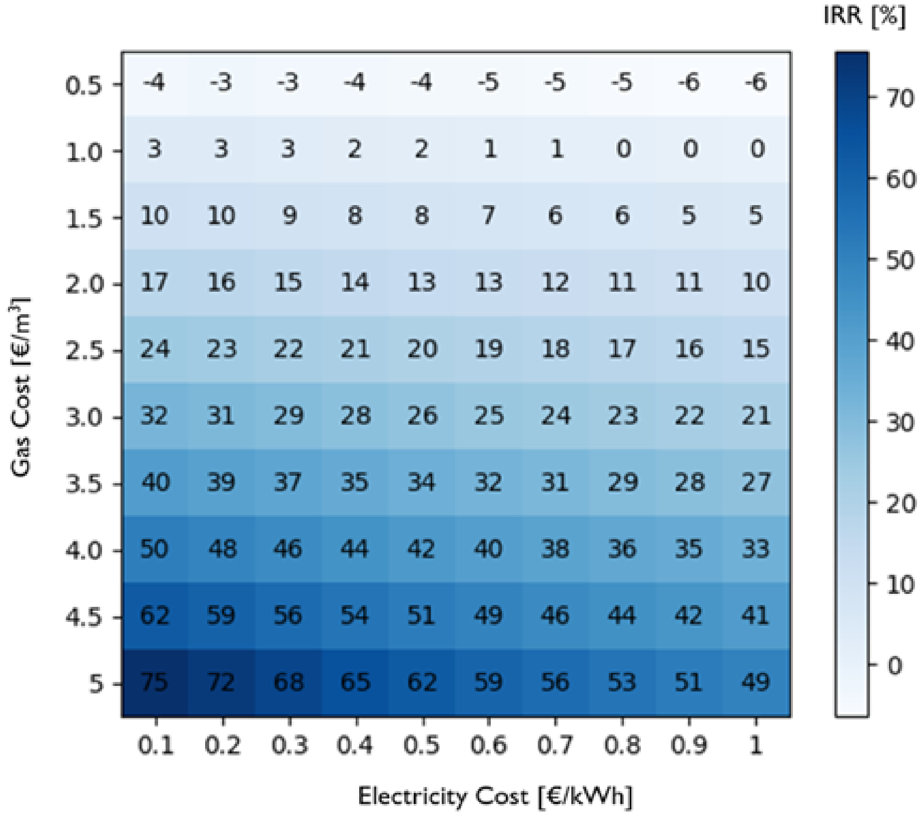


Figure 46: Heatmap SSP - HP + PV Integration



Gas Cost [€/m³] \ Electricity Cost [€/kWh]	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.5	-4	-3	-3	-4	-4	-5	-5	-5	-6	-6
1.0	3	3	3	2	2	1	1	0	0	0
1.5	10	10	9	8	8	7	6	6	5	5
2.0	17	16	15	14	13	13	12	11	11	10
2.5	24	23	22	21	20	19	18	17	16	15
3.0	32	31	29	28	26	25	24	23	22	21
3.5	40	39	37	35	34	32	31	29	28	27
4.0	50	48	46	44	42	40	38	36	35	33
4.5	62	59	56	54	51	49	46	44	42	41
5	75	72	68	65	62	59	56	53	51	49

Figure 47: Heatmap RID - HP + PV Integration

The RID figure precisely depicts the expected result, with the optimal solution at €5/m^3 for gas and €0.1/kWh for electricity characterized by an IRR of 75%. If one were to undertake an investment only when profitability exceeds 5%, an horizontal line should be drawn between gas costs of €1.0/m^3 and €1.5/m^3: independently from electricity price, for gas costs greater than or equal to €1.5/m^3, the investment can be considered advantageous, whereas for costs below this value, a heat pump and photovoltaic system should not be installed together.

The heatmap related to the case with SSP, on the other hand, shows a result different from expectations. From €0.5/m^3 to €2/m^3, the IRR increases with the rise in the electricity price, as also depicted in the graph [46], but for €2.5/m^3, there is a reversal of the trend, and economic feasibility improves with decreasing electricity costs. Therefore, the optimal solution is reached in the scenario with the highest gas price and the lowest electricity price, with a numerical value of 76%.
The peculiar behavior shown in this graph can be explained as follows: initially, the economic investment shows a positive trend because the contribution value from the 'Scambio Sul Posto' has a greater weight than the gain obtained from the non-use of gas. However, when the gas cost exceeds €2/m^3, there is an interruption of the main trend, and the profit from replacing the boiler with the heat pump surpasses the photovoltaic remuneration provided by the SSP.

Furthermore, this analysis suggests that those making the investment and transitioning to a more electrified system enhance their economic security and stability. A fluctuation in the cost of gas due to normal market oscillations or geopolitical situations poses a high risk of significantly increasing operational costs for the system. Conversely, a variation in electricity cost does not significantly impact the investor's economy.

In a more stable global economic situation, one could contemplate a variation in the price of gas similar to that considered for electricity costs: considering the case study presented earlier [6], gas costs ranging from €1.2/m^3 to €2.1/m^3 with a step of €0.1/m^3 are considered, ensuring that the cost of €1.68/m^3 is central to the analysis.

