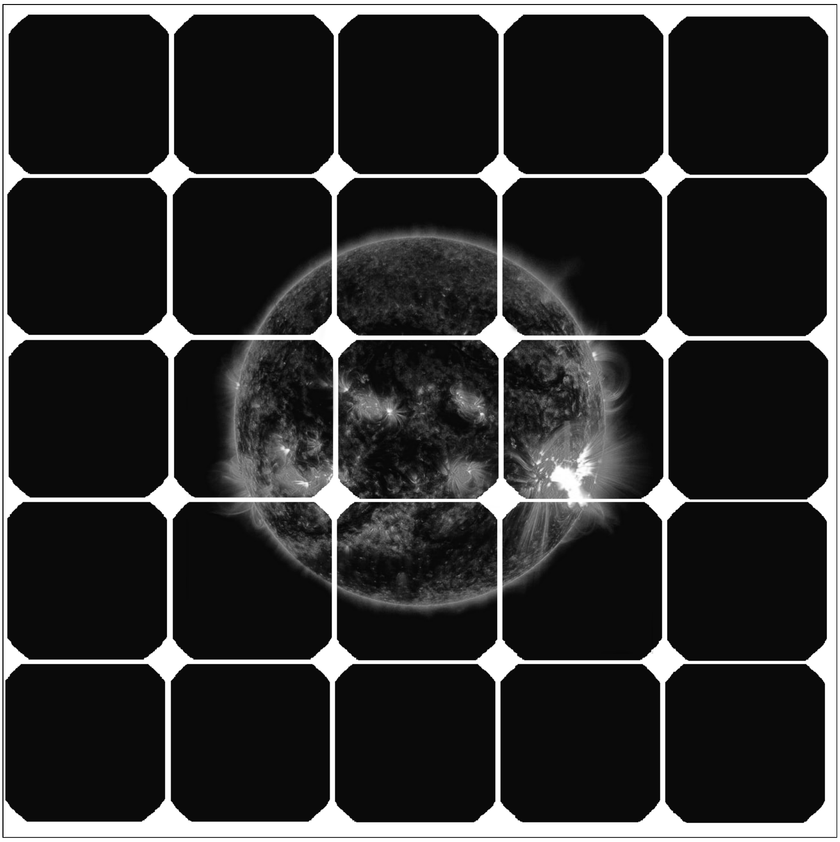
UNIVERSITY OF TRENTO

Doctoral School in Civil, Environmental and
Mechanical Engineering

Curriculum 4. Architecture and Planning, Landscape

Marco Lovati

Methodologies and tools for BiPV implementation in the early stages of architectural design.



2020 - Doctoral thesis

UNIVERSITY OF TRENTO

eurac research

Doctoral School in CIVIL, ENVIRONMENTAL AND MECHANICAL ENGINEERING
Curriculum 4 Architecture and Planning, Landscape
32nd cycle of Doctoral Programme (2016-2019)

Methodologies and tools for BiPV implementation in the early stages of architectural design.

doctoral candidate:
Marco Lovati

Supervisors:
Laura Maturi (EURAC, Institute for Renewable Energy)
Rossano Albatici (University of Trento, department of Civil Environmental and Mechanical Engineering)

Trento
Italy
May 2020

Aknowledgements:

This research has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement (EnergyMatching project N° 768766).
The author wish to thank Laura Maturi, Jennifer Adami, Mattia Dallapiccola and all the colleagues at EURAC, BOUYGUES and DALARNA UNIVERSITY that have helped with the development of this method and the relative tool.

Contents

1 table of symbols and acronyms

ANN	Artificial Neural Network
BAPV	Building Applaid Photo Voltaic
BIM	Building Information Model
BIPV	Building Integrated Photo Voltaic
c	cumulative electricity self-consumed in one year [kWh]
C	Condominium
$C_{B,0}$	Unitary investment cost of the electric storage [€/kWh]
CL	Charge Limit
CO	Capacity Optimization
COP	Coefficient Of Performance
CP	Charging Power
$C_{PV,0}$	Unitary investment cost of the PV system [€/kWp]
D	total Demand
DCF	Discounted Cash Flow
DOD	Dept Of Discharge
DP	Discharging Power
EPBT	Energy Pay Back Time
$E_{PV,0}$	Unitary energetic cost of a photovoltaic system [mWh/kWp]
ETIP	European Technology and Innovation Platform
EU	European Union
Eurostat	European Statistical Office
EV	Electric Vehicles
FIT	Feed In Tariff
G	irradiation over the plane of the PV array
GHG	Green House Gasses
HOY	Hour Of the Year
Hyear	annual cumulative irradiation
i	Annual Discount Rate
IMF	International Monetary Fund
IRR	Internal Rate of Return
KPI	Key Performance Indicator
KS	Korean Standard for BIPV
LCA	Life Cycle Assessments
LCEB	Lifetime Cumulative Electricity Balance
LCOE	Levelized Cost Of Electricity
LCOEself	Self-consumed LCOE
LCOS	Levelized cost of Stored electricity
LM	Load Matching
NPV	Net Present Value
NS	No Storage

NZEB	Nearly Zero Energy Building
PA	Public Administration
Pc	unitary price of the electricity for the consumer [€/kWh]
PPV	Power of the PV system
PR	Performance Ratio
PRC	People's Republic of China
Ps	unitary price of the energy for the provider [€/kWh]
PT	Payback Time
PV	Photo-Voltaic device
PVT	Photovoltaic Thermal device
RES	Renewable Energy Sources
s	cumulative electricity sold or lost in one year [kWh]
SCE	sum of Self Consumed Electricity
SFH	Single Family House
SOC	State of Charge
STC	Standard Test Condition
SSF	Self SufFiciency
t	year of installation
TH	Town House
TMY	Typical Meteorological Year
UK	United Kingdom
US	United States
USA	United States of America
WS	With Storage
WWR	Window to Wall Ratio
γ	charging power of an EV
η	efficiency of a PV module
μB	annual unitary costs for maintenance of the storage system [€/kWh year]
μPV	annual unitary costs for maintenance of the PV system [€/kWp year]
ωB	Capacity of Battery Installed
ωPV	Capacity of PV installed

2 abstract

Photovoltaic technology is among the best tools our civilization has to reduce the emissions of greenhouse gas that are currently altering the atmosphere composition of our planet. The idea of using photovoltaic surfaces on the envelope of buildings is called with the acronym of BIPV (building integrated photovoltaics), it offers the advantage of producing energy in the same location of the demand for electricity. Furthermore, BIPV allows to save monetary and environmental costs by substituting building materials with photovoltaic collectors. As every technology, BIPV follows an adoption pattern that is bringing it from a very limited niche product to a pervasive one. Nevertheless, the adoption rate of BIPV appears to be slow, and the industry has offered little opportunities of business for its stakeholders over the last 20 years. There are multiple reasons for this sluggish growth, and a considerable body of scientific literature has offered potential solutions to the problem. The building industry is notoriously slow in picking up innovation, furthermore the BIPV material needs to compete with much more mature, versatile and often cheaper cladding technologies and materials. Numerous research endeavors are focusing on the development of new BIPV claddings to have diversified colors, dimensions, shapes and other properties. The argument is that the technology is not mature and thus cannot be adopted by the bulk of architects and designers. Unfortunately, the premium characteristics of these new materials often come with a higher price and a reduced efficiency, thus reducing their market potential. Other research endeavors, among which this thesis, are focusing on the design of buildings: trying to include the use of photovoltaics into the architectural practice through education and software development. Numerous software has been developed over the last 20 years with the aim of calculating the productivity or the economic outlook of a BIPV system. The main difference between the existing software and the method presented here lies in the following fact: previously, the capacity and positions of a BIPV system are required as input for the calculation of performance, in this method the capacity and positions of the BIPV system are given as the output of an optimization process. A designer who is skeptical or disengaged about the use of BIPV could be induced to avoid its use entirely by the discouraging simulation results given by the lack of a techno-economic optimal configuration. Conversely, a designer who opt for a premium architectural PV material would, thank to the methodology shown, be able to assess the impact its unitary cost has on the optimal BIPV capacity of the building. Ultimately, the method presented provides new knowledge to the designer regarding the use of BIPV on his building, hopefully this can facilitate the spread of BIPV technology. The method described was translated into a software tool to

find the best positions and number of PV surfaces over the envelope of the building and the best associated battery capacity. The tool is based on the combined use of ray-tracing (for irradiation calculation) and optimization algorithms, its use led to the following conclusions:

- BIPV is profitable under a wide range of assumptions if installed in the correct capacities
- 20% of the residential electric demand can easily be covered by PV without the need for electric storage and in a profitable way
- Despite an interesting rate of return of the investment, the payback time was generally found to be long (over 10 years)
- More research is needed to assess the risk on the investment on BIPV: if found to be low, future financial mechanisms could increase its spread despite the long payback time
- The optimal capacity in energy terms (i.e. the energy consumed on-site minus the energy used to produce a BIPV system) tends to be far higher than any techno-economic optimum
- The specific equivalent CO_2 emissions for an NPV optimal system have been found to be between 70 and 123 [kg CO_2 eq/MWh] under the range of assumptions applied
- The installation of optimal BIPV capacity could change the overall residential CO_2 emission of -12%, +13%, -29% in England, France and Greece respectively
- despite the non optimal placement of a BIPV system compared to a ground mounted, south oriented one, and despite the non-contemporaneity of production and consumption, the BIPV still easily outperforms the energy mix of most countries when optimized for maximum NPV.
- The part of the building envelope that have the most annual irradiation (i.e. the roof) should not necessarily host the entirety of the system as other facades might have an advantage in terms of matching production and consumption times.
- when different scenarios are made in terms of techno-economic input parameters (e.g. degradation of the system, future costs of maintenance, future variation of electricity price etc..) larger capacities are optimal for optimistic outlooks and vice-versa
- the optimal capacity for the expected scenario (i.e. the 50 % ile) can be considered robust as it performs close to the optimum in optimistic and pessimistic scenarios alike.

- a reduction in price for the electric storage appears to have a positive effect on the optimal capacity of PV installed for the case study considered.

- when a group of households is optimized separately V.S. aggregated together, the aggregation have a huge positive effect on all KPIs of the resulting system: in the NPV optimal system of a case study examined the installed capacity (+118%), the NPV (+262.2%) and the self-sufficiency(+51%) improved thanks to aggregation.

3 Introduction

Throughout history, and especially recent years, the total production and use of energy has continually risen and there seems to be no indication for this trend to reverse. A low consumption scenario does not seem likely in the foreseeable future [1, 2]. It is foreseen, for what concerns buildings, that at the current pace, the global energy use could double or even triple by 2050, as the world's population living in cities is projected to increase further in the next decades[3]. Energy consumption is necessary during the use, or at least the production, of technology: therefore it is possible and likely, that the rise of energy production and consumption is a by-product of technological progress. The production and use of energy, results in GHG (Green House Gasses) emissions which alters the composition and properties, hence the energy balance, of the atmosphere [4]. The condition of GHG emissions as a by-product of enrgy related activities whose intensity is not within human control should be avoided* . For this reason all the practices, technologies and energy production methods characterized by low specific GHG emissions should be pursued. The 2030 climate and energy framework includes EU-wide targets and policy objectives for the period from 2021 to 2030[5], it mandates a minimum of 40% cut in GHG emissions compared to 1990 level and an overall 32% of the electricity produced from renewable energy sources. Thanks to price drops, good levels of public acceptance and political support, the renewable energy sector is experiencing a steady and vigorous expansion in recent years and is expected to grow one further 25% in the five years from 2018 to 2023 [6]. According to the report, renewables will have the fastest growth in the electricity sector, providing almost 30% of power demand in 2023, up from 24% in 2017. Among renewables, solar photovoltaic energy is interested by a strong growth albeit it still covers only about 2% of the global electricity demand. The last yearly report from the Solar Power Europe association reported that the LCOE (Levelized Cost Of Electricity) of Photovoltaic dropped a further 14% year-on-year in 2018. Compared to the aggregated renewables (which will gain 25%), the cumulative capacity of PV (Photo-Voltaic) is expected to increase almost 160% in the same time frame. This doctoral thesis aims at expanding the growth of the PV market, in particular the sub-sector of PV integrated into the envelope of buildings, also known as BIPV(Building Integrated PV). There are numerous definition of BIPV: [7] presents a collection of them. This thesis also aims to reduce, in an economically sustainable way, the energy use and GHG emissions associated to the building stock, which, according to the latest buildings performance fact-sheet of the Energy Performance of Buildings Directive [8], accounts for about 36% of the CO_2 emissions in Europe. While the reduction of energy consumption through energy

* The accurate assessment of the share of anthropic causes in the undergoing change in climate is not within the scope of this thesis, information about this topic might be found elsewhere. In this document the capability to produce a larger share of energy at low specific GHG emissions is considered as having value on its own.

efficiency is a valuable strategy and needs to be pursued *"unless clean energy supplies come on-line rapidly, slowing demand growth will only begin to reduce total emissions"*[9].[10]reviews the status in 2017 and outlook of BIPV market on a global and European scale. In particular, it provides a review of the market situation for a selection of european countries till the year 2020. The outlook seems quite optimistic, but, given the scarcity of disaggregated data for BIPV as a fraction of the whole PV market and the lack of an unequivocal definition of BIPV, it is very hard to obtain factual information and confirm the forecast that was made. In the study, the forecast provided is often referred to a *"potentially large market"*, this seems to suggest that BIPV will not reach its full potential in the EU unless something is done about it. Furthermore the study points out the existence of a need to educate and expose the relevant stakeholders to BIPV indicating a current generalized lack of awareness, expertize and *"know how"*, can we really expect a strong growth of this sector in the coming years? before diving into the BIPV related research, it is worthwhile providing a definition of BIPV, there is no single definition to be universally accepted and the scope of this paragraph is not to provide it. The definition of BIPV expressed in this paragraph is tailor made for the present thesis, and perhaps some other works that will be mentioned further on. This discussion does not imply that the definition offered in other sources are wrong or flawed* , it should rather be interpreted as functional to understand the viewpoint from which the technology of BIPV is examined. The lack of an absolute definition ensures a certain flexibility of interpretation for this technology and its future, in this context every research endeavour can explore different aspects of the same subject of study and envision a special research direction for developing the technology in the long term. A comprehensive collection of definitions is provided in [7]. The first section explores the definition derived from current standards and building codes, numerous definitions distinguish between BIPV and BAPV (Building Applied PV). EN 50583 [11] for example makes a distinction between PV modules and PV systems and considers PV modules to be building-integrated, if the PV modules form a construction product providing a function. Thus, the BIPV module is a prerequisite for the integrity of the functionality of the building. If the integrated PV module is dismounted, the PV module would have to be replaced by an appropriate construction product. Power generation alone do not qualify PV modules to be building-integrated. Similarly ISO/FDIS18178 [12] distinguishes between building integrated and attached PV and considers integrated only the systems whose modules *"replace"* existing building materials. In IEC 61730-1:2016 [13] PV systems are considered to be building integrated if the PV modules form a building component providing mechanical functions, weather/fire/noise protection, shading for

*no universal value judgement is in fact offered in this paragraph thermal purposes, daylighting or thermal insulation. Regarding thermal shading: in previous papers [14, 15] me and my colleagues explored the possibility of using PV modules as solar shading. It is functional to the discourse to notice that the type of modules used in shadings do not have to fulfil special requirements as element of the building skin(e.g. water tightness, noise absorption etc.), therefore standard PV modules can in theory be used for this purpose. IEC TS 61836:2016 [16] grants the status of BIPV to the systems whose modules provide one or more functions of the building envelope. Also the spanish technical building code(FOM/1635/2013)is reported and this as well stresses on the dual function for the PV system (i.e. production of electricity plus an envelope-related function). The korean standard (KS) C 8577:2016 contains some uncertainty, it mandates two requirements (structural and electrical), but it is not explicit about any envelope related functionality in the sense that it might simply mandate a minimum performance in terms of safety and durability. In other words, with the exception of the korean example, all standards and building codes reported associate around the concept of multi-functionality. Following the section about the standards, a section about the funding programmes is reported: also in this case the multi-functionality figures as the main requirement in all the examples reported in the EU (France, Spain, Switzerland and Italy are reported). As it happened for the standards, also the funding programmes include an outlier: the chinese funding agency in fact does not seem as concerned with multi-functionality as it seems concerned with the design process. according to the China National Photovoltaic Status Report [17] *“BIPV is defined as building-integrated PV, which requires that the building team along the entire supply chain - including architects, building designers, engineers, building owners and utility companies - works together to design and install the specially designed PV modules into the building’s "skin" as an element, from the inception of the project onwards. This applies particularly to the usage of solar building material, such as solar tiles, solar façades and solar shingles”*. The definition provided by the majority of standards and funding programmes does not provide a satisfying framework for the subject of this thesis because it excludes (i.e. it treats as not BIPV) a series of cases that are of prime interest for this work and because it focusses on a set of essential characteristics that are not paramount here. The concept of multi-functionality is intended as a typical function of the building envelope which should accompany the production of electricity(with the exception of the use in shadings). It follows that the determining factor for a module to be integrated is the existence of certain material properties (e.g. water tightness or noise reduction). This PhD thesis does not analyse the PV material from the technological point of view, accepting exclusively this definition would mean to direct the research only on material properties and technological details. There are numerous other approaches and areas of development that can bear fruits. Besides, The obstacle with this approach is that it narrows the domain of BIPV and so doing it miss the opportunity of expanding the domain of building. The idea behind multi-functionality is that PV should have at least one function of the building as opposed to only be producing electricity: but what if producing electricity is in itself a function of the building? Restricting the building domain only to functions which it has traditionally fulfilled might be short-sighted, the hypothesis that energy production will be a function of buildings alongside, say, weather protection and daylight regulation, cannot be excluded as of today. If the energy production is a function of the building, PV might be considered *"integrated"* even when not multi-functional. The subject of PV integration into an architectural context is explored thoroughly in [18], the paper explores the different architectural approaches with which the PV technology has been used in different built examples and identifies a set of strategies. According to the paper PV can be: applied invisibly, added to the design, it can add something to the architectural image, it can determine the architectural image or it can lead to a new architectural concepts. If it is applied invisibly it is not possible, or at least not easy, to know that the building is equipped with a PV system: this style of integration might rely on special material to modify the appearence and texture of the PV modules. The use of specific building related "invisible" modules fits the target of a large number of PV definitions, but it can sometimes be a symptom of a design process that did not consider PV in time and needs to camouflage it as an unwanted technical component. When PV is added to the design there is no real integration and likely falls within the "BAPV" category of numerous definition, the authors report about it that *"Building integration is not really used here, but this does not necessarily mean that architectural integration is also lacking. The 'added' PV system is not always visible"*. When the PV system adds to the architectural image it cannot be removed without changing the architectural character of the building: it might have no practical function (e.g. no shadow) but nevertheless be essential from the aesthetic point of view. Note that the EN 50583, the ISO/FDIS18178, the IEC 61730-1:2016 and the IEC TS 61836:2016 would not consider this type of integration as BIPV as long as it is not multi-functional. For the scope of this thesis the last two categories * are respectively equivalent: in both the cases an inclusion in the design process is needed with the main difference being apparently the capacity to bring an innovation into the design practice itself. Also in these last two cases the main definition of BIPV appear to be completely independent from the design criteria: a technologically integrated system could be simply a cladding that do not determine the architectural image, while a strong architectural element such as a PV

*i.e. PV determines the architectural image and PV system leads to new architectural concepts sail could have no envelope related functionality. In the study [18] the authors bids to ensure the satisfaction of a set of criteria for good PV architecture as defined by Task 7 of the IEA PVPS programme [19]. In [19] the criteria are reported as follows:

- **Naturally integrated:***The PV system is a natural part of the building. Without PV, the building would be lacking something the PV system completes the building.*
- **Architecturally pleasing:***"Based on a good design, the PV system add eye-catching features to the design"*
- **Good composition:***"The colour and texture of the PV system should be in harmony with the other materials. Often, also a specific design of the PV system can be aimed at (e.g. frameless vs.framed modules)"*
- **Grid, harmony and composition:***"The sizing of the PV system matches the sizing and grid of the building"*
- **Contextuality:***"The total image of a building should be in harmony with the PV system. On a historic building, tiles or slates will probably fit better than large glass modules"*
- **Well-engineered:***"This does not concern the watertightness of PV roof, but more the elegance of design details. Have details been well-conceived? Has the amount of materials been minimised? Are details convincing?"*
- **Innovative new design:***"PV is an innovative technology, asking for innovative,creative, thinking of architects. New ideas can enhance the PV market and add value to buildings"*

also in this case the criteria often seem unrelated to most of the definitions of BIPV. A selection of reportedly BIPV projects from the Trentino e Alto Adige/Sudtirol region of Italy [20] shows as well some examples that are not to be considered as BIPV according to the major standards on the matter (see Fig. 1).

The existing regulation regarding BIPV, while meaningful for product developers and for the good quality of the architectural details, does not provide an appropriate framework for this thesis, it focus on the technological and material aspect of the products rather than on the integration of the system in the built environment. The book [20], aside from the collection of BIPV examples, provides also a definition of BIPV which may fit well with the current work. According to [20] the "I" in BIPV has a triple meaning, which is technological,aesthetic and energy integration as shown in Fig.2. By aesthetic integration is meant the

Figure 1: examples of BIPV from [20]. A and C are examples of PV added to the design: despite this, the architectural character of their design was recognized by a group of expert who decided for them to be included in the book. B is an example of PV which determines the architectural design: all three examples would not be considered as BIPV according to the EN 50583 [11]

satisfaction of most of the criteria for good PV architecture as defined by Task 7 of the IEA PVPS [19](reported above). Also in this case, by technological integration is intended the multi-functionality aspect described by numerous standards: this is not deemed necessary in the thesis, it is therefore limited merely to the guarantee of safety and durability of the material and the necessary constructive details to preserve an acceptable architectural quality. By energy integration is meant the ability of a BIPV system to interact with the building or district underneath to maximize the consumption of *"on-site"* electricity. The energy integration would become more prominent if the energy generation is considered a standard function of a building.

To conlcude, a definition of BIPV is provided, from this point onward BIPV will mean: **A building attached PV system that is safe for the occupants and is functionally and visually durable. It can interact with the energy system of its building or district to maximize the use of *"on-site"* electricity, its technological details ensure an acceptable architectural quality.** This definition is not rigorous since displays elements which require interpretation such as "acceptable architectural quality", nevertheless this is not meant for deciding the eligibility to incentives or compliance to standards. This definition wants to convey a specific idea of BIPV as product and architectural practice, the literal interpretation of some of its elements is therefore left to the

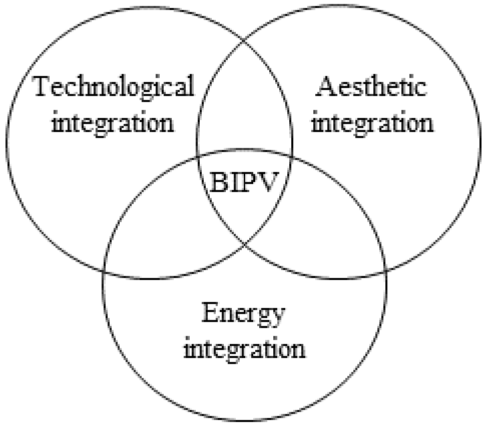


Figure 2: schematic representation of the three criteria for A PV system on a building to be defined BIPV

common-sense of the reader. This definition is in fact a slight modification of the definition presented in [20], from which the scheme in Fig.2 is reported. The concept of technological integration is modified to avoid the limitations of multi-functionality, and it only ensures that safety and durability are achieved. One way to increase the number of BIPV systems in the everyday practice could be the effective inclusion of PV system in the architectural workflow. An architectural design can be interpreted as an organic system, if a part of the project is changed the overall quality of the design will suffer unless the rest of the project is changed accordingly.[3] sustains that*"the double functionality of a BIPV product has to be taken into account from the first stages of design, merging energy, BIPV and building requirements. A close collaboration of all stakeholders, from manufacturers to planners, developers, architects and installers, will also help to accommodate the different national building codes and permits and administrative requirements"*. The inclusion of PV systems from the early stage of the architectural design could ensure a place for the electricity production among the functions of the building and the PV system as an integral element in a conceptual design or a design idea. This way of proceeding could secure the presence of PV in the face of technical difficulties. Furthermore, the integration of a PV system within the architectural work-flow would ensure that its safety, durability, energy compatibility, aesthetics and technological details are taken into account. Fig. 3 is an interpretation of what happens during the design of a new construction or a retrofit, it shows a schematic representation of the architectural design. The design team moves gradually from earlier to later stages deciding upon aspects of ever increasing detail. Every step of the architectural design

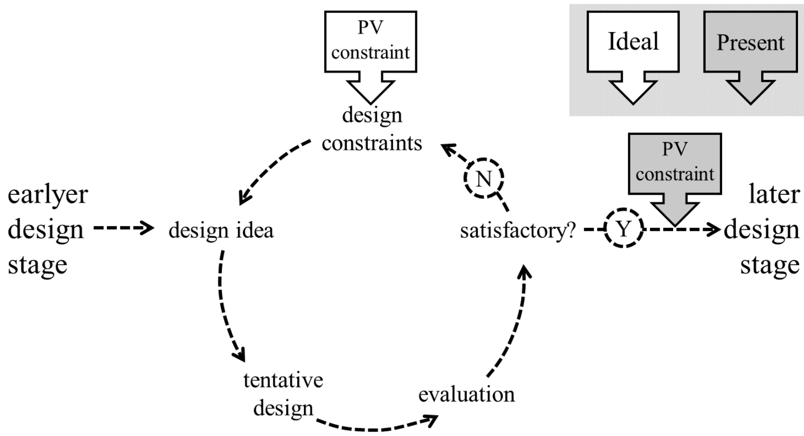


Figure 3: schematic representation of the architectural work-flow, the chart shows the position of the PV design as it often is in the AEC industry, and as it could become on par with the other elements of the architectural design such as windows or structures

is characterized by a set of constraints, these constraints are conceptual or strategic in the earlier stages and become increasingly technical and regulatory moving on. In contemporary practice PV systems are often considered too late in the architectural design. As the picture Fig. 3 shows, PV related constraints are applied once the design is already decided and cannot contribute to become a creative constraint such as other elements of the building (e.g. structure, plumbings or fenestration). In the present work-flow a PV system is often perceived as a nuisance, or as an undesired technical complication and it will be avoided whenever possible (e.g. not mandatory by law). The aim of this doctoral thesis is to provide a method for integrating BIPV into the architectural design work-flow, thus helping to boost the BIPV market and, subsequently, increasing the penetration of renewables into the energy mix.

3.1 State of the Art and related research

A report from ETIP (European Technology and Innovation Platform)[3] affirms that *"Despite its potential, there are several hurdles to overcome if we are to see BIPV as a common part of our cities' landscapes. These hurdles are mostly related to the low renovation rates and slow integration of on-site renewables in cities, but also with the historical lack of awareness of the benefits of BIPV products"*. According to this report the PA (Public Administration) is one of the main actor (if not the main actor) to enable an accelerated route toward more BIPV, the actions foreseen as major catalysts for change are reportedly:

- converting the PA building stock into Plus-Energy-Buildings by using BIPV, and therefore, generate best practice examples
- promoting new financing schemes for private property owners, such as energy contracting and leasing models for BIPV installations
- setting up efficient policies, grid regulations and incentives for a systematic electrification of buildings, heating and cooling, and transport.

Aside from the behaviour of the PA, if buildings will be conceived as requiring energy production the energy integration of BIPV systems will likely become a key aspect of construction. In fact, EU policies seem designed to boost and regulate the NZEB (nearly zero energy buildings) concept [21, 22] and on-site RES (renewable energy sources) exploitation [23, 24], with buildings moving from passive stand-alone units using energy from the grid to pro-sumers * [25, 26]. The retrofit of the existing building stock will surely play a major role in the energy transition and the upgrade of a building with energy producing technologies such as BIPV is imperative to the retrofit [27, 28]. Buildings strive to be "Energy flexible" i.e. able to consume, produce, store and exchange energy, this can cause deep transformation in the energy market throughout the EU, shifting from centralised, fossil-fuel based, national systems towards decentralized, renewable, interconnected and variable system [29]. The effect of this can clearly be seen in the draft of the new RES directive where the legislator introduces the concept of self-consumers and collective self-consumers, stating that "there is a need for a definition of renewable self-consumers and a regulatory framework which would empower self-consumers to generate, store, consume and sell electricity without facing disproportionate burdens"[30]. Especially, according to the IEA EBC Annex 67 project [31], a building can be considered flexible when it possess the ability to manage its demand and generation according to local climate conditions, user needs, and energy network requirements. Energy Flexibility is a property that can enable demand side management/load control or interactive behavior of the power absorption based on the interaction with the energy networks around [32]. In this context, there is a strong demand for new methods and tools to direct and improve the BIPV design, making BIPV functional, cost-effective, architecturally valid and compliant with the aforementioned aspects. Most of the forecast in the last fifteen years saw BIPV as a powerful market driver for the whole PV industry, in reality it never took off and still forms a modest niche market in the sector [33, 3]. Theoretical ways to boost the market of BIPV systems are continually explored in literature, most studies seem to refer to PV system in build-

* portmanteau of the words producer and consumer used to describe dwelling equipped with some sort of energy production device

ings as lacking or underdeveloped, this is perceived as a problem. These boosting strategies usually form two distinct categories i.e. the development of better products and materials [34, 35, 36, 37] or the insertion of BIPV into the architectural discipline [18]. Some researchers advocate for PV design notions within the architectural education curriculum to increase the BIPV installations [38, 39], other authors are focussed on design procedures based on performance and often considering multi-functional aspects of BIPV [40, 41, 42, 14, 43]. In the subject of this thesis the integration of BIPV into the design workflow is achieved by means of optimization: a strategy that is under-represented in the current set of tools and practices [44]. The optimization plays the role of an initial shaping and dimensioning agent which can provide creative design constraints(as in Fig. 3). The most prominent software tools used by the photovoltaic community are primarily built for simulation purposes[45], they do not offer the possibility to optimize the capacity and position of the PV system over the building surface in relation to its electric demand. Optimization can be employed by these tools, but only for the sake of inverter sizing and wiring design: [46] can perform optimization on the wiring layout and number of inverters, but it requires an arbitrary capacity as initial input. [47] can optimize the wiring strategy and automatically accommodate an array of modules on a roof or façade, but the capacity is only the one which fills the given surface and is not optimized according to a particular scope.[48] performs optimization only for deciding size and number of inverters. [49] is tailored for utility scale PV systems. [50] can calculate and report numerous financial metrics concerning PV and, with external scripts, be able to perform optimization, it could in theory serve the purpose shown in this thesis but it would need a comprehensive set of scripts for pre and post processing. In this sense [50] is a generic tool, which is very powerful and can be used for anything but requires very skilled users: in the future the procedure expressed in this manuscript could be carried on using [50] as PV calculation instead of the present day formulas written in Python. In recent years a number of optimization procedures have been tried with the aim of finding the optimal geometry of the PV system. These calculations rely on a parametric model built by the authors specifically for the purpose and are unrelated experiences rather than unified design processes. [37] employs a specific dynamic façade technology and requires a unique modelling technique for this purpose only. [14] and [15] also focused specifically on the technology of solar shading and required exclusive modelling. Some experiences were characterized by the use of optimization for maximizing the annual cumulative irradiation like in the cases of [51] or [52]: These did not constitute a full techno-economic analysis. [53] is similar to [14] in the way that it considers the angle that the PV modules form with the façade, it displays a higher degree of technological variability in the architecture, but still represents a parametric model designed specifically for a specific case study. Furthermore [53] evaluates only the annual cumulative production instead of considering demand matching. Techno economic estimation are available in literature, nevertheless most of them do not consist in optimization, they are therefore unfit for being part the design work-flow as described in Fig. 3. [54] Assesses the potential PV area over an excerpt of urban fabric of two square Km;[55] evaluates the changes in capacity of a BIPV system over a large building setting a threshold for the minimum acceptable irradiation over the system;[56] checks how a system built over the roof of a large building in the university campus can be profitable during its lifetime. It should be noted that most assessments measure the PT (Payback Time), LCOE or IRR(Internal Rate of Return) than on NPV (Net Present Value). This is an important aspect since all these metrics: IRR, LCOE and PT have their optimal value when the annual cumulative irradiation is highest and for IRR and PT the self-consumption is 100%. If, for example, a building is inhabited by 100 people of which 90 are on holiday during August and there is no monetary reward for feed-in PV electricity, the shortest PT will occur for a system small enough to only cover the electric demand of 10 people. This happens because even the smallest occurrence of over-production reduces the *"self-yield"* of the system [kWh sold/kWp] and so prolongs the PT (or conversely decreases IRR). This is one among numerous examples where IRR, LCOE or PT point toward a clearly under-dimensioned system in terms of impact on the energy demand and NPV. This does not mean that such indicators are wrong or devoid of interest, on the contrary they are absolutely paramount to understand the economics of a PV system. Nevertheless they cannot make a good reward function in a single-target optimization process due to their lack of a maximum respect to a varying capacity. The NPV is a measurement of profit calculated by subtracting the present values of cash outflows (including initial cost) from the present values of cash inflows over a period of time[57]. It can be interpreted as a measure of the value extracted from the money invested in something. The main innovation offered by the method described here lies in the fact that the PV capacity and position on the building envelope is not an input of the calculation, but an output. Optimization software are a strict minority among the simulation tools available [44], but the optimization technique seems appropriate for the inclusion in the architectural design work-flow, particularly for BIPV. A way of proceding where the characteristics of the system are required as an input cause a *"trial and error"* behaviour, instead an act of constrained freedom is surely a constructive process of design in architecture. Constrained freedom is a process enhanced by creative constraints [58]. The use of constraints seems a promising pathway in the architectural process as

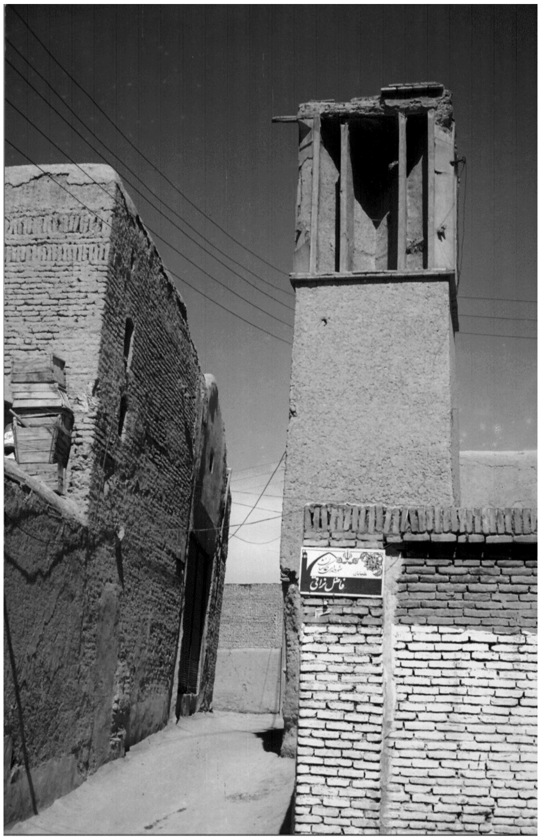


Figure 4: A wind-catcher *"baadgeir"* built with mud bricks constitute an example of constrained design because its form and materials are determined by its functionality. Source[62]

it is visible in numerous contemporary architecture and it appears to be the main process of formation of the vernacular dwellings around the world. For example, the creations of the Spanish architect Santiago Calatrava are strongly driven by the mechanical behaviour of their bearing structures. Throughout history and diverse geographical areas numerous typical buildings have formed which showed features made for good use of the local weather. These buildings could improve comfort by means of shape and properties of the material used and by clever architectural strategies [59, 60, 61](see Fig.4). Considering that vernacular buildings have a disseminated nature and there is often no clear inventor for a type, it seems unlikely that they were the result of a deliberate design, a long process of slow differential improvements based on imitation seems a more likely candidate. In similar processes many variations of a same prototype are evaluated and selected for a specific set of performances, this pattern of evaluating variations of a *"blueprint"* is common of the vast majority of optimization processes (e.g. [63, 64, 65]). Because it works in a similar way of known and consolidated design processes, optimization seems capable of generating rules to improve the effectiveness of an architectural system, these rules are, for all intents and purposes, creative constraints. Thanks to these design constraints there is the chance that PV systems will be part of the architectural work-flow as seen in Fig. 3. Only in this case the PV system will be considered among the building functions as it already happens for other architectural systems such as windows or bearing structures. Two examples of optimization of positions and capacity for BIPV are particularly relevant for this work: [66] has stunning similarities to the subject of this thesis, in this paper and in [67]capacity and positions of a large scale BIPV system are chosen out of a set of options where the hourly irradiation, used for calculating the PV production of every system evaluated, is calculated using the ray-tracing technique. The main difference respect to the present work lies in the reward function used: [66] evaluates and selects the PV systems thanks to a multi-objective optimization. One of the multiple rewards is SSF [%](Self-SufFiciency), which is defined as

$$SSF = \frac{SCE}{D}, \tag{1}$$

where the **SSF** is equal to the **SCE** (sum of the Self-Consumed Electricity as defined at page 33) divided by **D** (total Demand). This represents the fraction of the electricity consumed in the building which is produced by the BIPV system contemporaneously or by a PV fed electric storage. This KPI (Key Performance Indicator), unlike the NPV, does not show a maximum along the dimension of the capacity (it keeps increasing with increasing capacity). The problem is therefore constrained using an additional parameter which is related to the balance between the grid and the PV system. The multi-target function induces the formation of a front of Pareto * between SSF and the balance with the grid where increasing SSF invariably leads to a less balanced system/grid. The study gives an insight into this aspect of urban PV but, because the designer is left with one degree of freedom (i.e. could chose to sacrifice self-sufficiency or grid balance), it doesn't make a good design procedure. From a designer perspective, every capacity (which induces a SSF/grid balance pair)is absolutely equivalent to the others, the study therefore shows the relation between SSF and grid balance but does not provide design indications. In the study the capacity chosen for analysis is near the point of maximum curvature of the Pareto curve, but also others could be, because every point on a Pareto has, by definition, an identical reward relatively to the two KPIs. Furthermore the curve has a meaning only if there is no possibility to use ohmic-resistance to dissipate the excess production or smart inverter designed to work below the power of the load. Of course using these technologies means

* also called Pareto efficiency or Pareto optimality, is a state of allocation of resources from which it is impossible to reallocate so as to make any one individual or preference criterion better off without making at least one individual or preference criterion worse off

wasting part of the electricity produced, this is in fact the reason why there is a need for a reward function that has a maximum with respect to capacity. In other words the loss of part of the electricity produced can be acceptable if compensated by enough electricity self-consumed and by the avoidance of balance problems for the grid: if the capacity is to high there is too much loss of electricity, if the capacity is too little there is not enough impact on the electricity demand.[67] explains in detail the various effects of the placement of modules on the different façades of a building and analyses the impact of this on a collection of KPIs. This consists in a broad analysis and therefore does not seem to provide a clear design methodology, but rather shed light on a number of aspects. In the conclusions the paper appears to argue that electric storage is a superior option matching the load compared to the use of facade, if analysed using NPV tough, the use of storage or façade PV (or even over-capacity of PV on the roof) is ultimately a matter of relative unitary costs for PV and batteries. A function similar to the NPV, but focused on CO_2, would be useful to implement considering the specific emissions generated during production, transport and installation of a PV system and its lifetime electricity self-consumed. Storage and façade integration are not necessarily competitive strategies: in presence of load variation along the day the presence of electric storage suppresses the installation of PV on east and west when the south is available. In presence of variations along the year tough (difference between winter and summer), the electric storage would undermine the façade installation against the roof only in presence of a truly colossal battery (big enough for seasonal storage), and having part of the system with an higher tilt seems more sensible. In [67] the NPV is not among the serie of KPIs evaluated.

3.2 Aim of the thesis

The thesis presents a novel tool for the planning of urban photovoltaic systems, specifically meant to be used during the early stages of architectural design. The method retrieves the capacity and positions of a photovoltaic system over the envelope of a building and, if required, the capacity of an electric storage system by means of optimization. The input consists in: geometry of the building, surrounding shadings, local weather, hourly electric demand, unitary costs of the system and benefits for the production of electricity (sold or self-consumed). Among the input there are known values (e.g. PV installation costs [€/kWp] or present costs for the electricity [€/kWh]) and unknown ones (e.g. degradation rate [%/year], maintenance costs [€/kWp year] or discount rate [% /year]). The optimization is performed using the expected value of a chosen reward function (see optimization section at Pag. 30)out of a set of parametric scenarios generated by the unknown input values. It is shown that, if capacity and position of the system are tailored on its aggregated electric demand, a consistent penetration of photovoltaic electricity is profitable at current prices without incentives or even revenues from the grid. This method has the potential to hugely expand the installation of urban photovoltaic.

3.3 Statement of the research question

The previous chapter can be summarized by the following key concepts:

- The present PhD thesis aims at reducing the specific GHG emissions associated with the production of electricity for use in the urban environment

- the method presented aims to increase the market penetration of the BIPV technology, which is defined as: A building attached PV system that is safe for the occupants and is functionally and visually durable. It can interact with the energy system of its building or district to maximize the use of *"on-site"* electricity, its technological details ensure an acceptable architectural quality. This definition ensures 3 types of integration (i.e. technological, aesthetic and energy) as in [20], but the requirements for technological integration are limited to the guarantees for safety and durability and do not mandate multi-functionality. This definition of BIPV, contrary to most others, do not require the use of specially made products and can therefore admit system built with standard components. The use of standard components allows for lower price ranges compared to the present BIPV practices, this feature has the potential to enlarge the BIPV market from *"high-end"* niche-market to a more capillar one.

- In the present design work-flow the PV system is not seen as a design constrain, but is considered too late in the process. The aim of this thesis is to move the PV as shown in Fig.3 at page 15. This objective was advocated by [18], according to which the production of electricity is a function of the building and should be treated like others such as structural integrity,weather protection or daylight.

- There is good agreement among BIPV experts on the fact that the market is still under-performing respect to its potential, the main strategy for enabling the market boost are: the development of better products and materials, teaching of PV concepts within the architectural curriculum, adopting design procedures to increase the performance of BIPV (both energetic and multi-functional).

- numerous software tools have been developed for the simulation of photovoltaics, some of which have some BIPV capabilities. Nevertheless most cannot perform optimization (as most of building performance simulation tools according to [44])

- Some research experiences have considered optimization of BIPV but these require the construction of labour-intensive parametric models which are then connected to simulation engines and optimization algorithms.

- Few techno-economic assessment regarding BIPV have been found and most do not employ optimization techniques. Most assessment use PT,LCOE or IRR as KPI. These KPI, while certainly useful, cannot be used as a single-target reward function for the optimization of BIPV capacity. The reason for this is that they are monotonic relatively to the capacity (i.e. they do not present a maximum value over a given capacity range).