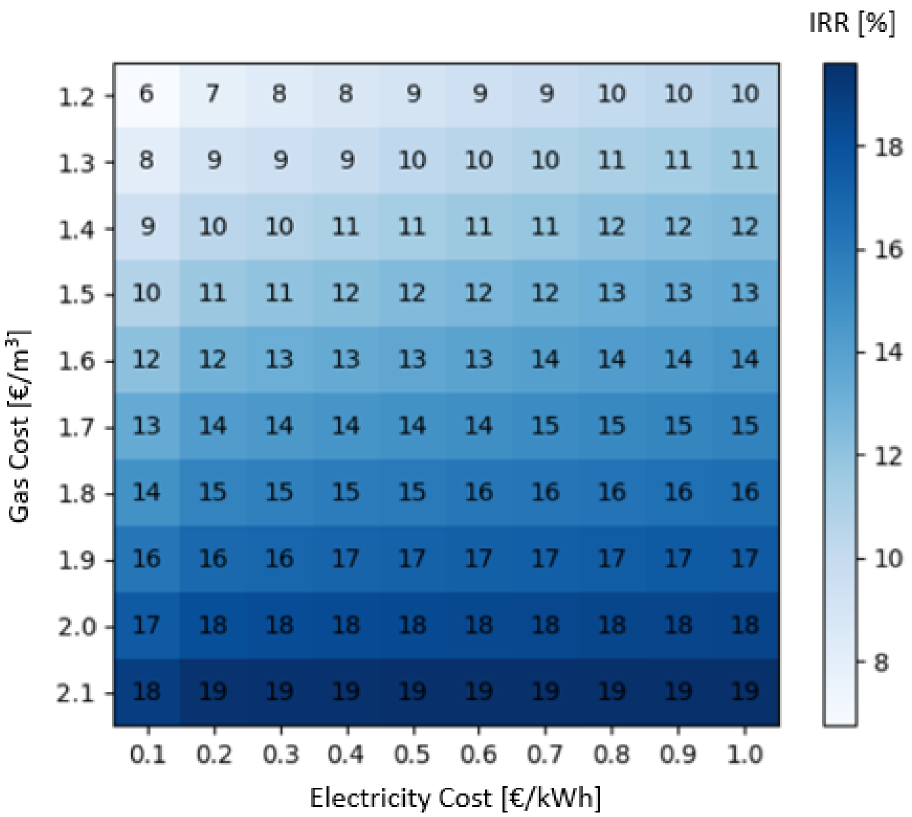


Figure 48: Heatmap SSP zoom - HP + PV Integration

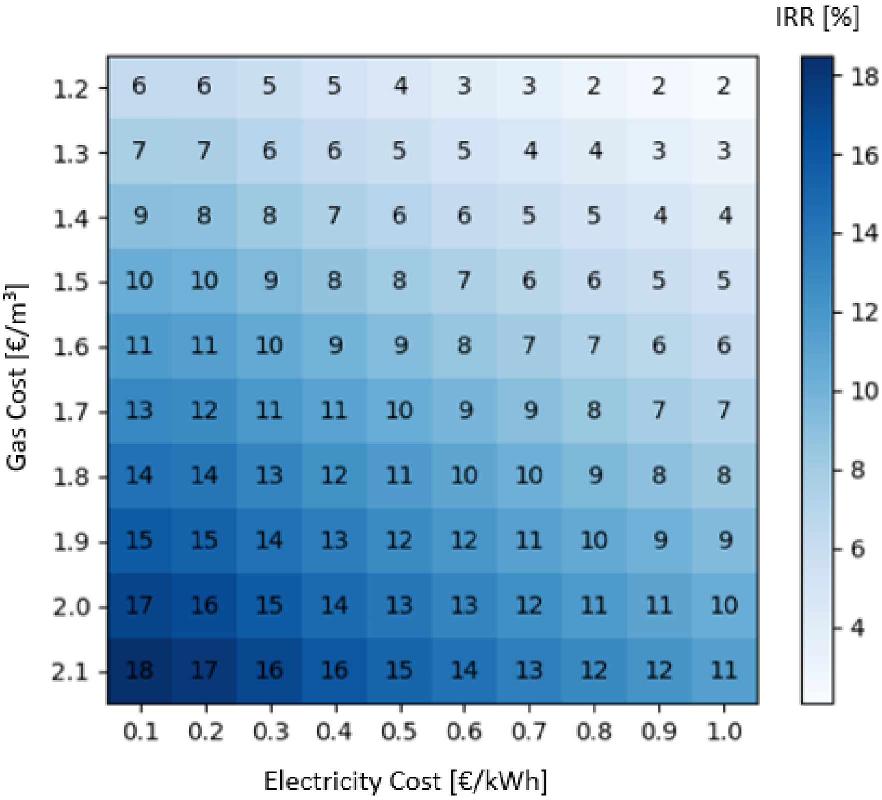


Figure 49: Heatmap RID zoom - HP + PV Integration

In this case, the variation in IRR is more contained with changes in the gas cost. It ranges from 6% to 18% when considering an electricity cost of €0.1/kWh, whereas in previous analyses [46][47], there was a difference of 79%.
Nevertheless, the fluctuation in gas costs remains more pronounced than that in electricity prices. Therefore, the consideration regarding the security provided by undertaking the investment holds true.

The optimal solution with SSP no longer coincides with that of RID: in the case where the chosen contribution is 'Scambio Sul Posto,' the best economic solution would occur at a gas cost of €$2.1/m^3$ and €1/kWh, while with 'Ritiro Dedicato,' a better return would be achieved if the electricity cost were €0.1/kWh.
Therefore, it is crucial to emphasize that the optimal economic solution cannot be uniquely defined, and various variables must be considered, including the cost of gas and electricity on the bill and the type of contribution applied to photovoltaic production.

8.4 Heat Pump, Photovoltaic, and Battery Synergy

Similarly to the sensitivity analysis conducted for the *Heat Pump Integration with Photovoltaic* configuration, in the scenario addressed in this chapter, a study was initially conducted on gas costs, followed by electricity prices, and finally their combined action. The photovoltaic system taken into consideration is the 5kW and 5kWh plant.

Starting with the analysis of gas costs, the obtained results with a constant electricity price equal to €0.32/kWh are as follows:

Gas Cost [€/m^3]	**IRR [%] - RID**	**IRR [%] - SSP**
0.5	-7.58	-4.31
1	-0.59	1.86
1.5	5.15	7.30
2	10.55	12.59
2.5	15.96	17.99
3	21.61	23.66
3.5	27.64	29.75
4	34.17	36.35
4.5	41.32	43.61
5	42.23	51.64

Table 16: Sensitivity on Gas Cost - HP + PV + Battery Integration

In this configuration as well, the IRR increases with the rise in gas cost and the SSP shows slightly higher values than RID.

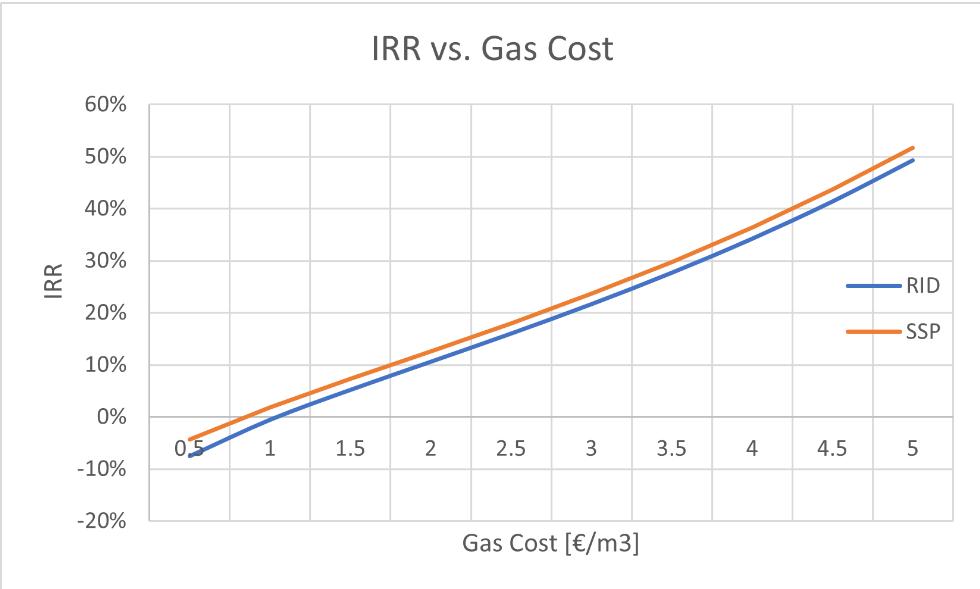


Figure 50: Sensitivity on Gas Cost - HP + PV + Battery Integration

Continuing with the sensitivity analysis on electricity costs, the results obtained are:

Electricity Cost [€/kWh]	IRR [%] - RID	IRR [%] - SSP
0.1	7.88	8.14
0.2	7.77	8.89
0.3	7.21	9.16
0.4	6.68	9.41
0.5	6.17	9.63
0.6	5.68	9.85
0.7	5.22	10.06
0.8	4.77	10.26
0.9	4.34	10.44
1.0	3.93	10.62

Table 17: Sensitivity on Electricity Cost - HP + PV + Battery Integration

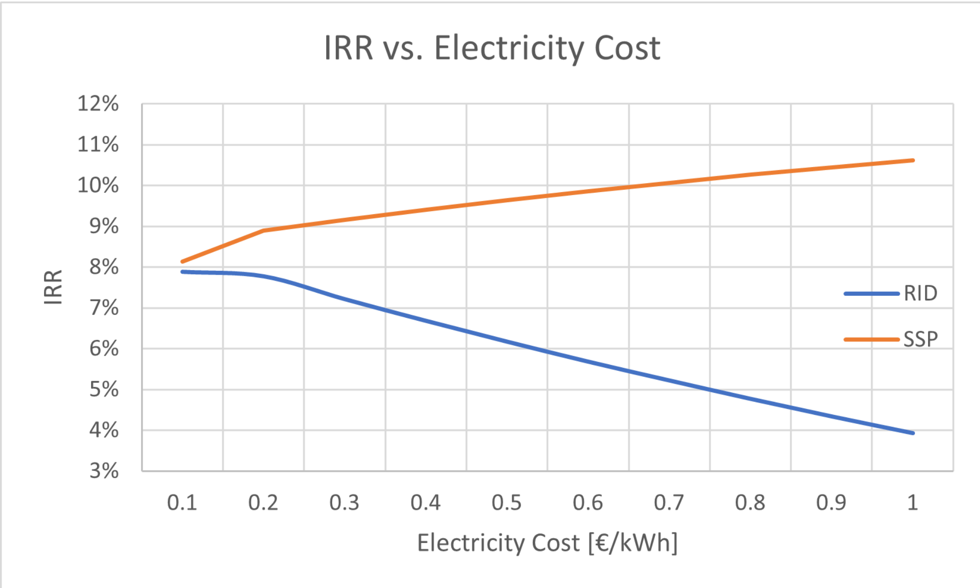
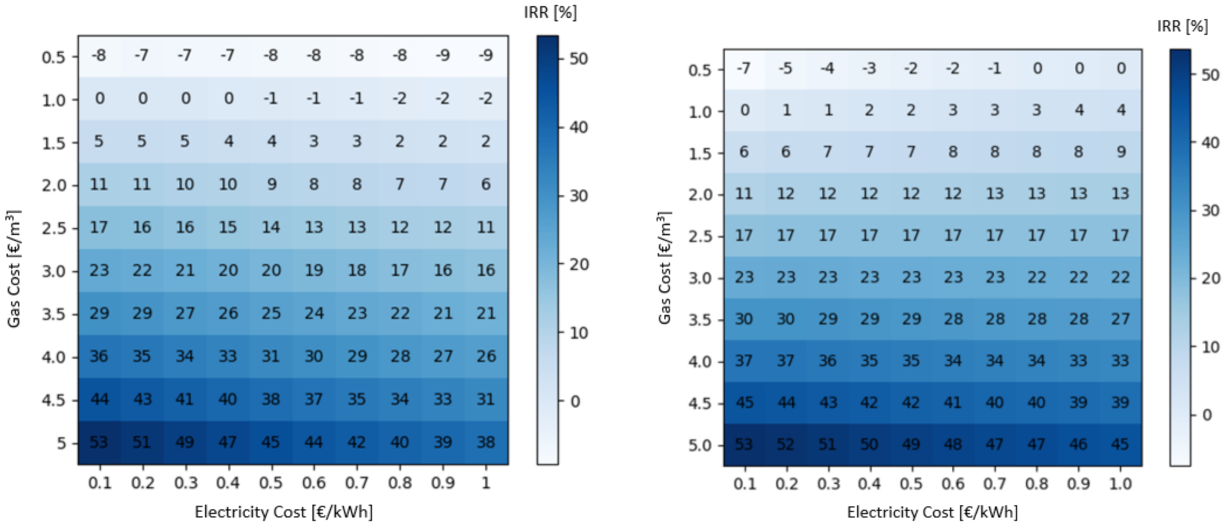


Figure 51: Sensitivity on Electricity Cost - HP + PV + Battery Integration

The considerations for this study are the same as the Heat Pump Integration with Photovoltaic case.