- The main innovation offered by the method described here lies in the fact that the PV capacity and position on the building envelope is not an input of the calculation, but an output. Optimization software are a strict minority among the simulation tools available [44], but the optimization technique seems appropriate for the inclusion in the architectural design work-flow, particularly for BIPV. The reason is that an approach where the capacity and position of PV are the input for the simulation would generate a *"trial and error approach"*, whereas an optimized capacity and positioning would constitute a *"creative constrain"* more fit for the architectural design work-flow. Examples of constrained design can be found in contemporary architecture, but they are especially evident in the so called *"vernacular"* architecture as described in the book [59] and exemplified in the picture Fig.4 at page 19.

- some studies such as [66, 67] have begun in recent years to optimize the placement and or the capacity of the system according to techno-economic parameters. The studies follow a work-flow similar to the one found in Fig. 3 at page 15. Nevertheless there are some research questions that in these are not addressed.

Is BIPV profitable with current day technologies, prices and economic conditions?Considering a work-flow based on techno-economic assumptions is spontaneous to ask whether it is possible to optimize a PV system so that it can generate an economic benefit (or at least do not results in a loss) without employing incentives. **What percentage of a residential electrical demand can be covered by PV in an**

economically sustainable way? Analysing the relation between self-consumption and capacity of the system * becomes apparent that the question is not whether PV is profitable or not, but rather how much of it. In consequence of this, a range of typical self-sufficiency values should be investigated through the optimization algorithm to find the optimal capacity. **Does an economical BIPV system breaks-even from the energetic point of view? what are the specific CO_2 emissions of an integrated system if only the self-consumed electricity is considered?** The fact that a system is sustainable from the economic point of view does not guarantee that it can be sustainable both in terms of LCEB (Life Cycle Energy Balance) or specific CO_2 emission [g CO_2 equivalent/kWh]. Furthermore, in a future in which there is high penetration of PV energy in the energy mix, it will become difficult to sell excess PV electricity when this exceeds the demand. The specific emissions and the LCEB should be assessed not only considering the electricity produced but the fraction of it that is self-consumed. The levelized emissions calculation is of course a staple of the LCA studies and has been performed extensively as reported in [68]. In a BIPV system, such value is determined by geometric factors of the building and surroundings (see [69]) and by the ability of the building to self-consume the electricity produced. Since the optimization in this thesis addresses energy and economic KPIs, it does not minimize CO_2 emissions per se: thus, the emissions from the self-consumed fraction of the electricity from the optimal system must be investigated to guarantee the validity of the procedure. **Is there one or more market possibility for façade integration?** In terms of annual cumulative irradiation, hence of yield [kWh/kWp], the roof tends to score better than the façade. Nevertheless in high rise buildings the roof surface might be limited, or there can be cases in which the roof cannot be dedicated to BIPV because of use as green roof or other uses. In addition to this, some load (e.g. heat pump for heating), might be more prominent in winter than summer and façade integration could suit these better. **what is the impact of prices on the capacity installed?** Often, in the current market environment, BIPV is so expensive that it is installed because of its appearance and not because it is an economic and technical asset for the building. The higher the unitary price of PV,the lower its optimal capacity for a given building. **Is electric storage profitable with current day technologies, prices and economic conditions?** The presence of storage can enable higher penetrations of PV, but a system with storage is more expensive than a system without it, the optimal balance between PV and storage capacity ultimately depends on the price ratio between the two. **What is the effect of a price drop of electric storage on the optimal capacity of PV installed?** The presence of storage would increase the value of PV according to the value measuring method proposed by [70]. **what is**

* the highest self-consumption is realized for a system that is very small compared to the load because all electricity produced is immediately consumed. Self-consumption shrinks amid growing capacity.

the impact of a growing penetration of EV (Electric Vehicles)on the capacity of PV installed and on other KPIs? The diffusion of EVs would increase the electric load, hence should encourage the use of a higher PV capacities, the prevalence of the electric load for EV during night-time tough might have a negative effect on KPI such as SSF or $LCOE_{self}$ (Self-consumed LCOE).

4 Method and assumptions

In the following section the procedure used for the optimization of the BIPV system is explained: in the first subsection, an overview of the workflow is provided complete with inputs, outputs and a description of the optimization algorithm with the relative reward functions. The workflow is followed by an explanation of all the assumptions made in the modelling of the PV and the storage system(see Pag.40), the section shows the level of detail of which every simulation in the optimization is endowed and explains why it was chosen as such. In the last subsection (starting at Pag 48) a revision of literature is performed to find plausible values to insert as input for the optimization. These values are subject to obsolescence, therefore a similar work could be repeated periodically (thus using the method here described as an evaluation method for measuring the progresses in urban photovoltaic installation potential).

4.1 Workflow

4.1.1 Weather, Geometry and Hourly electric demand:

as shown in Fig.5, a series of inputs are needed to retrieve PV and electric storage capacity and PV positions, the inputs are described as follow:

- **Weather file:** it is used to estimate the irradiation and temperature conditions that the system will experience in each HOY (Hour Of the Year) of its lifetime. These files are TMY (Tipical Meteorological Year), the format used in the tool is *.Epw, the databases from which the data is extracted in the examples preented are Meteonorm [71] and PVGIS [72].
- **Geometry:** The irradiation is retrieved over the geometry of all the potential surfaces of PV to estimate its interaction (blocking or reflecting light) with the surroundings. The input consists of two separate files in *.Obj format: one represents the whole potential area of the PV (i.e. the entire set from which the optimal system will be chosen) and contains some characteristics of the system (i.e. dimensions of the modules, efficiency and price), the other

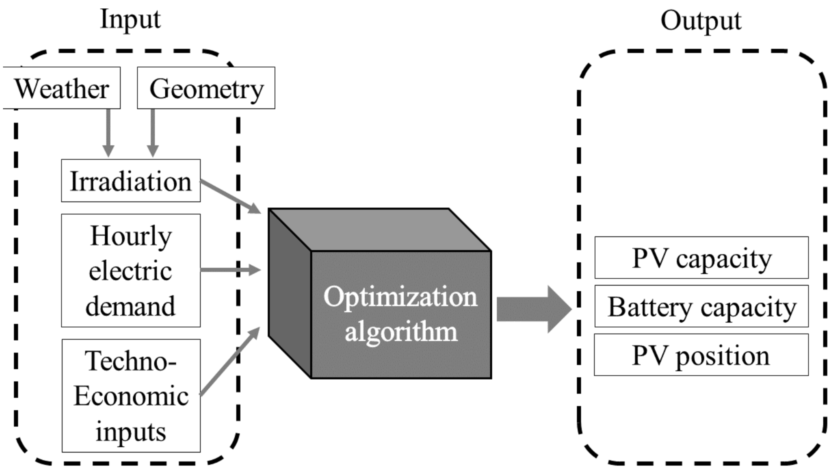


Figure 5: working scheme of the method, the diagram shows the capacities of the components as an output of the procedure, not an input as used in PV simulation software. The input are described from Pag. 25, the optimization algorithm is described from Pag. 30 and the output of the workflow is described at Pag. 35.

file represents the surroundings of the PV system that interact with the light before this reach it and contains geometrical and material information about the surroundings.

- **Hourly electric demand:** The electric demand is a single-vector file in *.Txt format containing the power demand of the building for each HOY, it is expressed in [W] and is used to estimate the contemporaneity between demand and production, thus calculate self-consumption and self-sufficiency ratios.This demand file can be inserted directly, or a residential load can be calculated from the number of inhabitants as explained in the section 4.3 at page 54.

4.1.2 techno-economic input:

- **BIM feature:** The acronym BIM stands for Building Information Model, the concept appears quite frequently in literature (e.g. [73, 74, 75, 76]), the idea is to produce and modify building models which contain information about the building. The BIM feature in this tool refers to the presence (or not) of information about the type of PV system used in each geometry. If the BIM feature is on, each geometry is associated to a specific PV technology, otherwise all the geometries are made of the same technology that is inserted by the user. The information about different PV technologies is contained in a database that associates dimensions, price, efficiency and temperature coefficient to every item. The user can select different technologies in a model by customizing the material in the *.obj file (see the Geometry section above): if the material used on a surface is present in the database, its characteristics will be assigned to it.

- **Module characteristics:** If the BIM feature is set to false it is possible to insert dimension and efficiency of the modules manually

- **System characteristics:** It is limited to a static performance ratio that takes into account reflection losses, soiling of the PV surface,ohmic resistance of the DC cables and inverter efficiency. If the temperature correction is set to false the PR also includes temperature effect on the efficiency of the system (see section 4.2 at page 43) and represents therefore the overall PR as shown in [77, 78, 79, 80, 81, 82, 83, 84, 85]. If the temperature correction is set to True some range of typical values are calculated and shown in Fig.14 at page 51.

- **Reward function:** The optimization, being single target, selects the parameters of the system (i.e. capacities and positions) in order to maximize the output of a specific reward function, the ones available for this tool are described more in detail at page 30

- **Price of the electricity for the consumer:** This input represents the price of the electricity that the building owners or tenants have to pay for one kWh, it does not include the fixed costs paid to the energy provider but it is not limited to the cost of the energy itself either. It represents the electricity costs that can be avoided by self-consuming PV electricity instead of purchasing it from the grid. Section 4.3 at page 57 shows the prices for household and commercial consumers in different EU countries.

- **Price of the electricity for the provider:** This is the price that is paid by the grid for each kWh that is sold to it (i.e. that is not immediately self-consumed). In the long term, considering an ever-growing penetration of PV into the energy mix, is reasonable to believe that this price will drop to 0 as nobody is willing to pay for energy during the central hours of a clear sky day (this can be intended as a consequence of the effect studied in [70]). A price for the provider of 0 assumes that there is no value for the electricity every time that the PV is over-producing, so in a sense reduces the value of PV.

- **Load matching feature:** If is set to True the tool will explore the use of PV system in parts of the building envelope that are less irradiated in order to increase the contemporaneity of the consumption and production.

- **Presence of net billing:** in some countries there is an incentive that allows the user to consume the electricity produced by its PV system without contemporaneity. This means that a system which over-produces at noon could use its own excess electricity after sunset to have some savings in the energy bill. This incentive is actually identical to a FIT (Feed In Tariff) except for the fact that is limited to the electricity that is consumed on-site within one year. The energy over-produced is not in fact necessarily stored anywhere, but an incentive is paid by the energy authority for every kWh sent to the grid until the cumulative over-production of energy reaches the cumulative residual demand (i.e. that not contemporaneously covered by PV)* .

- **Net billing premium:** When the presence of net billing is set to True it is possible to decide the size of the premium paid by the authority.

- **Battery capacity optimization:**When set to True not only the PV system capacity, but also the electric storage capacity is optimized.

- **Minimum battery size:** this input is expressed in [Wh] and represents the step for a battery energy capacity, if the step is small(e.g. 100 Wh) it means that is possible to install a tiny battery, or is possible for the algorithm to choose between two batteries that differ little to each other. A small amount in this quantity can generate a precise prescription for the battery capacity, but it might be unrealistic regard to the commercial models available on the market and might slow down the optimization for cases in which large battery capacities are installed

- **mandatory PV self-sufficiency:**if the reward function "minimum LCOE at prescribed self-sufficiency" is selected, it is possible to mandate a minimum level of self sufficiency.

- **Maximum price limit:** In numerous practical cases there can be the need to set a maximum budget that can be dedicated to the PV system, if the optimal capacity happens to be more expensive then that, the algorithm will choose as big as possible for the budget available.

* In Italy this form of incentive is present at the moment of the writing of this thesis: the incentive paid is almost equivalent to the difference between the wholesale price for electricity sold to the grid and the price of the electricity paid by the user

- **Time horizon in years:** It represents the planned life-span of the system, for each reward function chosen the calculation is performed over a set time horizon, generally a longer time horizon imply a larger capacity for the optimal system.

- **Cost of the system and of the battery:** The unitary turn-key cost (in [€/kWp]for PV and [€/kWh] for the electric storage) of the finished BIPV system.

Aside from this set of input there is a certain number of others that are not supposed to be known in the beginning of the lifetime of the system: these inputs have an intrinsic variability that is dependant on scarcely predictable future socio-economic developments or long term behaviour of the PV material. Because of their obscure nature these quantities are treated as stochastic variables (i.e. do not consist in a value but rather an interval of possible values). The stochastic input variables are the following:

- **Annual maintenance costs:** Expressed in [€/ kWp year] these are the annual expenses that the system owner has to undergo in order to guarantee a sufficient level of performance, they refer to cleaning and substitution of the modules and periodic inspections, they do not include the substitution of the inverter or electric storage. These costs can vary according to the weather conditions (hail can break some modules, dry weather can cause soiling related problems etc..) and the long-term behaviour of the system owner.

- **linear annual growth of the electric load:** This variables deal with the case for which in the future the electric demand of the building might not stay the same as it is at the time of the construction of the system: energy efficiency measures on one end or the increased use of technology on the other could alter the scale of the electric demand over time.

- **Linear annual efficiency losses:** The long term exposition of the PV system to sun and weather elements has the tendency to reduce its efficiency over time. This phenomena are studied but are not yet completely predictable, especially considering that the PV system technology underwent significant innovation over the last decade.

- **Annual discount rate:** The discount rate is equivalent to the interest rate applied in DCF (Discounted Cash Flows),it serves the purpose to determine the present value of future cash flows. The calculation used in this tool do not takes into account the inflation

- **Linear annual growth of prices for consumer and provider:** Unless there are long term contracts for locked prices the price of electricity that is bought from or sold to the grid might be subject to changes in the long term (i.e. get cheaper or more expensive).

4.1.3 Optimization algorithm:

In an optimization problem, a reward function is mapped throughout the space of one or more variables with a real number intuitively representing the "value" associated with each combination of variables. An optimization algorithm seeks to maximize a reward function by prowling for an effective combination of variables. The variables considered in this document are the quantity of PV capacity installed on each façade of the building and the quantity of electric storage. Taking for example the capacity of PV on a building in which there are two façades (roof and south façade): the set of variables [0,0] would represent a building without PV, [1,1] is a building where all the area available is covered by PV, [0,0.5] is a building where half of the area available on the south façade is occupied by PV while the roof is empty. The quantity of electric storage simply constitutes a parameter as it is. In the method explained in this thesis four different reward functions have been employed, they are described as follows:

Maximum Net Present Value: This fitness function regulates the parameters (i.e. the capacities and position of PV modules and the capacity of the electric storage) so to maximize the NPV at a specific time horizon. The formula for the calculation of the NPV is defined as follow:

$$NPV = \sum_{t=0}^{N} \left(\frac{c \cdot P_{\mathrm{c}} + s \cdot P_{\mathrm{s}} - \omega_{\mathrm{system}} \cdot \mu_{\mathrm{system,t}}}{(1+i)^t} \right) - \omega_{\mathrm{PV}} \cdot C_{\mathrm{PV,0}} - \omega_{\mathrm{B}} \cdot C_{\mathrm{B,0}}. \tag{2}$$

in Equation 2:

- **NPV:** Net Present Value, is the quantity that should be maximized by the optimization algorithm.
- **t:** represents the year from the installation of the system (10 would represent the NPV after 10 years from the installation), it can go from 0 to the time horizon **N** of the investment, involves all the quantities within the bracket of the sum.
- **c:** it is expressed in [kWh] and represents the cumulative electricity self-consumed (i.e. contemporaneously produced and consumed) throughout one year.

- $\mathbf{P_c}$**:** it is expressed in [€/ kWh] and represents the unitary price of the electricity for the consumer, it measures the avoided costs for the electricity enjoyed by the owner of the PV system.it can vary over the years and throughout a single HOY

- **s:** it is expressed in [kWh] and represents the cumulative electricity not self-consumed (i.e. sent to the grid or wasted) throughout one year.

- $\mathbf{P_s}$**:** it is expressed in [€/ kWh] and represents the unitary price of the electricity for the provider, it measures the revenues for the sale of electricity to the grid by the owner of the PV system. It can vary over the years

- $\omega_{\mathbf{system}}$**:** it is expressed in [kW_{peak}] referring to the installed capacity of the PV system, while in [kWh] when referring to the electric storage system

- $\mu_{\mathbf{system,t}}$**:** it is expressed in [€/$kW_{peak} \cdot$ year] and represents the unitary cost of maintenance. These costs include the annual cost of maintenance as inserted from input (see page 29) but also the substitution costs for the inverter and electric storage which occurs every 10 years. Notice that the unitary substitution cost of the inverter is considered static along the lifetime of the system while the unitary substitution cost of the electric storage follows a learning curve as described at page 54

- **i:** is an a-dimensional value that represents the discount rate, the definition can be found in the input section at page 29, but it is reported here as well for ease of consultation: *"is equivalent to the interest rate applied in DCF (Discounted Cash Flows),it serves the purpose to determine the present value of future cash flows. The calculation used in this tool do not takes into account the inflation"*.

- $\mathbf{C_{PV,0}}$**:** it is expressed in [€/kW_{peak}] and represents the unitary installation cost of the photovoltaic system at the year 0, in the equation it is visible that it grows linearly with the installed capacity $\omega_{\mathbf{PV}}$.

- $\omega_{\mathbf{B}}$:it is expressed in [kWh] and represent the installed capacity of the electric storage.

- $\mathbf{C_{PV,0}}$**:** it is expressed in [€/kWh] and represents the unitary installation cost of the electrci storage system at the year 0, in the equation it is visible that it grows linearly with the installed capacity $\omega_{\mathbf{B}}$.

It is visible from the Equation 2 at page 30 how numerous terms (such as installation and maintenance costs) are directly dependent on the system capacity, which is one of the parameters of the optimization: thanks to this, the NPV changes for each combination of capacities over the building enabling the optimization process.

Maximum Lifetime Cumulative Electricity Balance: All the other reward functions present in the tool are of a techno-economic type. They are concerned with guaranteeing a specific level of earnings or to improve the technical performance under certain economic conditions: Maximum LCEB is instead purely energy related. This function has the scope to maximize the net cumulative output of electricity self-consumed by the building-PV couple over the entire life-time of the system, the LCEB is defined as follow:

$$LCEB = \sum_{t=0}^{N} (c) - \omega_{\mathrm{PV}} \cdot E_{\mathrm{PV,0}}. \tag{3}$$

in Equation 3:

- **c:** it is expressed in [kWh] and represents the cumulative electricity self-consumed (i.e. contemporaneously produced and consumed) throughout one year.
- **ω_{PV}:** it is expressed in [kW_{peak}] referring to the installed capacity of the PV system, while in [kWh] when referring to the electric storage system
- **$E_{\mathrm{PV,0}}$:** expressed in [mWh/kWp] it represents the energy cost of producing the photovoltaic system, in this type of analysis the electric storage is not analysed and therefore cannot be optimized, the typical input values for this variable can be found at page 51.

As it is visible from the equation, in this reward function the initial energy cost of a PV system is subtracted from the lifetime electricity self consumed, this leaves only the net lifetime electricity balance of the system. The character of the function causes the sheer capacity of the system to grow until the over production of electricity does not become too pronounced (so neutralising the benefit of a larger capacity by a lower effectiveness). The energy expenditure (i.e. the embedded energy of the system) in fact grows linearly with its capacity, the self-consumed energy instead has a correlation that falls below the linear in the sense that growing capacity is characterized by a diminishing return in the increase of energy self-consumed.

Maximum Self-Sufficiency at prescribed payback time: The ultimate aim of this reward function is to maximize self-consumed electricity (SCE) during the lifetime of the system. Equation 4 expresses the lifetime cumulative electricity self-consumed weighted by electricity price for the consumer:

$$SCE = \sum_{t=0}^{N} c \cdot P_{\mathrm{c}}\,(t, HOY)\,. \tag{4}$$

The equation shows how the SCE (Self Consumed Electricity) is positively correlated with the self-consumed energy **c** [Wh] occurring during the lifetime of the system (**t** from 0 to the time horizon **N**). This equation (Equation 4) presents a problem because it is monotonic relatively to the capacity, so it cannot decrease amid an increase in capacity and it will indeed increase as long as there is a gain in self-consumption. This feature of the reward function would obviously cause the optimal set of parameters to converge on the largest possible capacity (i.e. [1,1,...,1]), hence causing a grossly over-dimensioned system and defeating the very purpose of an optimization process. To avoid the excess generated by the reward function in Equation 4 while still maximizing it and to avoid economically unprofitable solutions, the function is described as following Eq. (5), where the reward function is described according to two domains. The algorithm will thus maximize the lifetime SCE at the condition that the system cannot be unprofitable.

$$Reward\,Function = \begin{cases} SCE, & \forall\, NPV \geq 0 \\ -SCE, & \forall\, NPV < 0 \end{cases} \tag{5}$$

The reward function thus described serves the purpose of adding a condition (i.e. that the NPV, see Equation 2, is positive or zero) to the quantity that is maximized (i.e. the SCE). This interval-defined reward function presents an advantage compared to a simple condition because it makes the optimization process computationally less expensive. A condition would simply invalidate a given set of variables because their resulting reward function falls out of a set boundary, the value of this set of variables is thus lost and there is no fitness-landscape outside of the boundary of the admitted solutions. In other words the algorithm has no way of knowing whether it is close or far from the validity boundary nor which direction the boundary is located. In this case instead the NPV becomes negative when the PV+storage system is too big, and the SCE also grows amid growing system size. The negative effect of SCE in the NPV unprofitable space generates a reward for the algorithm to reduce SCE, thus to shrink the PV+storage system. In this way the algorithm is steered toward the direction of the boundary and is therefore faster.

minimum LCOE at prescribed self-sufficiency: In some cases a specific percentage of energy from renewable sources is mandatory to be achieved, being this thesis about photovoltaic technology (which also happens to be very effective in small scale application such as buildings),it has been added the feature of setting a specific PV electricity self-sufficiency that should be achieved. Once the desired self-sufficiency is achieved, the target is to achieve it with the smallest possible cost, hence to minimize the LCOE at a specific self-sufficiency. The LCOE of the electricity produced, which is the quantity to be minimized is calculated as in Equation 6:

$$LCOE_{\mathrm{self}}\, or\, (LCOE)^{*} = \sum_{t=0}^{N} \frac{\omega_{\mathrm{PV}} \cdot (\mu_{\mathrm{PV,t}} + C_{\mathrm{PV,0}}) + \omega_{\mathrm{PV}} \cdot (\mu_{\mathrm{B,t}} + C_{\mathrm{B,0}})}{c + (s)^{*}}. \tag{6}$$

In Equation 6:

- $\mu_{\mathbf{PV,t}}$**:** refers to the substitution cost of the inverters and the annual maintenance costs of the system as from the input (see input section at page 29)
- $\mu_{\mathbf{B,t}}$**:** refers to the substitution cost of the electric storage (see behaviour of the storage at page 44)
- **(s)*:** This term can be considered or not according to the type of information that should be considered for the LCOE. If the figure of interest is the production cost of the electricity this value should be included in the calculation, this because production-wise it does not matter whether the electricity is consumed on-site or sold. If the subject of the optimization is very large (e.g. a mall or an entire district), or if the optimization is supposed to be performed at very high penetration rates of PV (i.e. nobody likely needs to purchase electricity during over-production times) the sold electricity "s" should not considered because in these cases what is not contemporaneously consumed or stored is lost.

as in the previous reward function (see max self sufficiency at prescribed payback time at Pag. 33) the LCOE alone does not qualify the problem as there is a condition to be satisfied. In this case a minimum share of the electricity consumed should be provided by PV (i.e. there is a minimum self-sufficiency ratio to be respected as expressed in the input "mandatory PV self-sufficiency" at page 28). As in the previous case this condition is expressed as an interval-defined reward function (Equation 7):

$$Reward\, Function = \begin{cases} (LCOE_{\mathrm{self}} + LCOE)^{-1}, & \forall\, \gamma \geq \gamma_{\mathrm{min}} \\ -(LCOE_{\mathrm{self}} + LCOE)^{-1}, & \forall\, \gamma < \gamma_{\mathrm{min}} \end{cases} \tag{7}$$

Where:

- γ **:**is the self-sufficiency achieved by the system characterized by a specific set of variables (i.e. PV and storage capacities).
- $\gamma_{\mathbf{min}}$**:**is the self-sufficiency mandated in input phase (see at mandatory PV self-sufficiency at Pag. 28).