Finally, the heatmap for the combined study of the effect of gas and electricity prices is presented:

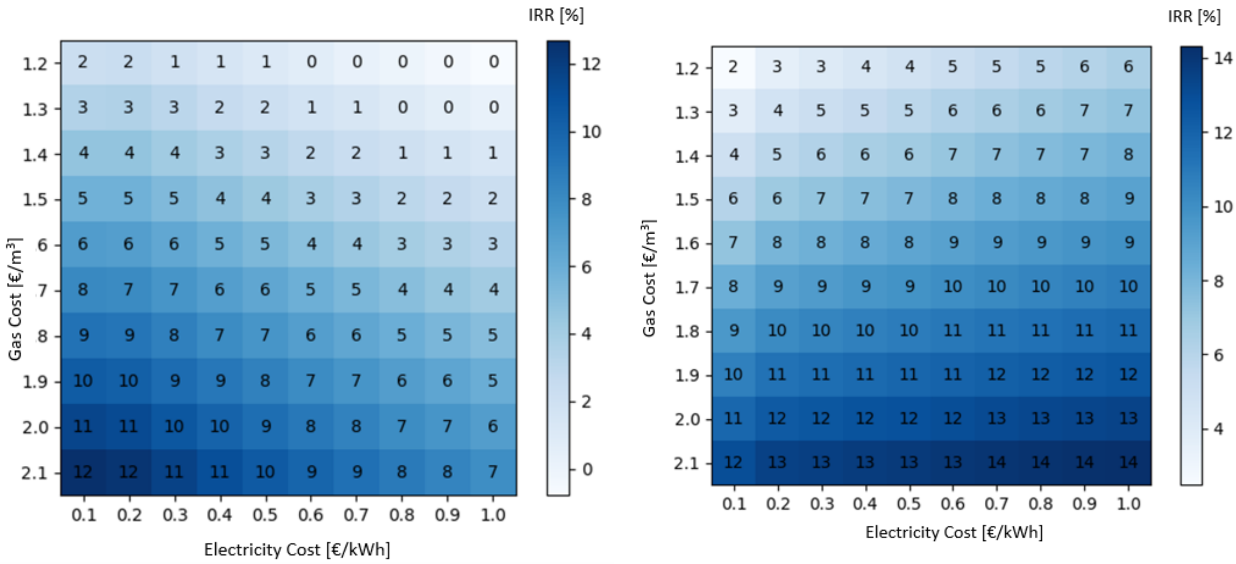


(a) RID *(b) SSP*

Figure 52: Heatmap - HP + PV + Battery Integration

Due to the increased investment cost resulting from the addition of the battery, the economic return occurs later compared to the adoption of only the heat pump with photovoltaics. This phenomenon is reflected in the IRR of all three sensitivity analyses, which, at the same values of methane price, is consistently lower when compared to the *Heat Pump Integration with Photovoltaic* configuration.

For completeness, as in Paragraph [8.3], the heatmap with an enlargement on the gas cost of the case study (€$1.68/m^3$) is also reported but no further considerations will be added beyond those already presented in the configuration without accumulation. In fact, again, the difference is only given by smaller values.



(a) RID *(b) SSP*

Figure 53: Heatmap zoom in - HP + PV + Battery Integration

9 Conclusion

In conclusion, the developed software has proven its efficacy in analyzing various scenarios related to the replacement of boilers with heat pumps. The consideration of incentives underscores the superiority of SSP (Scambio Sul Posto) over RID (Ritiro Dedicato). Additionally, the inclusion of batteries does not enhance the investment under different conditions, such as variations in deductions or scenarios without incentives, and remains unaffected by fluctuations in gas and electricity costs.

Furthermore, the study reveals that heat pump technology, while promising, is still in its early stages compared to photovoltaics. Without the deduction for heat pump expenses, the investment payback extends to the later years of its lifespan, making it less economically viable. In contrast, photovoltaics can prove financially beneficial even without deductions and can help offset the impact of heat pump investments. Therefore, additional efforts at both the national and European levels are essential to encourage more individuals to invest in these technologies.

A noteworthy observation is the divergent conclusions reached by SSP and RID when analyzing the variability of electricity costs over time. SSP exhibits increased economic returns with rising electricity costs, while RID demonstrates the opposite trend. This discrepancy can be explained by examining the formulas used for calculating the respective contributions. However, for gas costs exceeding €$2.5/m^3$, this consideration becomes inconsequential, with the sole influencing variable being the savings resulting from the reduced use of natural gas.

The software development process encountered several challenges, including determining optimal calculation tools, acquiring data for contribution calculations, creating the Graphical User Interface and, most of all, validating the calculation model, given the absence of comparable software in the market.
Despite these obstacles, the software has successfully achieved its intended purpose.
While there are areas for improvement, such as the automatic recognition of roof orientation and considering seasonal variations in the heat pump's Seasonal Coefficient of Performance (SCOP), the software has already met all defined goals throughout the thesis. It is now poised to be utilized effectively for providing optimal recommendations to clients, encompassing both current and future economic analyses.
The Towards Greener Homes (TGH) algorithm, with its robust solution for prediction and analysis in the face of volatile market prices, stands as a valuable tool for advancing sustainable and environmentally conscious investments.

10 Acknowledgements

I dedicate this chapter to everyone who has been by my side during this academic journey because the challenges I encountered tested not only myself but also all the people who supported me.

First, I am thankful to my esteemed professor Paolo Silva who accepted the role of my thesis advisor and provided mentorship and expertise throughout this research. I also extend my gratitude to Politecnico di Milano, my university, for imparting invaluable technical skills and opening my eyes to the ever-evolving world of technology. Beyond technical knowledge, the university introduced me to a diverse and inspiring community, providing not only the tools to solve technical problems but also valuable life lessons.