The optimization algorithm used is a simple direct search [86] iterated to improve its own solution: the initial condition is a system of 0 [kWp] capacity, a capacity is then found by the direct search and added on the chosen façade among the available ones (in this case roof or facade). The capacity added is the solution for this cycle of the direct search, but it will be the starting point for the next cycle. In other words, once the capacity is added, the direct search is repeated but with the new capacity as a starting point instead of the empty system. Making an analogy, the process is similar to the production of a painting: each stroke is a simple action but is a step closer to the completion of the painting. If the difference between an empty painting and a photo being imitated is a reward function, one stroke cannot find the minimum, but it can be a step closer to the minimum. The process can then be interpreted as painting a PV system on the surface of the building, where the parameters for each stroke are capacity and façade (e.g 62 kWp, roof)[87].

4.1.4 Output:

after the optimization algorithm has found the maximum value for the reward function, the optimal PV capacity and position and the optimal battery capacity are found, the following set of output is produced:

- **PV capacity and positions:** This output is produced in the form of a 3D file as shown in Fig. 6. The position of the PV modules is determined by their orientation but also by their annual cumulative irradiation, if on a large surface (i.e. whose potential is only marginally used by the PV system) there are no shading patterns along the year the PV modules will be positioned in a random pattern.

- **NPV over-time:** The output, represented by the chart in Fig. 7, shows the expected NPV (and other more or less likely scenarios) along the lifetime of the system

- **Electricity production, consumption and self-consumption:** Once the optimal system has been found, its electricity production and

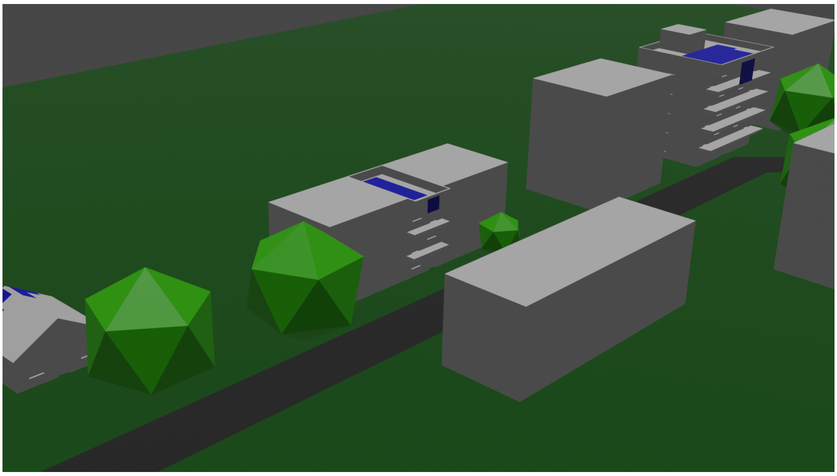


Figure 6: The main output of the optimization consists in the position of the PV solar collectors (which obviously includes an information about the capacity). The picture shows the capacity and position of the photovoltaic system in blue.

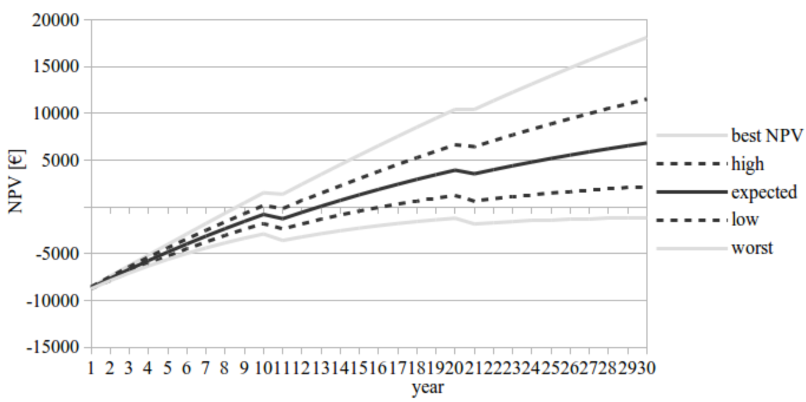


Figure 7: The expected NPV of the system is shown for every year after the installation, the risk is assessed through the stochastic variables and the best possible NPV, the worst, 75%ile and 25%ile are shown. In some years, due to change of the inverter or battery, the variation of NPV compared to the previous year is negative.

the relative self-consumed fraction are calculated for every hour of every year of the simulation and for every combination of degradation of the system and growth of the electric demand (see input section at Pag.29). The monthly cumulative values are shown for the first year after installation in Fig. 8.

- **expected payback time:** as the NPV also the payback time is affected by the stochastic inputs, the most likely value (i.e. the expected value) is reported for the optimal solution found.

- **Expected LCOE ans $LCOE_{self}$:** The cost of the electrticity produced (or that of the self-consumed fraction) is reported for the optimal configuration. The real values can vary according to the scenario (because of maintenance costs, discount rate, demand growth and degradation), therefore the value reported is an expected one.

- **Self-consumption and self-sufficiency:** The quantity of produced electricity that is self consumed (self-consumption), and the quantity of the electricity demand that can be covered are reported for the year 0 (i.e. the stochastic variables are not relevant). For the optimal configuration. Over the life of the building the self-consumption is likely to increase while the self-sufficiency is likely to decrease. This effect is due to the degradation of the PV system and , as often assumed, a gradual increase of the electric consumption

- **PV electricity production:** The value of the hourly power of the optimal system is reported.

- **specific equivalent CO_2 emissions for the electricity produced and for its self-consumed fraction:** The process to calculate the specific electricity produced is extremely straightforward: by dividing the embedded CO_2 with the total electricity produced during the planned lifetime of the system. The embedded emissions are modelled as linearly dependent on capacity and assumed 2.096 metric tonnes/kWp as shown in the relative section at Pag. 59. Also in this case the value reported is the expected one because the results are affected by degradation levels and growth of the electric demand over the life-time.

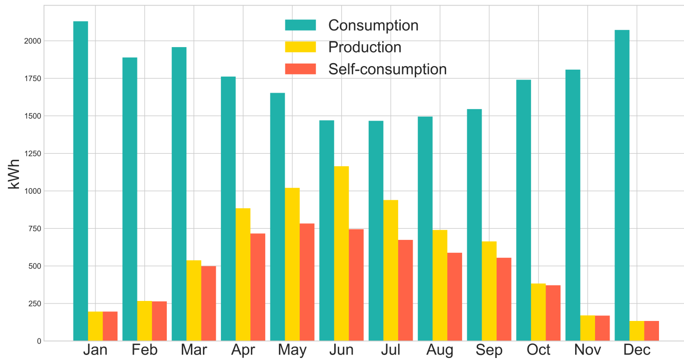


Figure 8: The chart shows the monthly cumulative values of production, consumption and self-consumed electricity for a specific building-system couple.

4.1.5 software used in the workflow

The method presented in this thesis have been translated in a software tool called POW (Photovoltaic Optimization Ware) written in Python programming language. The work-flow of the software is shown in Fig.9: the inputs, explained from Pag. 25,are inserted directly in the POW interface. The interface consists in an Excell sheet where the file paths of the input files (weather and geometry in *.EPW and *.OBJ), and the techno-economic inputs can be inserted (See Fig. 10). Once the input is collected through the interface, the software calls the open-source ray-tracing simulation RADIANCE [94] (explained more in detail from Pag. 43). Radiance calculates the irradiation over the mesh of the available area with hourly resolution, this irradiation is then fed into an optimization algorithm written in Python and explained from Pag. 30. The optimization algorithm produces the optimal area and positions of the PV system (in *.OBJ) and a serie of charts, Excell sheets and *.CSV files. These contain information about the optimal system (i.e. the optimal capacity of PV and of storage) and KPIs such as NPV, IRR, LCOE, payback time, self-consumption and self-sufficiency.

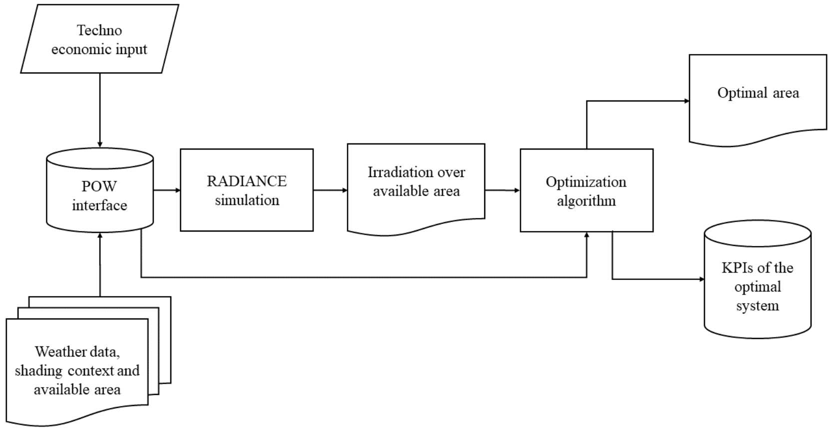
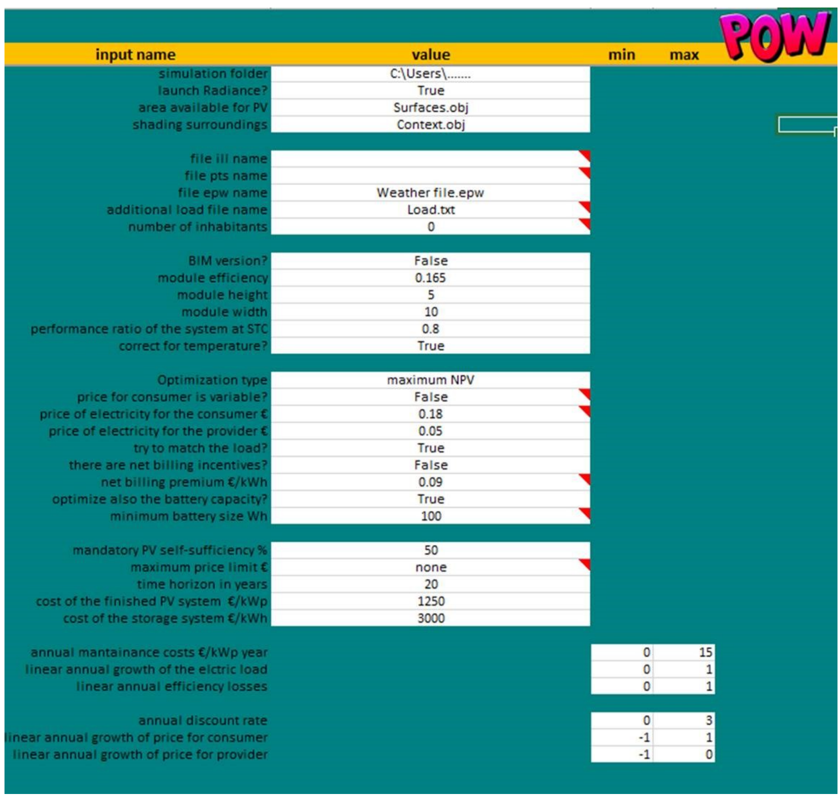


Figure 9: this flow-diagram presents the same process shown in diagram in Fig. 5 at Pag. 26 but carries a higher level of detail: in the present section the operations performed in the workflow and the formats/software used are presented.



input name	value	min	max
simulation folder	C:\Users\.......		
launch Radiance?	True		
area available for PV	Surfaces.obj		
shading surroundings	Context.obj		
file ill name			
file pts name			
file epw name	Weather file.epw		
additional load file name	Load.txt		
number of inhabitants	0		
BIM version?	False		
module efficiency	0.165		
module height	5		
module width	10		
performance ratio of the system at STC	0.8		
correct for temperature?	True		
Optimization type	maximum NPV		
price for consumer is variable?	False		
price of electricity for the consumer €	0.18		
price of electricity for the provider €	0.05		
try to match the load?	True		
there are net billing incentives?	False		
net billing premium €/kWh	0.09		
optimize also the battery capacity?	True		
minimum battery size Wh	100		
mandatory PV self-sufficiency %	50		
maximum price limit €	none		
time horizon in years	20		
cost of the finished PV system €/kWp	1250		
cost of the storage system €/kWh	3000		
annual mantainance costs €/kWp year		0	15
linear annual growth of the elctric load		0	1
linear annual efficiency losses		0	1
annual discount rate		0	3
linear annual growth of price for consumer		-1	1
linear annual growth of price for provider		-1	0

Figure 10: screenshot of the Excell sheet that serves as the interface of POW (Photovoltaic Optimization Ware).

4.2 model of the system and level of detail

The scheme representing the architectural work-flow in the aim section at Pag. 15 can be adopted for any stage of the architectural design, but the method shown in this thesis is to be applied only in the early design stage. If the architectural design work-flow is subdivided in three phases (i.e. preliminary, detailed and executive design) the tool would be useful in the phase of preliminary design and in the early stage of the detailed design. In the preliminary design the level of detail of the architectural product is very low, only an indication about the main volumes, the WWR (Window to Wall Ratio) and the function of the building are present. In preliminary design, the optimization can be used to have a general sense of the scale and positions of the BIPV element over the surface of the building, this might influence the design idea to include an honest display of PV material in it or more sophisticated ways to use it: in this phase the dimensions of the actual PV modules are not crucial, they are in fact a proxy for how fine the irradiation mesh should be. In the detailed design some level of architectural elements, such as floor heights, thickness of walls and slabs, outline of windows, balconies and detailed shape of the roof, is achieved: in this phase the tool can still be used to identify the most suitable areas of a set of façades considering a more detailed shading pattern, the realistic dimensions of the PV modules grow in importance as an input. The level of detail in modelling the PV system and the electric storage system results from a balancing act between accuracy, computing speed and flexibility of the calculation (i.e. reduction of the number of input required and versatility in the simulation of each system).

Behaviour of the PV system: The level of detail of the PV system modelling is applied so to avoid the requirement of specific products in the calculations and a detailed layout of inverters and cabling. The specific details of the brand and model of the modules, such as would be required by a one diode or more accurate models, would be appropriate for an executive design, but might be too high for the detailed design while being an overkill for the preliminary design phase. The need for compiling the model's parameters would require either to know the exact brand and technology of the modules (in order to know the ideality factor and the resistances), or to use default parameters (which could tough jeopardize the improvement in accuracy generated by the better model). The objective of the search is a preliminary estimate to find an adequate capacity and positioning of the system for the underlying building [87]. An accurate calculation, using tools such as PVlib [88], should be carried out in later stages of the design to have a more reliable figure on the electricity produced. In such a calculation the ability in forecasting meteorological data is crucial [89, 90, 91, 91] , is therefore beyond the scope of an early design tool for optimizing the economic performance over the next 25 years [87]. Another aspect that would harm the accuracy of the result regardless of the modelling of the PV system is the use of one hour time-step: in fact in the presence of variable production and consumption, there could be important mismatches that can be completely lost in averaging for an entire hour. For example, if a washing machine operates for 45 minutes at the power of 1000 W, the load file would display 750 W for one hour, if the PV system also happens to be producing 750 W the self sufficiency could be considered 100% in that hour while being only 75%. This mismatch error is the price to pay for using hourly data (which is easily available worldwide) instead of minute data (which is hard to come by and heavyer to handle for the computer). These errors are somehow acceptable in a simplified calculation as the one presented where some inputs are highly stochastic, but they question the usefulness of an extremely accurate PV simulation. Overkill matters aside, an accurate model would not be useful unless the electric layout of the PV array is known: in fact the losses provoked by the partial shading induced by trees or other buildings in the scene could dwarf the mismatches between an irradiation based model and a more complex one. There are studies in literature that dealt with the simulation [92] or even the optimization [93] of the wiring in an array of modules subject to a condition of partial shading, nevertheless there are some practical problems in the implementation of a similar procedure in the optimization process presented here. This optimization process has the positions and area of the arrays as parameters, this means that the optimization process continually modifies the geometrical layout of the system over the skin of the building (i.e. the arrangement of modules over the different façades). The need to optimize the wiring layout of the system would mean a wiring optimization procedure for each and every possible arrangement of the modules over the building envelope: in other words an optimization within the optimization that is difficult to handle in terms of computational burden. Furthermore, the way in which the parameters of the optimization are described in the present form of the method(i.e. in term of percentage of the facade occupied, Pag. 30) would not be possible if the wiring strategy is an element considered in the calculation. Sometimes, due to the stochastic nature of the Radiance ray-tracing software (see following paragraph about the calculation of the irradiation) it might happen that a configuration presents one or more modules that are detached from the main array (see the section relative to the output at Pag. 35): this type of arrangement would generate very long cables between one module and the others rendering the system severely unprofitable. Obviously, this type of solution is not strictly prescriptive in terms of positions of the real modules, but rather it should be interpreted as a prescription about the capacity to be installed on that façade. As the things stand, in the present work-flow, the ability to tell a prescriptive layout apart from a simple indication about capacity is entrusted to the person analysing the data, the inclusion of this human element in the process would require a heavy use of ANN (Artificial Neural Networks) or other advanced instruments that are beyond the scope of this thesis. To conclude: the possibility of a more accurate simulation of the PV system is an intriguing one, but it would raise the complexity of the calculation to a stunning height and make it difficult to manage. A major accuracy in this calculation is therefore postponed, if deemed necessary or useful, to a future endeavour with the help of specialist expertise. In this thesis the electric production of the PV system is considered proportional to the irradiation and corrected for the temperature of the cell according to the following relation:

$$P_{\mathrm{PV,HOY}} = PR \cdot \sum_{mod=0}^{N} G\,(mod, HOY) \cdot \eta\,(mod) \cdot A_{\mathrm{mod}}, \tag{8}$$

where:

- **$\mathbf{P}_{\mathbf{PV,HOY}}$:** is the power output of the entire PV system at a particular HOY.
- **PR:**is the performance ratio of the system as expressed in the inputs section at Pag. 27 as "system characteristics", and examined in its typical values at Pag. 50.
- **mod:** it represents one single module or one single mesh face as part of the complete system, it goes from 0 (i.e. the most irradiated spot of the most irradiated façade) to N (where N can change and depends on the variables of the optimization as explained at Pag. 30 *).
- **G:** represents the irradiation over the plane of a specific module mod in a specific HOY, it is calculated using the open source ray-tracing software RADIANCE [94] as explained in the relative paragraph Pag.43).
- **$\eta_{\mathbf{mod}}$:** represents the efficiency of the module, if the BIM feature is activated (see input section relative to the BIM feature at Pag. 26)different parts of a BIPV system can possess different efficiencies, hence the efficiency is relative to the module mod.
- **$\mathbf{A}_{\mathbf{mod}}$:**represent the area of a specific module, also in this case the area can change from one module to the other when the BIM feature is activated(see Pag. 26)

* in a large configuration of PV (one that has many modules) the number N will be big

temperature correction: The voltage of open circuit,i.e. the voltage at which the electric current ceases to flow through the solar cell,is negatively correlated to the temperature at which the cell is operating. For this reason, when the solar cell is heated by the sun, the open circuit voltage drops, and so does the power output of the cell. Considering that the nominal efficiency of a PV module is declared at STC (Standard Test Condition), the efficiency of the module has to be reduced (or increased) when the cell temperature is above (or below) NOCT (Normal Operating Cell Temperature), which is the temperature the cell reaches at 1000 [W/m^2] irradiation and 25 °C ambient temperature. The efficiency is modified through a coefficient of -0.5 [%/°C $^{-1}$], the temperature of the cell is assumed equal to that of the whole module, which in turn follows the relation:

$$T_{\text{mod,HOY}} = T_{\text{amb}} + k \cdot G_{\text{mod,HOY}} \tag{9}$$

where:

- $\mathbf{T_{mod,HOY}}$**:**Represents the temperature of the module "mod" (i.e. one of the modules forming the system under simulation) in the hour "HOY"
- $\mathbf{T_{amb}}$**:**is the ambient temperature
- **k:**is called "Ross" coefficient, it is measured in [m^2· °C/W], and is assumed 0.03 in accordance with the values found in [95]
- $\mathbf{G_{mod,HOY}}$**:**is the solar irradiation on the module "mod" at the time "HOY"

Calculation of irradiation in the plane of the PV modules: To calculate the irradiation on the plane of the modules the technique of Ray tracing was used,this procedure has the advantage of working in the same manner both for simple and complex geometries. The ray-tracing technique is in fact a stochastic approach and the computational effort, which depends on simulation parameters such as the number of rays traced from each measurement position, is less dependent by the complexity of the geometry compared to a deterministic geometrical approach. Thus, the Ray-tracing approach particularly fits for BIPV applications where there are effects of partial shading and reflections from nearby objects [87]. The ray tracing technique is achieved thanks to the use of the free software RADIANCE [94] In the section about the inputs, the geometry of the context and the geometry of the potential area to be dedicated to PV are mentioned (see Pag. 25). These are the main input required for the RADIANCE simulation (as visible in Fig. 5 at Pag.26). The potential area to be dedicated to PV is then divided in rectangular arrays of smaller mesh elements (which can represent simple mesh quads or PV modules according to the level of detail of the geometry) that are then used to generate a PoinTS (PTS) file. The PTS file contains a list of points (x,y,z) associated each with a vector (vx,vy,vz): it can be interpreted as a sort of grid made of sensors which can measure the irradiation in a specific location and direction, each point of the PTS is placed at the centroid of a PV module (or mesh quad). In a ray-tracing simulation a number of virtual rays are projected in random directions from a measuring spot (in our case each point reported in the PTS can project rays in the half-space defined by its plane), these rays can interact with the scene (i.e. be reflected or refracted) until they eventually either reach a source of light or reach the limit number of bounces* . The RADIANCE software is designed to perform both outdoor and indoor renderings or irradiation calculations, hence it features a large variety of light sources, nevertheless here the only light source consist always of the half sphere of the sky which is described according to the function [96]. The sky vault is divided into a checkerboard of smaller rectangular elements which constitute light sources whose radiance is established by [96] according to the direct and global irradiation values from the weather file (see the input section at Pag. 25).The irradiation on every module (or at the center of every mesh quad) is then used for calculating the entire system power as described by Equation 8, this is of course repeated for many different layouts of the PV system during the optimization process. The RADIANCE simulation requires a set of accuracy-related parameters, in this thesis the parameters have been set to an average level of accuracy according to established practices within the RADIANCE community of users, the parameters that are not set to default are hereby reported:

* for reasons of computational speed the limit of bounces of each ray should be set to a finite number

- **-lw:** the limit weight (i.e. minimum contribution to the total irradiation over one measuring point) under which a ray is not traced. it is set to **0.0001**.
- **-ab:**the maximum number of ambient bounces without encountering light sources before a particular ray is ignored by the simulation. it is set to **5**.
- **-ad:** The value is called ambient division. The error in the calculation of indirect illuminance will be inversely proportional to the square root of this number. It is set to **10000**

behaviour of the electrc storage: Aside from the photovoltaic system also the battery can be optimized: the role of the electric storage is to de-couple partially the time of electricity production. A model for the electric storage is incorporated in the tool given the impact on the ratio between self-consumed and sold electricity and their relevance on the revenues and avoided costs. The control strategy of the storage is explained in Fig. 11, the efficiency of the storage is considered static as there are no time dependent losses or temperature effects. Better models for the electric storage, both in terms of accuracy and smart control strategies, need to be incorporated in the future. Nevertheless, given the early design use of the tool and the simplified nature of the PV simulation (for the reasons shown in the section about the PV system behaviouir at page 40), the battery model presently has a level of accuracy adequate to the scope of the calculation and to the other functions in the software. Fig. 11 shows the structure of the events taking place in the battery as a decision tree. All the elements in the decision tree will be described in the following list proceeding from the branches on the left first and moving on the right when all the secondary branches of the left branch are completed in their description.

- **Balance $\geq$ 0?**The first and foremost choice, represented at the top of the chart, regards the energy balance of the PV+ building system (i.e. whether the system is producing or consuming electricity overall). If the balance is positive (left branch)the production from PV is higher than the electric demand of the building

- **SOC $\geq$CL?** The SOC (State Of Charge) is an adimensional number that can vary from a minimum of 0 (empty battery) to a maximum of 1 (full battery) and is equal to the amount of energy present in the battery [kWh] divided by the battery capacity. if the SOC is higher than the CL (Charge Limit) the battery is unable to store electricity anymore. The CL could be equal to 1 but often it is set between 0.9 and 0.99 as a security buffer to avoid over-charging the battery (which could develop a faster degradation of performances during the lifetime).

- **Balance to grid**when the SOC exceeds CL any excess production (which corresponds to the point-in-time energy balance) will either be lost or sold to the grid.

- **balance > CP?** In case the SOC is smaller than the CL some electricity might still be stored in the battery, but if the excess of power is higher than the CP (Charging Power) part of the electricity can be lost. The CP is measured in [W] and represents the maximum speed at which the electericity can be transferred to the battery.

- **(Balance - CP) to grid** if the excess power from the PV system is higher than the CP the battery is charged at the CP rate **balance = CP** and part of the power is curtailed or sold to the grid.

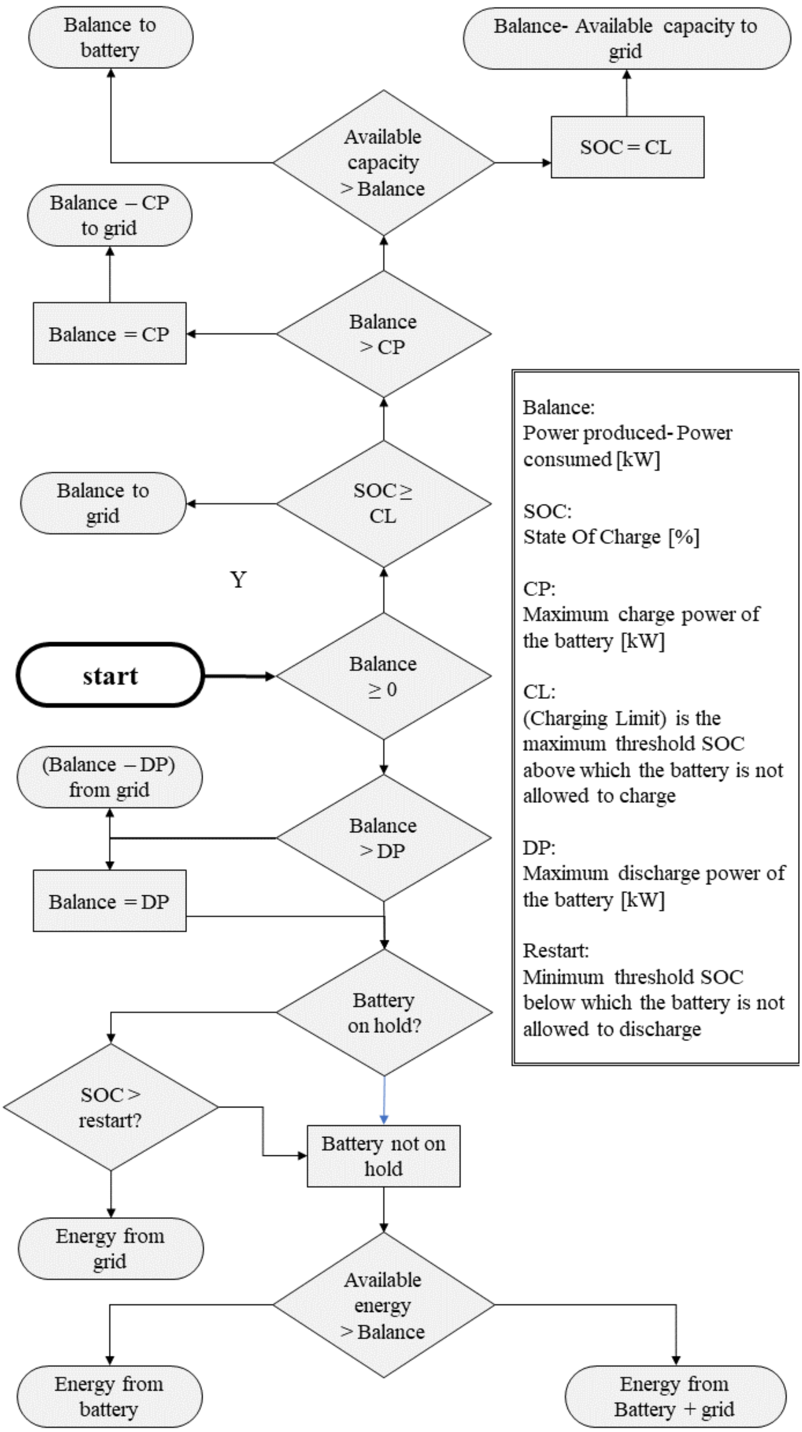


Figure 11: The electric storage works as a decision tree that takes a specific action according to the condition in which it operates.

- **Available capacity > Balance?** in a previous decision it was shown that the SOC was lower than CL, but the electricity balance might overcharge the battery if the empty space [kWh] is lower than the excess electricity produced in that hour.

- **Balance to battery** if the available capacity exceeds the energy balance, the latter is transferred whole to the battery.

- **SOC = CL** if the available capacity is lower than the energy balance the battery is charged till the charge limit is reached and the rest is curtailed or sold to the grid (**Bal-Available capacity to the grid**).

- **Balance > DP** If the energy balance is negative means that the system is consuming electricity (either from the grid or from the battery). If the power needed by the PV+building system is larger than the DP (Discharge Power), part of it must be provided by the grid (**(Balance - DP) From grid**).

- **Balance = DP** If the power needed by the system is larger than the DP, the fraction of it that interests the battery is limited to DP

- **Battery on hold?** To increase the lifetime of the battery is possible to avoid that it spends too much of its lifetime at very low SOCs: for this reason the battery can be put "on hold" (i.e. locked and unable to discharge) until it reaches a threshold SOC called "Restart" in the decision tree(**SOC < restart?**)

- **Balance from grid** if the battery is on hold and it has not yet reached the threshold SOC the electricity required by the system is purchased from the grid.

- **Battery not on hold** If the SOC has surpassed the threshold value the battery is unlocked and can provide electricity to the system.

- **Available energy > Balance** If there is enough energy in the battery to provide what is required without reaching the maximum allowed DOD (Depth Of Discharge) all thi electricity is provided by the battery(**Energy from battery**), otherwise it is complemented by some power received from the grid (**Energy from battery + grid**).

The Battery capacity decreases linearly with an aging rate of 0.011 [%/cycle](i.e. loses 30% of the initial capacity within the first 2700 cycles). These values are extrapolated to any capacity from the datasheet of a 13.5 [kWh] Tesla Powerwall home system. The battery is substituted for a new one every 10 years regardless of its residual capacity (i.e.

could either be completely degraded or relatively new). This assumption is made necessary by the changing capacity of the storage during the optimization. In fact small or large batteries would create unrealistic substitution rates if changed at a specific level of degradation (i.e. too frequently or never in the lifetime). The fact that an under-dimensioned storage ages too quickly is considered anyway because a small battery will spend most of its 10 years with an extremely small residual capacity.

4.3 typical input values

The outcome of the doctoral thesis is not limited to the results themselves, but is in fact the method and the tool that can be used on a large number of examples. In some case studies where the tool was used the input values were taken from specific requests by the beneficiary of the calculation (e.g. owner of the building or partner in a research project). Nevertheless, to give the reader an idea of what are probable values and to answer some questions regarding a present day realistic techno-economic performance, a brief review about relevant reports and publications about the figures required as input is offered in this section.

Cost of residential photovoltaic system: There is a tolerably vast literature about the price of photovoltaic systems, nevertheless, because of rapidly falling production costs and huge differences in market practices, the price estimation varies wildly across different countries and year of installation. Some direct and indirect figures are confronted to provide a range of possibilities for the price of the whole system and its components. The report *Tracking the sun IX* [97], relative to the year 2015, gives an overview of the prices of installed PV systems relatively to their size and type of installation. Applying an €/$ change of 0.9 (relative to December the 21st of 2015) the following chart (Fig. 12) can be derived. The price of the american system for residential buildings is the average value of more than 100 K installations. The report shows a strong difference between the price in the USA and that of other countries (especially Germany and Australia). The prices for a residential PV system in Germany are around 40% of those in the US, a pronounced difference between these countries (or broadly speaking between the US and the EU) is found in other documents as well.[97] shows the relation between capacity and price, in fact for residential systems the average price of a system in the 8-10 kWp costs 84 €cents for every €of a system in the 2-4 kWp range. If a percentage price drop for every kWp is assumed, it would be in the range of 2-5%/kWp. This relation do not hold true for larger systems, in fact in commercial plants of capacity > 1000 kWp the cost reaches about 57 €cent for each €of a 10 kWp plant,

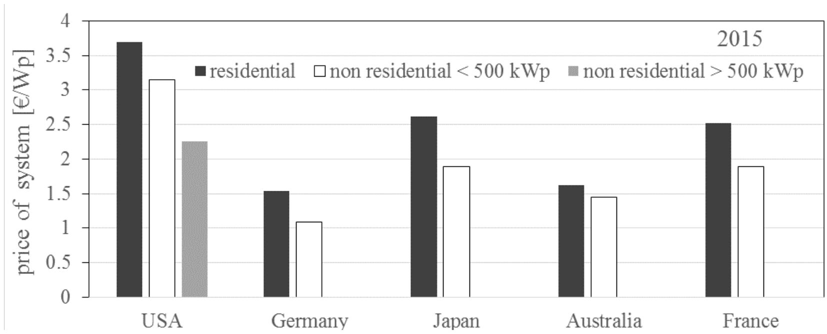


Figure 12: average pre-tax system prices in different countries for the year 2015 according to [97].

this means that the reduction in price is for sure lower than 0.06%/kWp. The report [98] relative to residential rooftop prices (3-10 kWp) for the year 2018 shows slightly lower prices both for its current year and for the year 2015, in fact the average price for a residential system in 2015 is set at 3.23 $/W against the 3.69 of the previous report. In [97] german and french prices are shown to be respectively 0.41 and 0.68 of the american price, from this in general an european price of about 0.55 the american price can be assumed. Applying the price for 2018 from [98] and the national difference from [97] an european price for 2018 of ca. **1.3 €/Wp** can be assumed. On the other hand, if a reduction of price of about 16% is assumed between the years 2015 and 2018 the median european price from [97] can be assumed as equal to **1.69 €/Wp**.[98] provides information about the importance of different element in the final price with modules and inverters being on average 23.3% and 4.3% of the turnkey price of the system. [99] recorded the installation costs of residential PV systems in Portugal for the year 2017 in order to assess their performance with varying business models. In a regime of self-consumption (i.e. where no fee has to be paid for the installation of the system) and for a range of capacities from 0.5 to 4 kWp the installation costs are about 1.63 €/Wp with a small variability across the range (1.59 to 1.66 €/Wp). Also in this case the price is not assumed for the year 2018 and therefore a price reduction of 4.9% according to [98] should be assumed for a final price of **1.54 €/Wp**. [100] provides a list of prices for utility scale plants in differet countries for the year 2018, Italy Germany and France are represented as european countries. The averace cost for PV system for these three countries would be around 89 €cents per Wp, nevertheless, considering a 57 €cent for each €as in [97] for utility-to-rooftop scale, a price of ca. **1.57 €/Wp** can be assumed. The report [101] relative to the year 2018 provides a direct price for rooftop PV system in Germany equal to **1.4 €/ Wp**, while in Italy [102] reports **1.8 €/Wp** for systems smaller than 20 kWp. This difference seems to

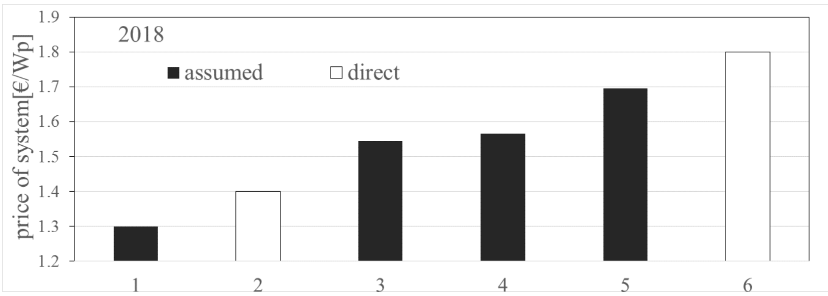


Figure 13: synthetic representation of the unitary pre-tax system prices for a PV system in the EU. The prices are divided into direct and assumed, where the assumed are derived from more reports in the absence of a direct value.

suggest that in Germany smaller systems could be cheaper than in Italy, however for the scope of this paragraph the geographical level of detail will be limited to the wider EU area and both are therefore considered as european prices.

Performance ratio of a BIPV system: The simulation as described in the section 4.1 at page 43 considers a performance ratio which is static except for the temperature effect as it is described. To make sure that the PR used in the following calculations represents plausible values, a series of empirical measurements from literature have been collected. These value represents the whole PR compared to the nominal capacity of the system, because of this the effect of temperature is included in the ratio. In [77] the typical performance ratio of 13 BIPV and BAPV systems in Norway has been measured, the findings show that *"A well-functioning system without significant shading may achieve PR above 0.85, in agreement with similar findings for Europe"* some lower PR are shown in the study for systems that are affected by partial shading. In [78], a study analyzing a roof-top system in Kuwait (North-West part of the Arabian Peninsula), the authors affirm that *"The findings of the study, based on solar irradiation collected, the performance of the module technology and the effectiveness of the automated cleaning systems, show that the performance ratio was maintained between 0.74 and 0.85"*. Another system, examined in [79], consists of a facade integrated multi technologies system located in Incheon (on the waterfront of Seoul). Among the technologies measured, the PR varies significantly with crystalline technologies ranging from 0.7 to 0.85 and thin film technologies ranging from 0.4 to 0.7. [80] applies a monitoring system to a residential rooftop building in Shanghai, showing a PR between 0.78 in March and almost 0.85 in November. In [81] a grid-connected system is monitored in Jiangsu province (North-East PRC), the findings show the PR ranges from 0.75 to 0.89. The study [82] pro-

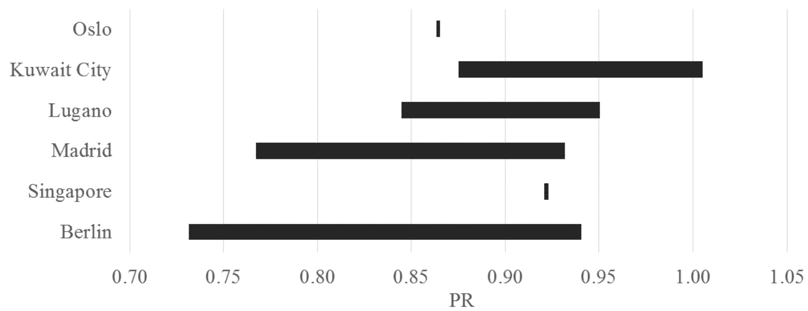


Figure 14: Pre temperature correction PR values (i.e. do not include the temperature effect).The overall PR values obtained using these ranges are taken from the literature as follows: Oslo from [77], Kuwait City from [78],Lugano from [82],Madrid from [83], Singapore from [84], Berlin from [85].

vides PR values ranging from 0.8 to 0.9 for a serie of BIPV installation in an experimental test-facility located in Lugano. [83] shows the results related to the first year monitoring of a building located in Madrid,the unshaded parts of the system appear to have a PR ranging from 0.7 to 0.85 with most of the values close to the 0.75-0.8 rage. There is one part of the system which shows much lower values as it is affected by partial shading. The study[84] examines the performance of a very large BIPV system installed into a NZEB (office)located in the city of Singapore, the measurments show that the overall PR amounts to about 0.81. Another study [85], albeit slightly dated, is relevant as it shows the PR values for about 100 installations in Germany: this study as well registers a variation of the PR value in the range of 0.7-0.9 with a median PR of about 0.84 and with newer systems performing consistently better than older ones. To take into account the temperature effects, an horizontal PV system was simulated with the tool described in this thesis both considering the temperature effect and not, the system was simulated for some of the locations analysed in the paragraph. The PR before temperature correction that should be inserted to obtain the values retrieved from literature is reported in Fig.14.

Energy cost of a photovoltaic system: The reward function explained in Equation 3 at page 32 deals with the net electricity balance resulting from the cumulative self-consumed electricity of the system minus the energy spent for its manufacture. The electricity produced and self-consumed is calculated internally by the tool according to the inputs of the simulation, the embedded energy for the PV system is in turn linearly dependent on the capacity and proportional to a unitary energy manufacturing cost expressed in [MWh/kWp]. This unitary energetic cost is calculated from values found in literature, it was extracted from more pervasive KPI using the following equation (Equation 10)because this dimension is not usually reported directly:

$$E_{\mathrm{PV},0} = \frac{\left(H_{\mathrm{year}} \cdot PR \cdot \eta \cdot EPBT\right)}{\eta}. \tag{10}$$

In Equation 10:

- **$E_{PV,0}$:**expressed in [MWh/kWp] is the unitary embedded energy of the turn-key photovoltaic system (i.e. the energy it takes to produce one kWp of the system).
- **H_{year}:** expressed in [kWh/m^2 year] it represents the annual cumulative irradiation under which the module in the study analysed was exposed.
- **PR**: Performance Ratio at which the system in the studies was operating.
- η: a-dimensional value, it represents the efficiency of the modules: as it is visible from the equation it does not have any influence on the embedded energy, nevertheless it was included to make more intuitive the operation performed.
- **EPBT:** measured in [years] it represents the energy payback time as measured in the studies under exam

All the values reported in the following table (Table 2) were found in [68], for the sake of making a conservative estimation only the values relative to mono-crystalline silicon PV modules were included. The average value of $E_{PV,0}$ for all the studies reported would be ca. 5.8 [MWh/kWp], if the studies before the year 2000 are removed from the pool the value shrinks to ca. 4.3 [mWh/kWp]. This reduction in $E_{PV,0}$ is visible in the data reported here, it is also consistent with well known technological trends in the PV industry such as average higher efficiency and reduced thickness of PV cell over time.