I address my sincere appreciation to Equa S.r.l., where I had the privilege to work during my thesis research. Their competence and kindness in providing access to data greatly enriched my study. The insights and hands-on experience gained at the company were instrumental not only in enhancing the practicality of my research but also for improving my technical knowledge.

My family played a crucial role in achieving this milestone. Your understanding throughout the days dedicated to studying and your support during exam sessions were invaluable. You are the ones who, more than anyone else, endured my moods, and despite everything, you always tried to understand me. A special thanks goes to you, Marco and Alessia, my parents, who made this journey possible. The success of this endeavor is also thanks to you, and for that, I am grateful.

I would also like to express my gratitude to my boyfriend, Gianluca. You have been the light in the dark and in the most challenging moments of my academic journey. Your trust in me and the love we share have been a powerful motivation behind every tough day. Thank you for remaining my pillar despite all the obstacles that arose.

To all my friends, both inside and outside the university, to the furthest and the closest, thank you so much for being there, for sharing moments of joy and lightness, and for always supporting me throughout these five years. The time spent together has been a sweet distraction in the path of growth I have undertaken.

The conclusion of this thesis marks the end of a journey and the beginning of a new adventure, the one into the working world. My greatest hope is to embark on this new journey with all of you by my side, for as significant as the destination may be, nothing is more precious than the path we take before reaching it.

A Appendix

A.1 PV Modules Datasheet

jinkosolar.us

JinKO Solar
Building Your Trust in Solar

Eagle 72 HM G2
390-410 Watt
MONO PERC HALF CELL MODULE

Positive power tolerance of 0~+3%

KEY FEATURES

Diamond Cell Technology
Uniquely designed high performance 5 busbar mono PERC half cell

High Voltage
UL and IEC 1500V certified; lowers BOS costs and yields better LCOE

Higher Module Power
Decrease in current loss yields higher module efficiency

Shade Tolerance
More shade tolerance due to twin arrays

PID FREE
Reinforced cell prevents potential induced degradation

Strength and Durability
Certified for high snow (5400 Pa) and wind (2400 Pa) loads

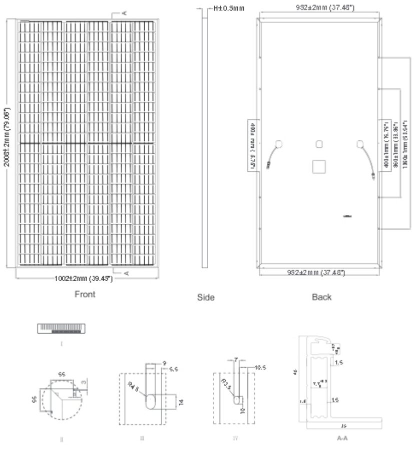
- ISO9001:2008 Quality Standards
- ISO14001:2004 Environmental Standards
- OHSAS18001 Occupational Health & Safety Standards
- IEC61215, IEC61730 certified products
- UL1703 certified products

Nomenclature:
JKM410M-72HL-V

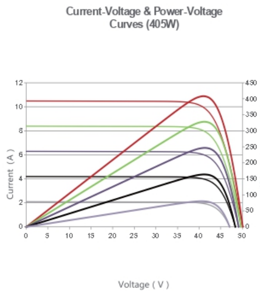
Code	Cell	Code	Cell	Code	Certification
null	Full	null	Normal	null	1000V
H	Half	L	Diamond	V	1500V

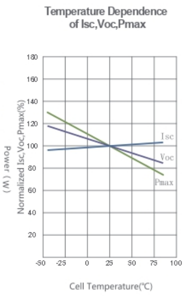
LINEAR PERFORMANCE WARRANTY
10 Year Product Warranty • 25 Year Linear Power Warranty

Engineering Drawings



Electrical Performance & Temperature Dependence





Mechanical Characteristics

Cell Type	Mono PERC Diamond Cell (158.75 x 158.75 mm)
No.of Half-cells	144 (6×24)
Dimensions	2008×1002×40mm (79.06×39.45×1.57 inch)
Weight	22.5 kg (49.6 lbs)
Front Glass	3.2mm, Anti-Reflection Coating, High Transmission, Low Iron, Tempered Glass
Frame	Anodized Aluminium Alloy
Junction Box	IP67 Rated
Output Cables	12AWG, (+) 1400mm(55.12 in), (-) 1400mm(55.12 in) or Customized Length
Fire Type	Type 1

Packaging Configuration

(Two pallets = One stack)

26pcs/pallet, 52pcs/stack, 572pcs/40'HQ Container

SPECIFICATIONS

Module Type	JKM390M-72HL-V		JKM395M-72HL-V		JKM400M-72HL-V		JKM405M-72HL-V		JKM410M-72HL-V	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	390Wp	294Wp	395Wp	298Wp	400Wp	302Wp	405Wp	306Wp	410Wp	310Wp
Maximum Power Voltage (Vmp)	41.1V	39.1V	41.4V	39.3V	41.7V	39.6V	42.0V	39.8V	42.3V	40.0V
Maximum Power Current (Imp)	9.49A	7.54A	9.55A	7.60A	9.60A	7.66A	9.65A	7.72A	9.69A	7.76A
Open-circuit Voltage (Voc)	49.3V	48.0V	49.5V	48.2V	49.8V	48.5V	50.1V	48.7V	50.4V	48.9V
Short-circuit Current (Isc)	10.12A	8.02A	10.23A	8.09A	10.36A	8.16A	10.48A	8.22A	10.60A	8.26A
Module Efficiency STC (%)	19.38%		19.63%		19.88%		20.13%		20.38%	
Operating Temperature (℃)	-40℃~+85℃									
Maximum System Voltage	1500VDC(UL)/1500VDC(IEC)									
Maximum Series Fuse Rating	20A									
Power Tolerance	0~+3%									
Temperature Coefficients of Pmax	-0.36%/℃									
Temperature Coefficients of Voc	-0.28%/℃									
Temperature Coefficients of Isc	0.048%/℃									
Nominal Operating Cell Temperature (NOCT)	45±2℃									

STC: Irradiance 1000W/m² Cell Temperature 25°C AM=1.5

NOCT: Irradiance 800W/m² Ambient Temperature 20°C AM=1.5 Wind Speed 1m/s

* Power measurement tolerance: ± 3%

CAUTION: READ SAFETY AND INSTALLATION INSTRUCTIONS BEFORE USING THE PRODUCT.