Table 2: Values of year of installation, place, annual cumulative irradiation, PR, EPBT from [68]. The value of PR was assumed as 0.8 in the studies that do not reported it, the assumed values are marked by "*".

ref.	year	Place	H_{year} $\left[\frac{kWh}{m^2}\right]$	PR	EPBT [years]	$E_{PV,0}$ $\left[\frac{MWh}{kWp}\right]$
[103]	1996	UK	573-1253	0.8	7.4-12.1	3.4-7.1
[104]	1997	Japan	1427	0.81	15.5	17.9
[105]	1998	Japan	1427	0.81	8.9	10.3
[106]	1998	EU	1700	0.85	9	<11.6
[107]	2000	EU	1700	0.75	2.5-3	3.2-3.8
[108]	2001	USA	1700	0.8	4.1	5.6
[109]	2002	India	1800	0.8*	3.2	4.6
[110]	2005	EU	1700	0.75	2.6	3.3
[111]	2005	Switzerland	1117	0.8*	3-6	2.7-4
[112]	2006	Singapore	1635	0.8	5.9	7.7
[113]	2006	UK	800	0.8	8	5.1
[114]	2006	EU	1700	0.75	2.1	2.7
[115]	2007	Switzerland	1117	0.75	3.3	1.8
[116]	2008	EU	1700	0.8	2.7	3.7
[117]	2009	EU	1700	0.75	1.8	2.2
[118]	2010	PRC	1702	0.78	2.5	3.3
[119]	2010	PRC	1600	0.8*	7.3	9.3
[120]	2012	USA	1800	0.8	1.4	2
[121]	2014	S.Korea	1301	0.8	4.7	4.8

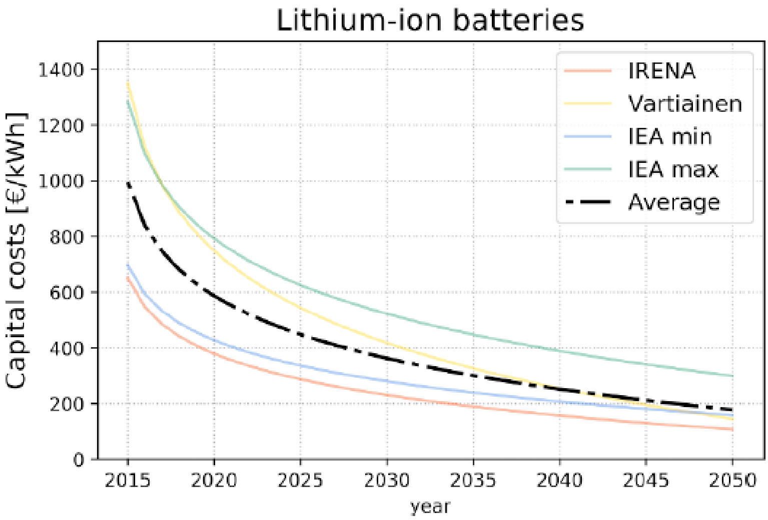


Figure 15: forecast of the learning curve for electric storage technology taken from [122].

Learning curve for the cost of storage: One crucial aspect of the electric storage is its short lifespan compared to that of the rest of the photovoltaic system (with the exclusion of the inverter). For this reason the electric storage is changed every 10 years alongside the inverters with a cost directly proportional to its capacity(see maintenance costs in the input section at Pag.29). The electric storage (particularly today's most popular electro-chemical kinds such as lithium-ion and redox flow batteries) is presently undergoing a fast evolution in terms of production technologies and costs, and therefore it is reasonable to expect that when the battery is changed after 10 years its price will be greatly reduced compared to the first batch of batteries bought today. The phenomenon of dropping prices, common among emerging technologies, is caused by the learning curve in production of components and their assembly and constitutes subject of extensive study and forecast. For the simulations performed in this thesis the values were assumed as in Fig.15 from [122] which in turn derived data from [123, 124, 125]. In case of present price of storage inserted lower than the beginning of the curve, only the sections of the curve right of the present price are considered (i.e. a price increase to return to the median of the curve is not possible). The price of electric storage is assumed constant after 2050

Residential electric demand generation: The method presented in this thesis is in general meant to be used with measured or simulated electrical demand data. Nevertheless in [126] it is shown, even when

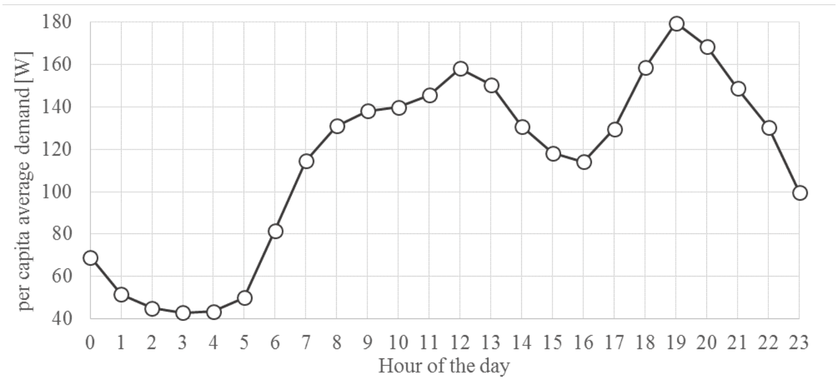


Figure 16: average per capita electricity demand during the day.

applying a static demand curve, to generate large NPV gains in a regime of self-consumption when compared to other sizing methods. In fact, if the PV system is dimensioned using the Italian law (D.Lgs. 28/2011) or in order to cover the annual cumulative consumption with its production, the system is either too big or small and generates a much lower (if not negative) NPV. If the system is dimensioned with the method described in this thesis, even in the case that the actual consumption demand is unknown and a static* demand curve is applied, the resultyng system vastly outperforms the other methods in terms of NPV. A static demand curve was found in [126] to under-estimate the optimal capacity of the PV system when compared to the real demand curve, this is likely to happen because the night time electric consumption is in general lower than the daytime one both in Italy and in the rest of Europe. Despite the dip in electric consumption in the central hours of the day (due to the absence of the working population from home), the daytime consumption still exceeds the very low baseline that characterizes the sleeping hours. For this reason a constant demand curve worsen the contemporaneity of PV production and electric consumption compared to a realistic demand curve, thus leading to larger over-production, and guiding the algorithm towards smaller systems. To avoid this short-coming (i.e. to improve the accuracy of the result), in case a simulated or measured demand curve is not available and the residential appliances and lights are the main load, a measured aggregated demand curve is used instead of a constant one (see Fig.16 and Fig.17). These curves represent a fraction (to obtain the per capita value) of the measured electric consumption of a residential district in northern Italy. This demand, albeit closer to a realistic one than a static one, holds the risk of over-dimensioning the system. This is due to the fact that an aggregated demand which represents the consumption of a number of households(40 in this case), is in general smoother and less "bumpy" than a single household curve. A

* or constant, i.e. a curve where the power do not changes during the day or the seasons

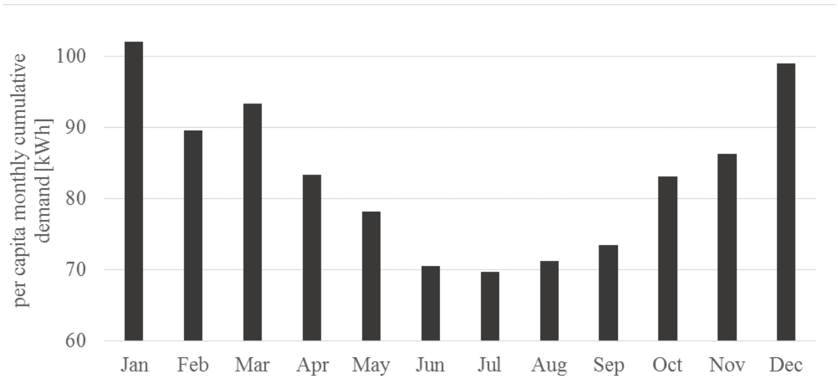


Figure 17: per capita cumulative electricity consumption along the year.

smooth curve, which smoothness is caused by the non-contemporaneity of the demand associated to a particular load (e.g. using an electric kettle in the morning) is in general easier to match for the PV production. A "bumpy" curve is characterized by a low baseline ridden with tall spikes, so that, if enough power to cover the spikes is provided by PV, a large over-production occurs in between the spikes (when the only load is the low baseline). One way to mitigate this problem is the addition of a white noise to the curve of each single household and the construction of aggregation of load through the sum of an appropriate number of "noisy" single household curves. Such a noise is applied to the standard electric demand curve from Fig. 16 and Fig. 17 to contrast the installation of PV for disaggregated load. This effect had played a role in the results of the profitability section starting at Pag. 61. To asses the amplitude of the spikes in a residential hourly demand, a pool of residential households have been simulated using LPG software [127], each household was re-simulated multiple times in order to generate its average (i.e. smooth) demand curve and measure the deviation of the n^{th} households compared to the average. The result of this operation for three different types of households is shown in Fig.18. The chart in Fig. 18 does not show to be symmetrical to the average (represented by the 0 line),but it is taller in the positive side (i.e. where the average curve is higher than the n^{th}). This means that the n^{th} demand curve is frequently below the average and rarely above it. Despite this, those times that the n^{th} curve does exceed the average it can exceed it by a large factor (i.e. the tail in the negative side is much longer). Fig. 18 shows in fact a sizable number of instances in which the n^{th} curve reaches a size of 1.5 times the average demand (in proximity of the -1.5 mark). This phenomenon is due to the fact that high outliers are needed to elevate the average consistently above the n^{th}. Fig.18 in practice shows that the n^{th} curve, for every type of household simulated, is formed by a low

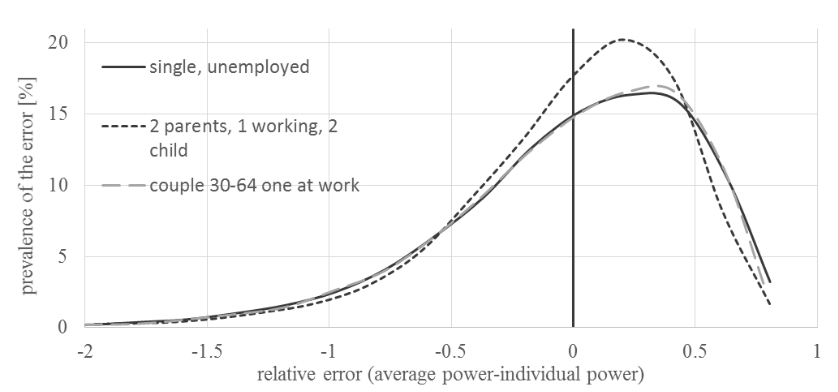


Figure 18: the chart represents the relative error of the nth household when compared to its own average (as it was simulated multiple times using LPG[127] to generate a smooth version of itself.)

baseline (i.e. high frequency of instance below average) ridden by tall spikes (i.e. high error in the instances above average). The behaviour of the nth curve toward its average is thus as expected, it was then found that a distribution of the error derived from a gamma distribution [128] could approximate this behaviour. The gamma distribution function is described by two parameters which are shape (k) and scale (Θ): where k is relative to the skewness of the curve respect to 0 and Θ is relative to the average amplitude of the error. The two parameters were swept over two respectively significant domains (see Fig. 19) in order to generate a tolerably good approximation of the behaviour of the nth curve compared to the average (see Fig. 20).

Typical electricity prices in the EU: The electricity prices used in the simulations in the relative section (starting from Pag.61) are referenced to the data provided by the European Statistical Office (Eurostat) available at [129]. Fig.21 shows the electricity price, including VAT (Value Added Tax) and other taxes for the second half of the year 2018. The price for the United Kingdom (which was used in the sections about the current profitability at Pag.61, energy profitability at Pag.73 and CO_2 emissions at Pag.77) was retrieved by the same source and (in €) it amounts to 0.1401 €without taxes and 0.2024 €including taxes, the change of currency applyed is not reported by the source.

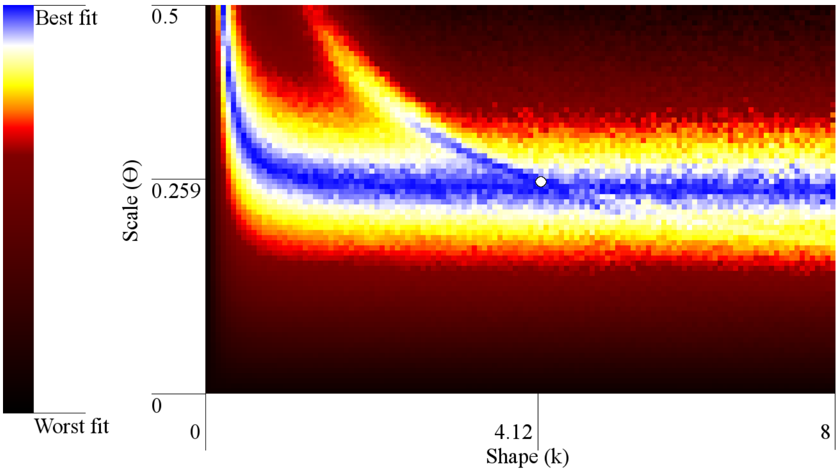


Figure 19: the heat-map represents the ability to fit the error distribution of the household of a single unemployed person by the gamma derived distribution function. The parameters that demonstrated the best fit are Θ = 0.259 and k= 4.12

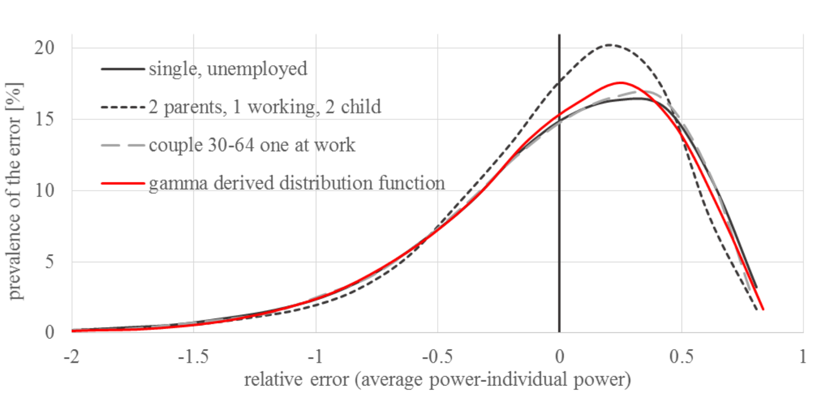


Figure 20: the chart represents the error distribution of the simulated households against a function derived from a conveniently chosen gamma distribution function.

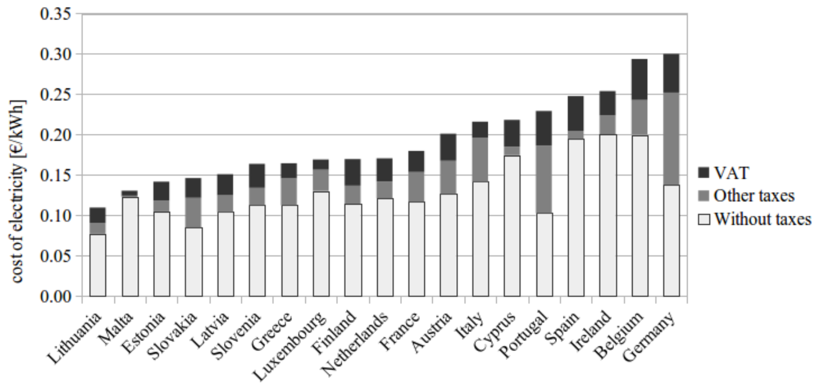


Figure 21: average household electricity prices [€/kWh] for countries in the euro area, the chart reports the price for electricity plus the additional costs for VAT and other taxes.

Calculation of the CO_2 equivalent emissions: To estimate the CO_2 equivalent emissions of a BIPV system is essential to understand the emission of GHG gasses derived from the production and transport of PV modules, inverters, cables and structures. The calculation should include the emissions associated with mining operations of quartzite (i.e. the natural occurring material from which silicon is extracted), production of metallurgical grade silicon its refinement etc. There is a vast literature concerning this theme of PV system, in this thesis the specific emissions of PV are based on the meta-analysis performed by [130]. In the study the authors analysed 397 life cycle assessments (LCAs) relevant to PVs which yielded 13 studies on crystalline silicon (mono and poly-crystalline) that met minimum standards of quality, transparency, and relevance. The specific equivalent emissions for the studies (i.e. [114, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142]) were multiplied by the total electricity production of each system declared in [130], thus the unitary embedded CO_2 equivalent [tonne eq/kWp] was obtained. The 13 studies produced a larger number of results as some hosted more than a single example, in Fig.22 and in the relative values the ground-mounted system have been discarded. The paper goes on harmonizing the examples reported in term of specific emissions for the electricity produced [g CO_2 eq./kWh], but of course the interesting value here is given by the initial emissions as this will be divided by the number of kWh produced during the whole life of the system (considering geographic location, presence of shadings, geometry of the building and in general all the aspects described from Pag.40 to Pag.44). Some of the studies reported include the lifetime emissions due to maintenance of the system, these are tough usually negligible according to [131]. Fig. 22 shows a large variation among the values obtained, especially among

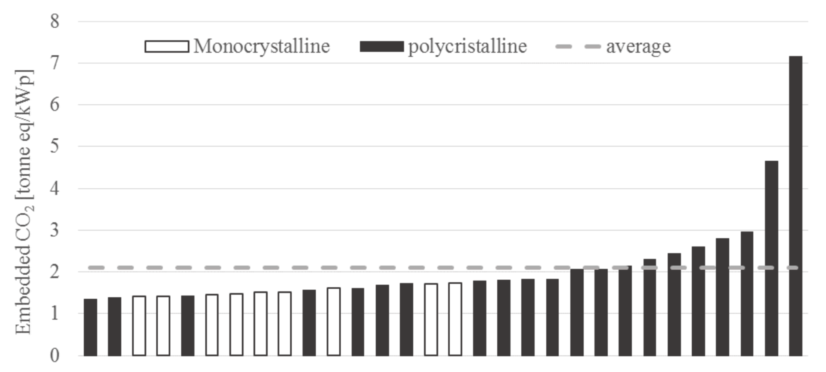


Figure 22: The chart shows the embedded CO_2 emissions reported from the 13 studies from [130]. The average emissions for the non ground mounted systems, regardless of the technology is 2.096 metric tonnes per kWp of PV, in this thesis a conservative value of 2.138 metric tonnes per kWp was assumed (i.e. a value higher than 75% of the examples reported).

the poly-crystalline technologies, the average equivalent emissions are equal to 2.096 metric tonnes/kWp of PV system produced. The average value is in general higher than the majority of examples reported due to the high outliers among Poly-crystalline technologies,nevertheless in this thesis a value of 2.138 [t eq./kWp] *was assumed as a conservative value.

* this value is higher than the 75% of the examples reported in [130]

5 Applied examples

5.1 Current BIPV profitability:

In the section where the research question is stated at Pag. 15, the first one is:**"is BIPV profitable with current day technologies, prices and economic conditions?"** this question is obviously ill posed as the answer depends on the economic framework and on the quantity of BIPV, nevertheless it gives out the basic concept of the study that has being done. For what concerns the economic framework, this paragraph and the most of the following ones are concerned with the economic performance of urban PV without incentives and in an high penetration scenario: for this reason no FIT or net metering are accounted and the value of the excess PV electricity is generally considered null. The basic source of revenues or savings (which are not treated differently from one another in calculating the NPV of the system as shown in the formula at Pag.30) is the avoided costs for the purchased electricity (as assumed in the section about the typical input values at page 57). The other variable affecting the urban PV profitability overall is the size of the system compared to the electric demand in an economic framework of self-consumption (as appears from the applied examples section starting at Pag.61). This considerations leads to the second research question: **"What percentage of a residential electrical demand can be covered by PV in an economically sustainable way?"**. To answer this question a set of prominent residential building types has been analysed under largely diverse climatic conditions. The residential building types chosen (shown in Fig. 23) are a Single Family House inhabited by 3 people, a town-house inhabited by 6 people and an apartment-block inhabited by 20 people. Fig. 23 shows all the areas available for a PV system, obviously this does not mean that the PV system would occupy all, the area represent the potential maximum dimension of the system out of which the optimization algorithm can select a sub-portion. In general the three building types have been chosen to show three different levels of aggregation of the load (3,6,20 inhabitants): a higher level of aggregation smooths the curve rendering it more profitable for PV (spikes and drops in the demand often results in excessive or insufficient production as will be shown from Pag. 101). The aggregation is not the only aspect, there are also morphological differences in the shape of the buildings that affect the irradiation falling on the areas available for PV (i.e. higher shading from parapets for the town house compared to the condominium, sloped roof in the Single Family House etc.). The interplay of aggregation, morphology and geographical location creates opportunities for discussion, nevertheless the example offered is in no way sufficient to draw general conclusions on the topic. For example,

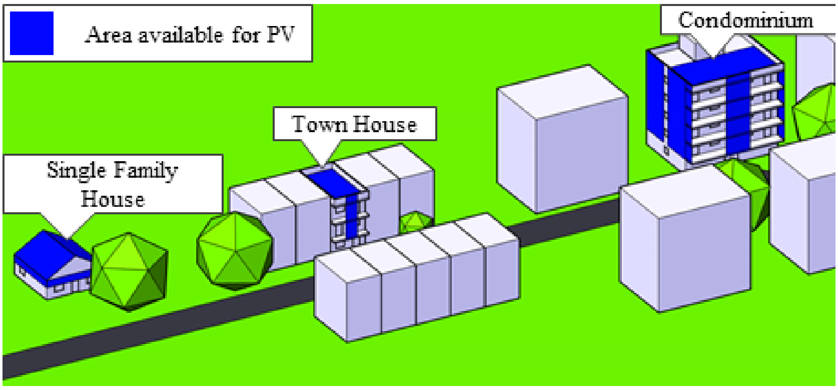


Figure 23: the picture shows the three type of residential buildings under study (i.e. Single Family House, town house and condominium) and the whole area that is possible to dedicate to PV (marked in blue).

it should be noted that the condominium shown in this chapter (ca. 20 inhabitants) can by no means be considered large, and the aggregation of demand in far larger buildings and even districts is possible. The optimization of the PV system over these three building types was performed in three European cities: the Greek city of Athens, the French city of Lyon and the English city of Leeds. These three cities were chosen for their high variation in latitude and weather with Athens being one of the driest and southernmost places in Europe, Leeds one of the most rainy and located in the North and Lyon somewhat in between in both regards. The three cities have been chosen as they approximate quite well two extremes and an average of the two in terms of radiation and days of precipitation, these are not guaranteed to be the most and least profitable cities in Europe, but they are particularly spread nonetheless. In this thesis the profitability of a BIPV system is assessed under a limited range of possibilities, the question should ultimately be tackled in a case by case basis, here are reported the variations on the principal KPIs observable under widely diverging European climates (see Fig 24). The scope of the study is not to analyse the effect of local weather on the optimal capacity of PV but rather to assess its profitability, therefore different household electricity prices were assumed from [129]. Being these "home systems", it can be argued that the discount rate could be assumed null as the house owners or tenants are not likely to invest the money potentially dedicated to a PV system in other fields: nevertheless, considering a small incentive for the inhabitants in investing for PV and to make a more conservative estimate, a discount rate interval centered around the expected growth rate of the global economy was assumed (3.3% as shown in the World Eonomic Outlook by the IMF [143]). The price of the electricity bought from the grid has been considered country

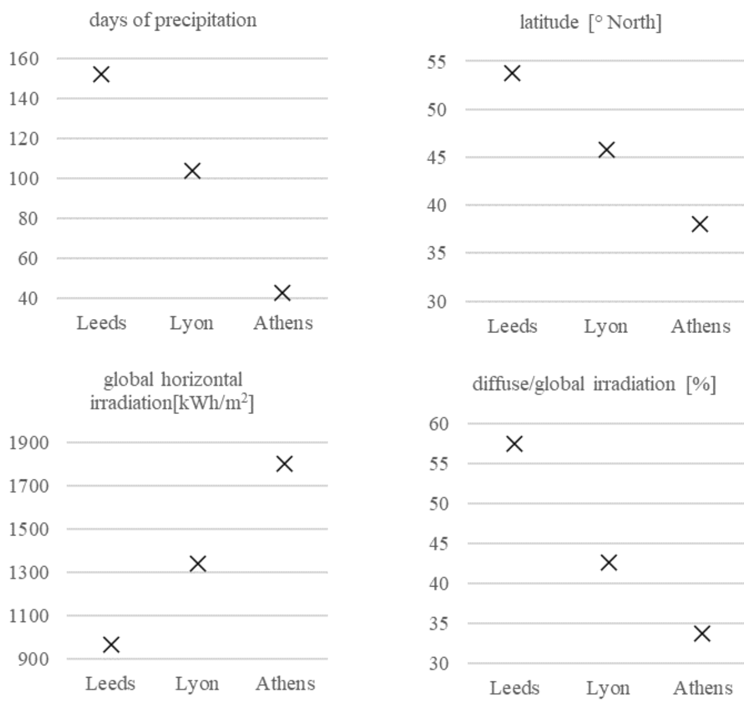


Figure 24: the four charts represent precipitation, latitude, annual global horizontal irradiation and proportion of the diffuse horizontal irradiation over the global for the three cities under study.

Table 3: list of techno-economic input used in the optimization.

Input :	value	
Module efficiency	16.5 %	
Performance ratio of the system at STC	80%	
Price of electricity sold to the grid [€]	0	
Price of electricity bought from the grid [€]	country specific	
Time horizon [years]	30	
Cost of the finished PV system [€/kWp]	1500	
Cost of the storage system [€/kWh]	670	
Input :	min	max
Costs for maintenance (excluding inverter change) [€/kWp year]	0	30
Linear annual growth of the electrical load	0	2
Linear annual efficiency losses	0.5	1.5
Annual discount rate	2.8	3.8
Linear annual growth of bought electricity	-2	2
Linear annual growth of sold electricity	0	0

specific, while the cost of the PV system has been assumed constant in all the three locations. The reason for this is that better data is available for the price of the electricity compared to the cost of PV (visible in the bar chart at Pag. 59 versus that at Pag. 50). The difference in the data is due to the type of market: dominated by a small number of sellers for the electricity and by a wide variety of sellers for the design and installation of PV. Thus, while it is reasonable to assume that the electricity is cheaper in a country rather than in another, it is not safe to assume the cost of a PV contractor mainly on the country (although there might be differences where incentives are concerned). The cost of the PV system depends heavily on the competition in the market at a localized level and on the outcome of a negotiation, thus it has lower precision as a guess compared to the electricity price and deserves a lower spatial resolution.. The set of inputs used in this serie of optimizations is shown in the following table.

optimal solutions to maximize NPV the figure 25 shows the optimal capacity per capita (i.e. divided by the number of people who share the PV system), the per capita price is reported on the right axes, this price by input (see input section at page 29) is proportional to the capacity

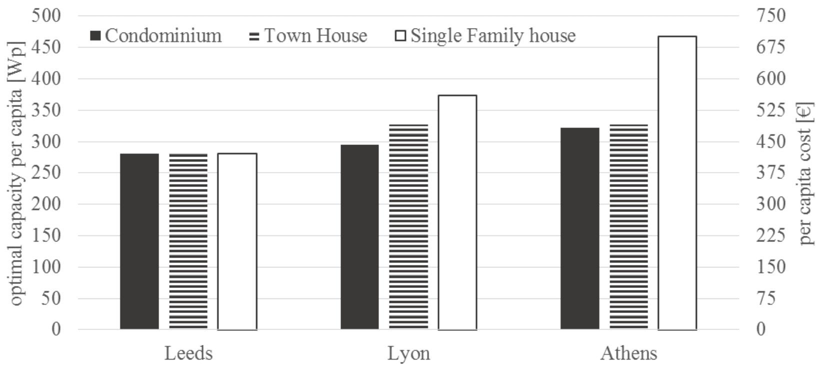


Figure 25: The chart represents the optimal per capita capacity (to maximize the NPV) for the three types of houses and in the three cities taken into account. The chart also reports (on the right axes) the per capita cost of the optimal system which is linearly correlated with the capacity(by type of input, see unitary cost input at page 29).

that each person has to install. With the exception of the Single Family House, all the other optimal capacities are comprised between 250 and 350 [Wp/inhabitant]. Moving towards lower latitudes, a higher capacity is installed for all the examples: the condominium shows a modest increase for each jump in latitude, while the Single Family House undergoes a huge change from the capacity installed in Leeds to that in Athens. The town house shows a different optimal capacity from Leeds to Lyon, but then the shows the same capacity in Athens. Looking at the Fig. 23, it is visible how the roof of the town house is surrounded by a shading parapet. This is probably the reason why the capacity from Lyon to Athens cannot grow. for the purpose of maximizing the net present value is not feasible, because of low yields, to install part of the system on the facade, therefore, the capacity cannot increase compared to that in Lyon otherwise it would be shaded. The condominium is affected by the shading similarly to the town house, although in a minor way, while the Single Family House, which has the two slopes East and West where to install the PV system, shows linear growth of optimal capacity along the diminution of latitude and annual rainy days. Fig. 26 shows the payback time [years] for the tree different system in the 3 different locations. It shows that a payback time below 12 years is never obtained for the optimal capacities in order to maximize the NPV. This implies that aiming for a pay back time below 10 years will, in turn, reduce the NPV obtainable in the lifetime of the system. In other words, forcing a payback time of 10 years, would of course reduce the overproduction to render the payback time shorter, but it will result in a self-sufficiency that is too low to maximize the NPV. in Leeds in par-

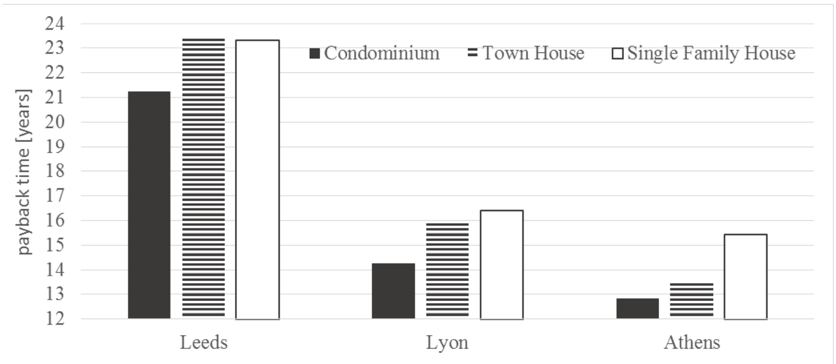


Figure 26: the chart shows the payback time of the PV system in the three building types and in the three locations. A good weather and the aggregation of the electric demand are the dominating factors despite shape of the building and variations in electricity price.

ticular the payback times are extremely long, this is because the NPV, even in its optimal configuration, is extremely low when compared to the initial investment for the system in all the house types examined. The condominium shows a significantly lower payback time compared to the other solutions. The long payback times in a regime of self-consumption without incentives are so that many investors will be unwilling to invest in this technology. Despite this, the internal rate of return of these different systems is quite high along their lifetime. In fact by design, as it has a positive NPV applying a real discount rate of ca. 3.3%, it is certainly higher than the aggregated growth rate of the average European country. For this reason, the investment in PV can be considered as an interesting one, because, risks considered using the stochastic parameters, the internal rate of return is moderately high. Of course, given the very long payback time, involvement of financial institutiosn is of Paramount importance for a significant spread of this technology. The next figure Fig.27 shows the per capita final NPV in relation to the cost of the system per capita for the 3 different house types in the 3 locations. Bear in mind that the NPV represents the amount of money that are gained compared to another investment having a return rate equal to the discount rate applied in the calculation. This means that, for example in Leeds, if the equivalent of the initial cost of the system (i.e. per capita cost a little over 400 Euro) was spent investing in a title which generates 3.3 percent per year of interest rate, there would have been a loss of around 100 Euro per person for the Condominium type, and a little less for the Single Family House. the chart shows that at lower radiation level, the 3 building types are very similar both in terms of the initial investment(per capita cost) and the in terms of final net present value. Moving to lower latitudes, the condominium show to obtain higher NPVs de-

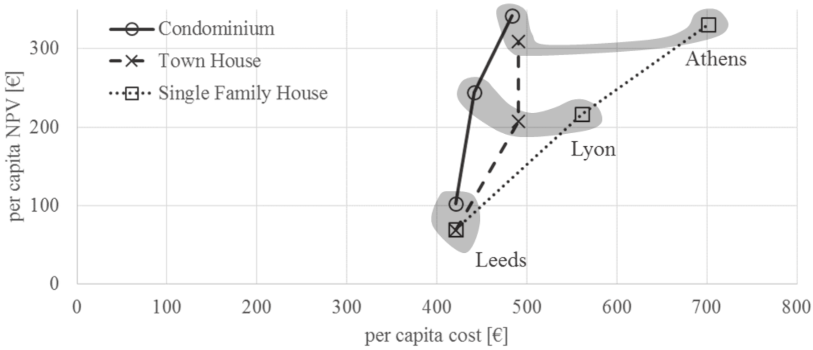


Figure 27: the chart shows the per capita NPV over the life-time for all the combinations in relation to the per capita capital expenditure: despite the late payback time in Leeds the NPV constitutes a large fraction of the initial investment, this is due to the long persistence of savings after the system is paid back.

spite lower per-capita investment (per capita cost)compared to the other systems. It is interesting to notice that, despite a higher aggregation of the load, the town house usually shows a lower net present value compared to the Single Family House. This is likely due to the shape of the building and to the superior capacity that is possible to install in the Single Family House (which has two different slopes) making use of the load matching function. Unsurprisingly, the average per capita NPV in Athens is higher than in Lyon, which is in turn higher than in Leeds. The Town House shows to have the same per-capita cost both in Lyon and in Athens: despite having the same capacity, the Town House show a higher NPV in Athens because of the higher yield. In all the locations the condominium features a higher per-capita NPV, this is because the aggregation of the internal load creates an advantage (this will be more accurately explored in the relative section at Pag. 101). The chart in Fig.28 puts in relation to the two LCOE, the one relative to the electricity produced and that of the electricity self-consumed. The diagonal line in the center of the chart represents a system in which all the electricity produced is a self-consumed instantaneously, this is because if there is some over production, the $LCOE_{self}$ obviously raises as the fraction of the electricity that is consumed shrinks. Unsurprisingly, the LCOE gets cheaper the more a system is placed towards lower latitudes (and the lesser rainy locations). It is also visible how, going to lower latitudes, the data points move slightly further from the 100 % self-consumption line: this is a consequence of the fact that the algorithm, given the higher yield, can afford to fall at lower level of self consumption. In every location examined, the condominium shows, in general, a lower LCOE in both types of energy considered compared to the other two.

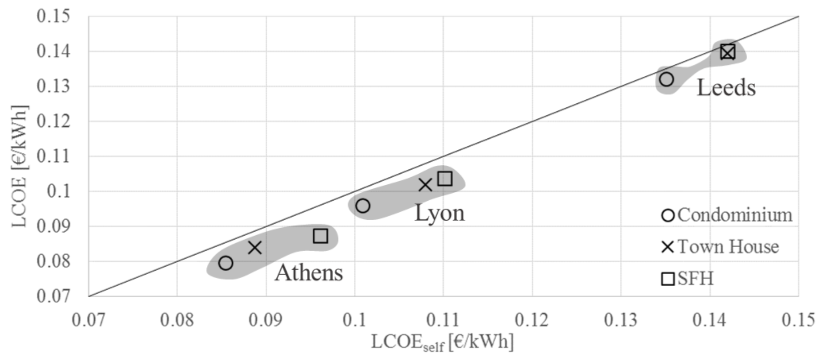


Figure 28: In this chart the LCOE of the electricity produced is confronted with the LCOE of the self-consumed fraction only, the diagonal line represents the equality between these two values (i.e. a 100% self consumption scenario). In Leeds, where the algorithm is more prone to limit the PV capacity, the difference between the two costs is minor (i.e. the data points are closer to the line)

In all the examples considered the LCOE, even that of the electricity self consumed, is comfortably below typical European household electricity prices. The next chart (Fig.29)shows the relation between self-consumption and self-sufficiency, it is possible to notice that the two values are negatively correlated with each other. In fact, those with a lower self-consumption have the highest self-sufficiency and vice versa. This is likely caused by the fact that the only surface that is used for the installation of PV is the roof and therefore having a larger capacity, while increases the self-sufficiency, inevitably decreases the self-consumption of the system as it promotes over-production. As already seen in the other charts, the aggregation of the demand creates in general a benefit, although in this chart the interpretation is not as straightforward as in the previous ones. In Leeds, which is the city that obviously position itself at the highest end of the self-consumption scale and at the lowest one of the self-sufficiency, the tree building types are ordered strictly according to their level of demand aggregation with the condominium having the most self-sufficiency and the least self-consumption. In Lyon the Single Family House and the town house have a very similar performance among each other, meanwhile the communion dominates them, having a higher self consumption and self sufficiency at the same time. In Athens there is a very large dispersion of the results, with the Town House having a much lower self-sufficiency and the higher self-consumption due to the limited capacity installed compared to, for example, the Single Family House. The Single Family House, given its two slopes in the roof, has the possibility to install way more capacity and therefore can achieve a slightly higher self-sufficiency even than the condominium at

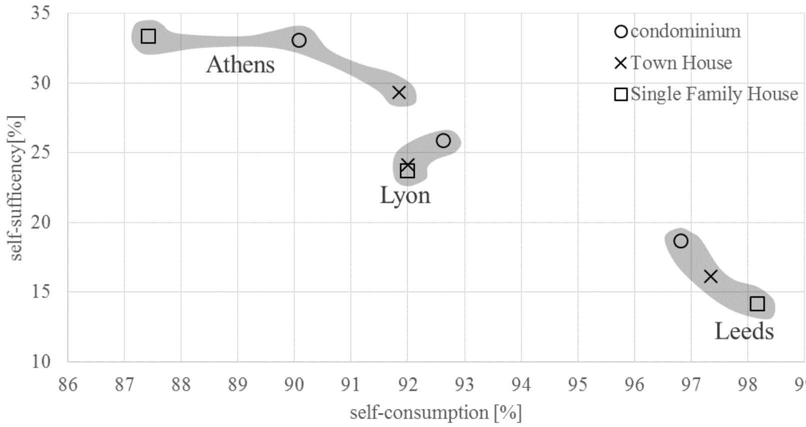


Figure 29: The chart shows the self-consumption against the self-sufficiency of the PV + building system. There is a trade-off between the two KPIs, in fact, in absence of electric storage, increase the electricity self-consumed necessarily implies increasing the over-production. In Athens, where the yield is higher, the algorithm can economically afford a larger system and therefore a lower self consumption to the advantage of an higher self-sufficiency

the price of the lower self-consumption.

Optimal solutions to maximize self-sufficiency the figure 30 shows the optimal capacity per capita for the three housing types and weather conditions, as for Fig.25 the per capita price is reported on the right axes. The relative capacities are somewhat similar to those of the optimal NPV system although the values are in general almost double, short of 500 and 700 [Wp/inhabitant](with the exception of the Single Family House in Athens as before). Compared to the algorithm that maximizes the NPV this one is less "greedy", in fact it suggests the installation of a larger capacity, which would lead to larger over-production, to make available more electricity to increase self-sufficiency as long as it does not become a net-cost over the lifetime of the system. As for the optimal NPV, a higher capacity is installed for all the examples in lower latitudes: the condominium shows a modest increase for each jump in latitude, but its increase gets smaller from Lyon to Athens for the same reason of the halt in capacity experienced by the Town House in the previous example (see Pag. 65). This time the optimal capacity of the Town House does increases from Lyon to Athens, but the gain is much smaller than from Leeds to Lyon, again the reason is in the shading parapet which hampers the gain when PV is installed in a shaded position. Also using this reward function the Single Family House, which has the two slopes East and West where to install the PV system, shows linear growth of optimal capacity along the diminution of latitude and annual

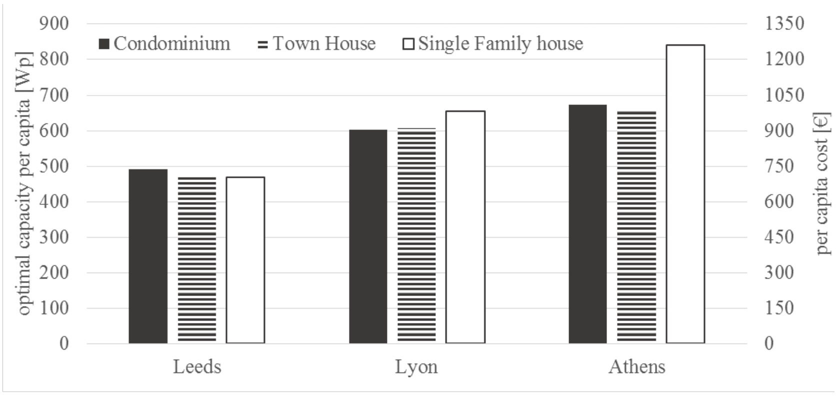


Figure 30: The chart represents the optimal per-capita capacity (to maximize the self sufficiency without resulting in an economic loss) for the three types of houses and in the three cities taken into account. The chart also reports (on the right axes) the per-capita cost of the optimal system which is linearly correlated with the capacity(by type of input, see unitary cost input at page 29).

rainy days. This chart (Fig. 31) is somewhat similar to the one in Fig.29, but instead of relating the initial cost to the NPV it relates it to the self-sufficiency. Showing the NPV would not be meaningful at all with this fitness function since any NPV available would be used by the algorithm to increase the self-sufficiency, thus leaving the NPV almost 0 for all the examples considered. In other words this chart is the parallel of Fig.29 but it shows the output of a different reward function. Similarly to Fig.29, the performance of the system (self-sufficiency in this case) benefits from the lower latitude,sunnier weather and from the aggregation of the demand with the condominium in Athens comfortably above 40% self-sufficiency while the Single Family House in Leeds stays at barely more than 20%. In this case the Town House does not have the same capacity in Lyon and Athens but for sure the gain in capacity is smaller than that from Leeds to Lyon from the same reason: also using this fitness function the Town House shows to be under-performing in Athens compared to the other two building types. The Single Family House, thanks to its double sloped roof, has a much better performance in locations where the clear sky day are more prevalent since it can better exploit the load matching potential of the moving sun. In fact its performance, relative to the other types, improves inversely to the latitude and to the rainy days (i.e. from Leeds to Athens). It is comforting to see how huge levels of self-sufficiency can be achieved with tolerably affordable prices. Also using this fitness function the self-sufficiency grows at the expense of the self-consumption as shown in Fig.32,this is due to the fact that in locations where the economics of PV are more convenient the system can afford to lose a larger share of the electricity