JKM390-410M-72HL-V-A1-US

A.2 Optimizers Datasheet

Ottimizzatore di potenza

Per installazioni residenziali

S440 / S500 / S500B / S650B

OTTIMIZZATORE DI POTENZA

Ottimizzazione di potenza fotovoltaica a livello di singolo modulo

- Specificatamente progettati per funzionare con gli inverter residenziali SolarEdge
- Rilevamento di comportamenti anomali nei connettori fotovoltaici, prevenendo potenziali problemi di sicurezza*
- Riduzione automatica della tensione a livello di modulo per la sicurezza di installatori e vigili del fuoco
- Efficienza superiore (99,5%)
- Riduce tutti i tipi di perdite dovuti al disaccoppiamento dei moduli, dalla tolleranza di fabbricazione all'ombreggiamento parziale
- Installazioni più rapide con una gestione semplificata dei cavi e un facile montaggio con un unico bullone
- Progettazione flessibile del sistema per il massimo utilizzo dello spazio
- Compatibili con i moduli fotovoltaici bifacciali

* Funzionalità soggetta al modello di inverter e alla versione del firmware

solaredge.com

solaredge

Ottimizzatore di potenza per installazioni residenziali
S440 / S500 / S500B / S650B

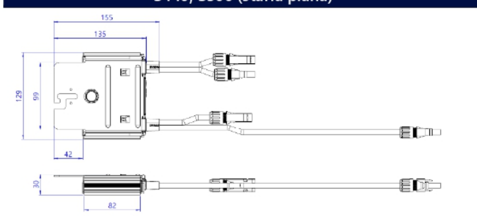
	S440	S500	S500B	S650B	UNITÀ
INGRESSO					
Potenza CC nominale in ingresso(1)	440	500		650	W
Tensione in ingresso massima assoluta (Voc del modulo alla minima temperatura)	60		125	85	Vcc
Intervallo operativo MPPT	8 - 60		12,5 - 105	12.5 - 85	Vcc
Corrente massima di cortocircuito (Isc) del modulo fotovoltaico collegato	14,5	15			Acc
Massima efficienza	99.5				%
Efficienza ponderata	98,6				%
Categoria di sovratensione	II				
USCITA DURANTE IL FUNZIONAMENTO					
Corrente in uscita massima	15				Acc
Tensione in uscita massima	60		80		Vcc
PARAMETRI IN USCITA DURANTE LO STANDBY (OTTIMIZZATORE DI POTENZA NON COLLEGATO ALL'INVERTER O INVERTER SPENTO)					
Tensione di sicurezza in uscita per ottimizzatore di potenza	1 ± 0,1				Vcc
CONFORMITÀ AGLI STANDARD(2)					
EMC	FCC Parte 15 Classe B, IEC61000-6-2, IEC61000-6-3, CISPR11, EN-55011				
Sicurezza	IEC62109-1 (classe di sicurezza II), UL1741				
Materiale	UL94 V-0, resistente ai raggi UV				
RoHS	Sì				
Sicurezza antincendio	VDE-AR-E 2100-712:2018-12				
SPECIFICHE PER L'INSTALLAZIONE					
Massima tensione ammessa dell'impianto	1000				Vcc
Dimensioni (L x A x P)	129 x 155 x 30		129 x 165 x 45		mm
Peso	720		790		gr
Connettore di ingresso	MC4(3)				
Lunghezza del cavo di ingresso	0.1				m
Connettore di uscita	MC4				
Lunghezza del cavo di uscita	(+) 2.3, (-) 0.10				m
Intervallo di temperatura operativo(4)	Da -40 a +85				°C
Classe di protezione	IP68				
Umidità relativa	0 - 100				%

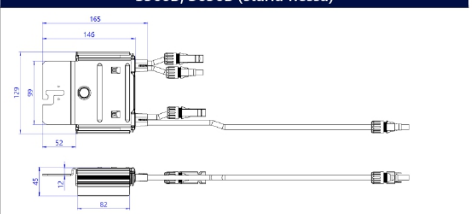
(1) La potenza nominale del modulo a STC non deve superare la potenza CC nominale di ingresso dell'ottimizzatore di potenza. Sono permessi moduli con tolleranza di potenza fino al +5%.
(2) Per informazioni sulla conformità CE, vedere Dichiarazione di Conformità - CE.
(3) Per altri tipi di connettori, contattare SolarEdge.
(4) Per temperature ambiente superiori a +70 °C si applica una riduzione della potenza. Per i dettagli, fare riferimento alla Nota tecnica sul declassamento per temperatura degli ottimizzatori di potenza.

Progettazione dell'impianto fotovoltaico con un inverter SolarEdge(5)		Inverter Wave SolarEdge Home Monofase	Inverter Trifase per Stringhe Corte SolarEdge Home	Trifase per rete da 230/400 V	Trifase per rete da 277/480 V	
Lunghezza minima di stringa (ottimizzatori di potenza)	S440, S500	8	9	16	18	
	S500B	6	8	14		
Lunghezza massima di stringa (ottimizzatori di potenza)		25	20	50		
Potenza continua massima per stringa		5700	5625	11250	12750	W
Massima potenza collegata consentita per stringa (consentita solo quando la differenza di potenza tra le stringhe è inferiore a 2.000 W)		Vedere(6)	Vedere(6)	13500	15000	W
Stringhe parallele di lunghezze o orientamenti diversi		Sì				

(5) Non è permesso combinare gli ottimizzatori di potenza della serie S e della serie P in nuove installazioni.
(6) Se la potenza nominale CA dell'inverter è inferiore o uguale alla potenza nominale massima per stringa, allora la potenza massima per stringa potrà raggiungere la potenza massima CC in ingresso degli inverter. Fare riferimento a Nota Applicativa: Linee guida per la progettazione a stringa singola.

S440, S500 (staffa piana)	S500B, S650B (staffa flessa)





CE RoHS

A.3 Solaredge Report

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EQUA

PANORAMICA DEL SISTEMA — 6 Moduli FV | 1 Inverter | 6 Ottimizzatori

RISULTATI DELLA SIMULAZIONE

Potenza CC Installata	Potenza Massima CA Ottenuta	Produzione Annuale Di Energia	Emissioni Di CO2 Evitate	Alberi Equivalenti Piantati
2,46 kWp	2,46 kW	3,00 MWh	768,55 kg	35

Potenza CC Massima Ottenuta	Sovradimensionamento CC/CA	Potenza Attiva CA Max	PR Rapporto Di Performance	Indice Di Performance
2,46 kW	82 %	3,00 kW	89 %	1.220 kWh/kWp

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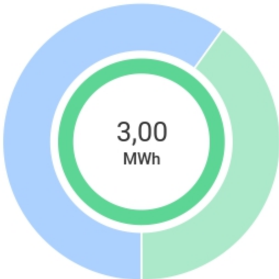
EQUA

PRODUZIONE DEL SISTEMA

Produzione totale - 100 %
3,00 MWh

Autoconsumo - 60 %
1,80 MWh

Esportata - 40 %
1,20 MWh

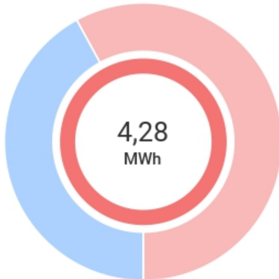


CONSUMO

Consumo totale - 100 %
4,28 MWh

Autoconsumo - 42 %
1,80 MWh

Importata - 58 %
2,48 MWh



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ENERGIA MENSILE STIMATA

Energia totale tagliata: 0%

	Mese Produzione Solare (kWh)	Consumo (kWh)	Auto-consumo (kWh)	Energia troncata (kWh)
Gen	148	356	110	-
Feb	181	356	122	-
Mar	277	356	165	-
Apr	278	357	169	-
Mag	335	357	195	-
Giu	362	357	203	-
Lug	379	357	202	-
Ago	360	357	191	-
Set	271	357	154	-
Ott	177	357	119	-
Nov	120	357	86	-
Dic	114	357	84	-

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EQUA

MODULI FV

# Modulo	Modello	Potenza di picco	Tipo di supporto	Orientamento	Azimut	Inclinazione
6	JinkoSolar Holding Co. Ltd., JKM-410N-54HL4-B Tiger Neo N-Type Black	2,5 kWp			178°	20°
Totale: 6		2,5 kWp				

DISTINTA MATERIALI (BOM)

Componenti	Codice Prodotto	Quantità	Prezzo (€)	Totale (€)
Prezzo base		1	12317,00	12.317,00
SE3000H		1	283,00	283,00
S500B		6		
JKM-410N-54HL4-B Tiger Neo N-Type Black		6		

Prezzo totale: **12.600,00 €**

PROGETTAZIONE ELETTRICA

Inverter & Accumulo	Stringhe per inverter	Ottimizzatori per stringa	Moduli FV per stringa
1 xSE3000H 2.46kW | 82%	1 x stringa	6 x S500B	6

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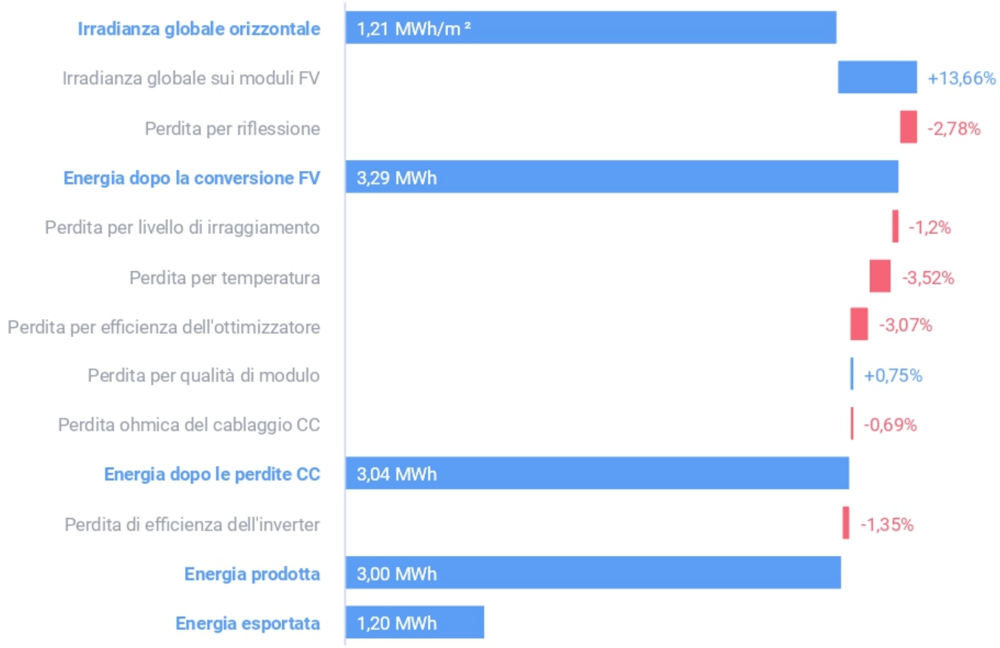
EQUA

DIAGRAMMA DELLE PERDITE DEL SISTEMA



PARAMETRI DI SIMULAZIONE

LUOGO & RETE

Fuso orario	CEST (Rome)
Stazione meteo	Como (8,12 km distanza)
Altitudine stazione	283 m
Stazione sorgente dati	Meteonorm 7.1
Rete	400V L-L, 230V L-N

FATTORI DI PERDITA

Ombre vicine	Abilitato
Albedo	0,20
Albedo bifacciale	0,30
Sporcizia/Neve	0%
Effetto Angolo di Incidenza (IAM), ASHRAE b0 Param.	0,05
Fattore di Perdita termica Uc (cost.) montaggio complanare	20
Fattore di Perdita termica Uc (cost.) montaggio inclinato	29
Fattore di perdita per LID	0%
Indisponibilità del sistema	0%

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EQUA

PANORAMICA FINANZIARIA

Pagamenti netti	Risparmi in bolletta a vita (NPV)	Vantaggi del sistema (NPV)	Tasso di rendimento interno (TRI)	Periodo di ammortamento
€ 12.767	€ 9.039	€ -3.728	0,24 %	19,5 anni

RISPARMI STIMATI IN BOLLETTA ANNO 1

Annuale

Bolletta annuale attuale	Bolletta annuale con SolarEdge	Risparmio annuale netto in bolletta	Scostamento in bolletta
€ 1.320,30	€ 660,04	€ 660,26	50,01 %

Risparmi in bolletta netti a vita stimati

€ 9.039

Gestore della rete: **Enel** | Tariffa elettrica: **Italy F1 + F2 + F3 (3) (0.3 €/kWh) (31/12/2020 - 29/12/2040)**

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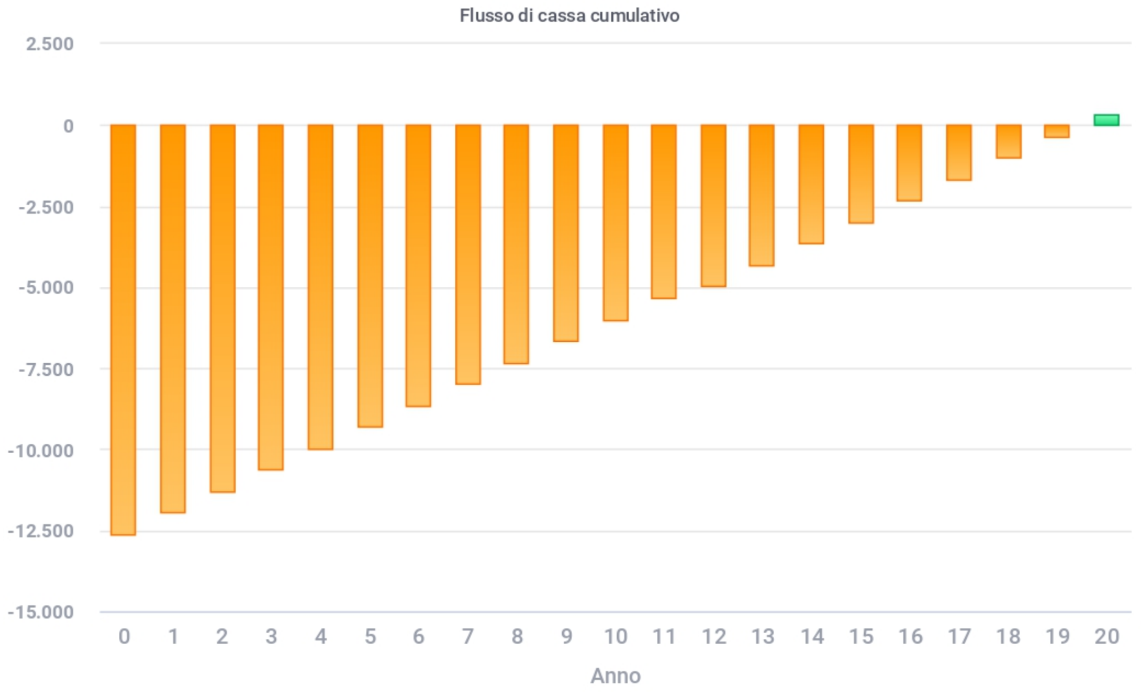
EQUA

ANALISI FINANZIARIA DETTAGLIATA

Prezzo del sistema	Costo manutenzione (NPV)	Guadagni da incentivi (NPV)	Pagamenti netti	Risparmi in bolletta a vita (NPV)
€ 12.600	€ 167	€ N.D.	€ 12.767	€ 9.039

Vantaggi del sistema (NPV)	Tasso di rendimento interno (TRI)	Ritorno dell'investimento (ROI)	Costo livellato dell'energia (LCOE, Levelized Cost Of Energy)	Periodo di ammortamento
€ -3.728	0,24 %	-29,2 %	€/kWh 0,325	19,5 anni



FLUSSO DI CASSA ANNUALE

# Anno	Prezzo del sistema	Costi di sostituzione	Risparmio netto in bolletta	Flusso di cassa annuale	Flusso di cassa cumulativo
0	€ -12.600,00		€ 0,00	€ -12.600,00	€ -12.600,00
1			€ 660,26	€ 660,26	€ -11.939,74

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EQUA

FLUSSO DI CASSA ANNUALE (CONTINUA)

# Anno	Prezzo del sistema	Costi di sostituzione	Risparmio netto in bolletta	Flusso di cassa annuale	Flusso di cassa cumulativo
2			€ 660,26	€ 660,26	€ -11.279,48
3			€ 660,26	€ 660,26	€ -10.619,22
4			€ 660,26	€ 660,26	€ -9.958,96
5			€ 660,26	€ 660,26	€ -9.298,70
6			€ 660,26	€ 660,26	€ -8.638,44
7			€ 660,26	€ 660,26	€ -7.978,18
8			€ 660,26	€ 660,26	€ -7.317,92
9			€ 660,26	€ 660,26	€ -6.657,65
10			€ 660,26	€ 660,26	€ -5.997,39
11			€ 660,26	€ 660,26	€ -5.337,13
12		€ -285,00	€ 660,26	€ 375,26	€ -4.961,87
13			€ 660,26	€ 660,26	€ -4.301,61
14			€ 660,26	€ 660,26	€ -3.641,35
15			€ 660,26	€ 660,26	€ -2.981,09
16			€ 660,26	€ 660,26	€ -2.320,83
17			€ 660,26	€ 660,26	€ -1.660,57
18			€ 660,26	€ 660,26	€ -1.000,31
19			€ 660,26	€ 660,26	€ -340,05
20			€ 660,26	€ 660,26	€ 320,21
Totale:		€ -285,00	€ 13.205,21	€ 320,21	

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