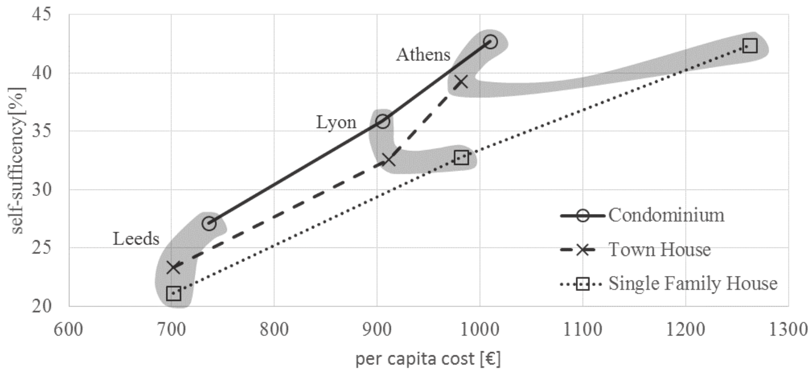


Figure 31: the chart shows the overall self-sufficiency for all the combinations in relation to the per-capita capital expenditure: the condominium, probably due to the aggregation of the demand, consistently exhibit a better self-sufficiency for its initial cost

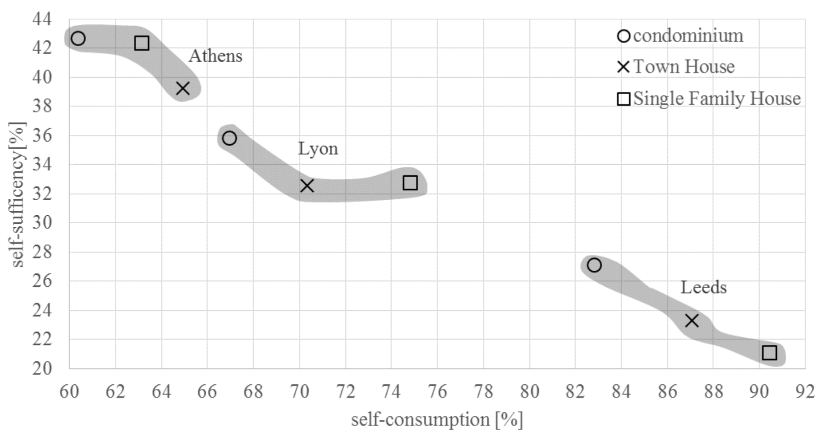


Figure 32: The chart shows the self-consumption against the self-sufficiency of the PV + building system. Also in this case, as in the optimal NPV case shown in Fig.29,there is a trade-off between the two KPIs. In absence of electric storage, increase the electricity self-consumed necessarily implies increasing the over-production. In Athens, where the yield is higher, the algorithm can economically afford a larger system and therefore a lower self consumption to the advantage of an higher self-sufficiency

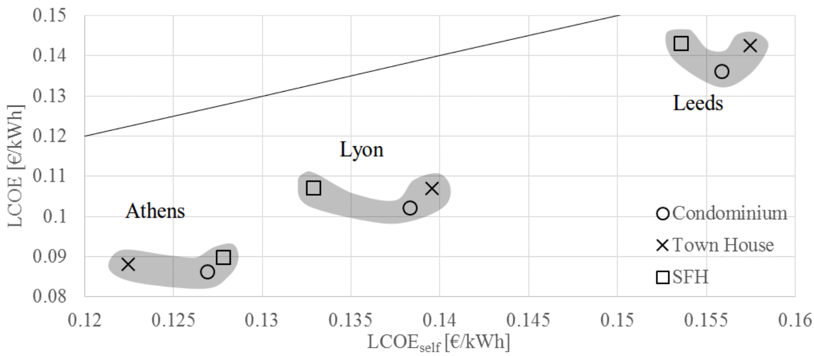


Figure 33: In this chart the LCOE of the electricity produced is confronted with the LCOE of the self-consumed fraction only, the diagonal line represents the equality between these two values (i.e. a 100% self consumption scenario). In Leeds, where the algorithm is more prone to limit the PV capacity, the difference between the two costs is minor (i.e. the data points are closer to the line). In general can be seen a major distance compared to the optimal NPV case in Fig. 28, this is because the latter fitness function maximizes the self-sufficiency instead of the NPV and is therefore mor prone to over-production.

to the grid without actually becoming unprofitable. The condominium is consistently higher in terms of self-sufficiency compared to the other types, while the Single Family House gains ground in lower latitudes compared to the Town House. Strangely in Athens, despite a lower capacity installed, the condominium outperforms the Single Family House but it has a lower self-consumption, this is due to the higher yield experienced by its system where the flat roof allows a horizontal installation instead of an East-West tilt. It is interesting to notice how the level of performance of the Single Family House is comparable to that of the condominium despite a lower level of aggregation, it is reasonable to believe that endowing the condominium with an east-west sloped roof would outperform its current form in terms of self-sufficiency achievable in locations with an high prevalence of clear sky days along the year. Coming finally at the LCOE (Fig.33): it is visible how, also in this case, all the three housing types are closer to the 100% self-consumption line when they are located in Leeds. Compared to the data points in Fig. 28 all are actually further from the 100% self-consumption line as the algorithm in this case accepts higher over-production. In terms of LCOE of the whole production the best alternative is consistently the condominium where there is an ample horizontal area on top of the roof. In terms of LCOE$_{self}$ it is usually the Single Family House to dominate (thanks to its better load matching), but in Athens, where the installed capacity per capita in the Single Family House is huge (see Fig. reference), the cheapest option becomes the Town House (albeit the low

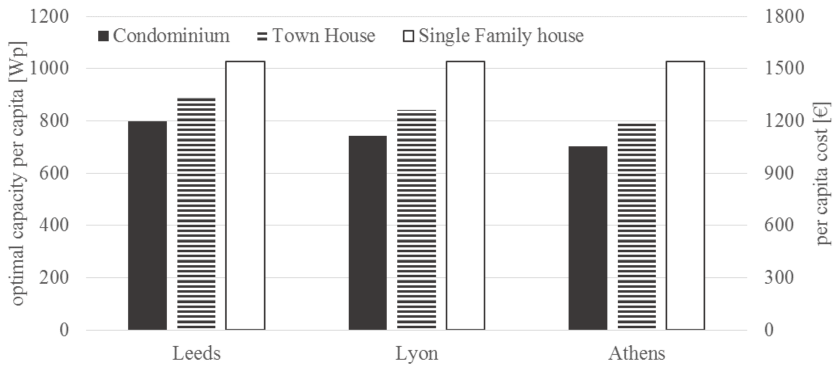


Figure 34: The chart represents the optimal per-capita capacity (to maximize the life-time cumulative energy balance) for the three types of houses and in the three cities taken into account. The chart also reports (on the right axes) the per-capita cost of the optimal system which is linearly correlated with the capacity(by type of input, see unitary cost input at page 29).

$LCOE_{self}$ is counter-balanced by a lower self-sufficiency).

5.2 Energy sustainability of an economically sustainable system:

In this section the optimization is repeated using the same set of input of the NPV calculation (see table 3 at pag.64) but using the fitness function described at Pag. 32 i.e. to maximize the balance between the PV electricity self-consumed during the lifetime of the system and its energy costs (which are proportional to the capacity as explained in the relative section at Pag.51). This fitness function does not take into account the NPV, therefore the suggested solution can be hugely unprofitable in economic terms as long as the Balance of energy (i.e. self-consumed minus embedded energy) is maximized. This chart (Fig. 34) is the direct parallel of the two capacities charts of the previous section (see Fig. 25 at Pag.65 and Fig. 30 at Pag.70). At first sight the capacities are easily above the optimal economical ones (even those of the maximization of self-sufficiency, see Pag.70). The higher capacities associated with this fitness function signifies that from an energetic standpoint the PV system is much cheaper than from the economic one and can therefore afford to loose a larger share of its produced electricity to the grid. Contrary to the other cases, the condominium has a lower optimal capacity compared to the other two solutions and at lower latitude the optimal capacities are lower (or the same at best) than the techno-economic cases. The reason of this apparent paradox lies in the self-consumption which acts as the main limiting factor for the growth of capacities, in fact the self sufficiency that is possible to reach varies mainly for the location

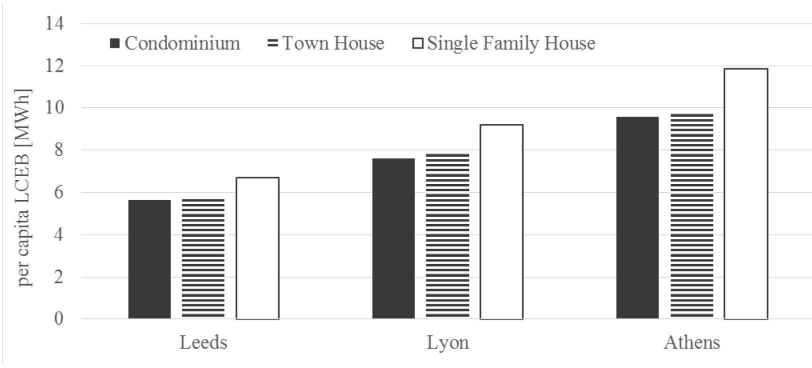


Figure 35: The bar-chart shows the per-capita LCEB for the different types of houses in the three different locations, the balance is obviously more positive in locations with a higher irradiation (in this case the price of electricity is not taken into account by the fitness function), but an ample margin is found in Leeds as well.

(i.e. as a consequence of the yield) and is fairly stable across the different types despite the different per-capita capacity installed. In other words, a higher effectiveness in covering the demand, or a higher yield of the system, bring the algorithm to hit a self-consumption *"barrier"* in the sense that the self-consumption drops due to excessive PV production and causes the most efficient solutions (i.e. highly aggregated demand or high yield) to have a lower optimal capacity. In this sense it is interesting to see how the Single Family House, thanks to its better matching capability due to the double sloped roof, can mantain the same capacity in all location and, in fact, outperform the other solutions in Lyon and Athens despite its lower aggregation of the demand (See Fig.38). In this chart (compared to Fig. 25 at Pag.65 and Fig. 30 at Pag.70) the trends are more clear due to lack of difference in energy price, and the capacities installed are comparatively more stable throughout europe. Fig. 35 shows the per-capita lifetime cumulative electricity balance of the three housing solutions, all the solutions in every weather show to have a positive lifetime electricity balance in terms of self consumed electricity (see fitness function description at Pag. 32). Therefore, the balance shown in Fig. 35 does not take into account a large quantity of electricity that is potentially usable in case of storage, demand side management or aggregation. As for numerous KPI in the previous optimization the performance increases with a lower latitude and a better weather condition. Nevertheless, in this case the condominium type does not appear to be able to outcompete the others, on the contrary the Single Family House clearly outperforms the other solutions thanks to its better matching capability. Both the Town House and the condominium show part of the system installed on the

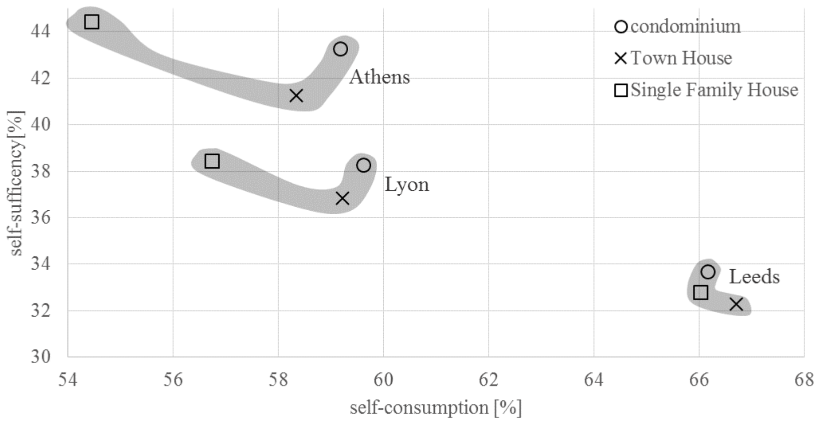


Figure 36: The chart shows the self-consumption against the self-sufficiency of the PV + building system. Also in this case, as in the other two cases shown in Fig.29 and Fig32,there is a trade-off between the two KPIs albeit less prominent due to the decreasing capacities of Town-House and Condominium at higher irradiations. In absence of electric storage, increase the electricity self-consumed necessarily implies increasing the over-production.

south façade. The chart in Fig. 36 corresponds to the charts in Fig.29 at Pag. 69 and in Fig.32 at Pag.71 from the previous session. Also in this example there is a trade off between self-consumption and self-sufficiency, but the whole cluster of points is shifted towards much lower self-consumption and higher self-sufficiencies. Compared to the chart in Fig.32 at Pag.71 the results are quite similar although in this case the capacities are higher and the whole points are shifted to the top-left so that the results for Leeds are roughly similar to those in Lyon for the maximum self sufficency (Fig.32). On the contrary, the LCEB performance for Lyon cannot reach the level of performance achieved by the maximum self-sufficiency performance for Athens. As testified by the higher capacities, is possible to notice that the level of self-consumption required to reach the maximum LCEB are always below 70%. This means that from an energetic stand-point the PV material is extremely cheap to produce and the maximum is reached despite a huge amount of energy losses. This is a good news because it means that if there are improvements in the economic outlook of PV, the system can be hugely profitable and generate large amount of free energy as a bonus(i.e. the energy that is considered lost from this perspective can be considered free by other actors in the grid). Despite having a slightly lower per-capita LCEB (see Fig.35), the condominium is strictly more performing than the Town House in terms of self-sufficiency in every location, the reason is that the higher efficiency in matching the demand, due to higher aggregation, makes the system less resistent to the long term

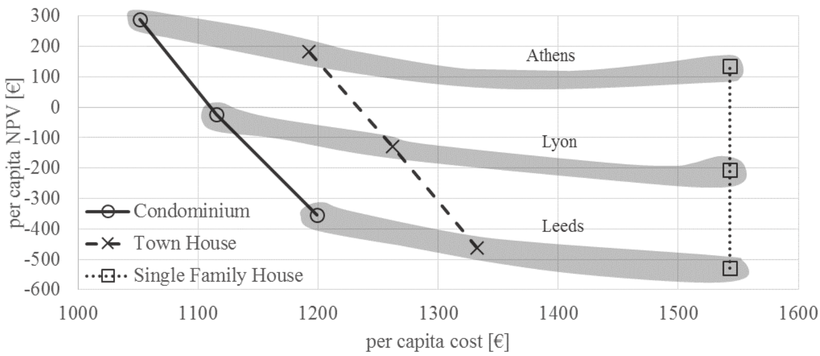


Figure 37: the chart shows the per-capita NPV over the life-time for all the combinations in relation to the per-capita capital expenditure: contrary to the example where the NPV was maximized (see Fig.27)most of the solution present a negative NPV and so result in an economic loss. It is interesting that in the techno-economic conditions of Athens the energy-optimal solution is not an economic loss.

changes such as degradation of the system and changes in electric consumption. The Single Family House at low latitude can achieve a highest performance both in terms of self-sufficiency and LCEB, this might one day (i.e. if the price of PV become sufficiently low) put into serious question the desirability of the south facing slope compared to the east-west one. Unfortunately, as Fig.37 shows, the energetic optimum is still unprofitable for every housing solution for two out of three location examined, although the condominium always reach an NPV of 0 in Lyon (as it can be expected since the optimal capacity is only slightly higher than the one for maximum self-sufficiency). In terms of NPV, since it involves the economic aspects of the installation, the performance order from the previous section have been restored with the condominium over-performing and the Single Family House underperforming. Also in this chart (like Fig.27 at Pag.67) the Single Family House appears to diverge from the other two when moving toward lower latitude, but instead of the Single Family House increasing the cost is the other two types decreasing it. The difference in NPV between the different housing solutions are minor when compared with the differences in initial investment(per capita cost), this gives the chart a characteristic look in "horizontal stripes". In terms of self sufficiency (Fig.38) the situation is similar although the Single Family House performs much better for the reasons explained previously.

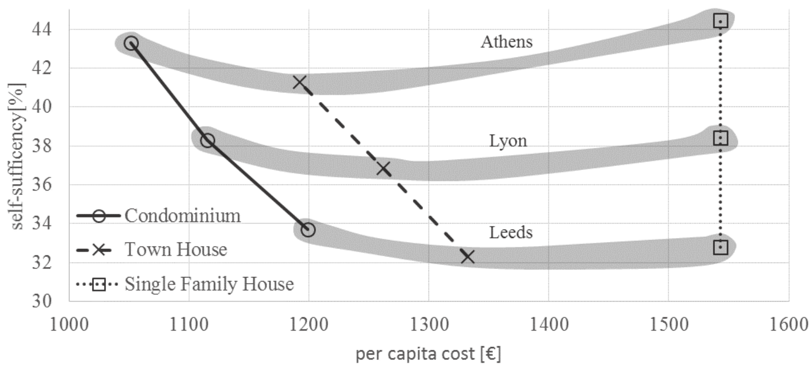


Figure 38: the chart is identical to the previous one (Fig. 37) except that it shows self-sufficiency instead of NPV. Due to the bigger capacity installed these self-sufficiencies are higher than those shown so far (see Fig.32 and Fig.29). The Single Family House shows a unique behaviour (with larger capacities that are location-independent) probably due to the different orientation of its PV-available area.

5.3 Specific CO_2 emissions of the systems:

In this section the optimal configurations of the section about the current BIPV profitability (starting at Pag. 61) are analyzed in terms of specific CO_2 equivalent emissions: the emissions are considered to be caused by the mining of resources, construction, transportation and installation of the system and are proportional to the capacity of the system in the measure described in the relative section at Pag.59. The specific emissions are retrieved by dividing the sheer initial emissions by the number of kWh produced (or self consumed only) during the lifetime of the system. For the input used in the optimization please refer to Table3 at Pag.64 since the inputs and results are the same. As shown in the section about the calculation of the specific CO_2 emissions at Pag.59 the emissions of a BIPV system cannot be considered null despite the absence of GHG emissions during the operational phase of its lifetime. The chart in Fig.39 shows the levelized equivalent emissions relative to the three different housing solutions in the three location examined. As for the other KPI, also in this case the condominium consistently outperforms the other types: this is mainly due to the aggregation of the demand but also (albeit with a lesser impact) helped by an higher yield of this type compared to the other two. The yield has a stronger impact when due to a change in weather conditions with the systems in Athens having on average emissions that are 60% of those in Leeds. No clear pattern seems to appear among the values in difference between the emissions for the whole production and those for the self-consumed fraction, nevertheless this difference is absolutely negligible in Leeds while it approaches a

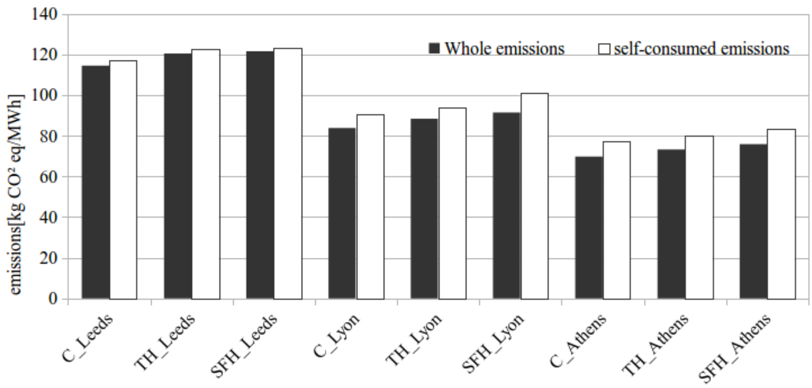


Figure 39: The chart shows the levellized CO_2 emissions for the three housing solutions in the three different weather conditions, the $LCOE_{self}$results higher as the emissions due to the installation are divided by a lower number of kWh (i.e. the self consumed fraction only). The results are shown for C (Condominium), TH (Town House), SFH (Single Family House).

+10% of the whole emissions both in Lyon and Athens. The emissions shown in Fig.39 has but little value if not contextualized with the local energy mix of the country in which it is installed. Assuming the average specific emissions accdording to [144] the energy mix of the UK, France and Greece emits 459, 64 and 649 [kg CO_2 eq/MWh]respectively. The chart in Fig.40 shows the levelized emissions of each BIPV system compared to those of its local energy mix: thanks to the huge contribution of nuclear energy in the French mix, BIPV does not show to be competitive and results in an increase of the CO_2 of its host building. On the contrary, in England and Greece, due to the higher specific emissions of their energy mix, the BIPV system can achieve huge improvements in specific emissions: considering the self-consumed electricity only (i.e. a conservative assumption) the improvements compared to the energy mix are in the order of 74% and 88% respectively for england and Greece. Because the PV electricity does not satisfy 100% of the electric demand of the building, the variation in actual CO_2 emissions should be multiplied by the self sufficiency reached by the BIPV system. Obviously also in Fig.41, as in Fig. 40, the variation for a building located in France represents an increase in equivalent emissions, the increase is comprise between 10% and 15% according to the type of building with the Single Family House having the worst effect. In Leeds, due to a low self-sufficiency, the reduction that is possible to obtain with the maximum NPV is moderate and goes from a minimum of ca. 10%, obtained for the Single Family House, to a maximum of about 15% obtained for the condominium. Athens appears to be very interesting in terms of reduction potential with the condominium cutting more than 30% of its

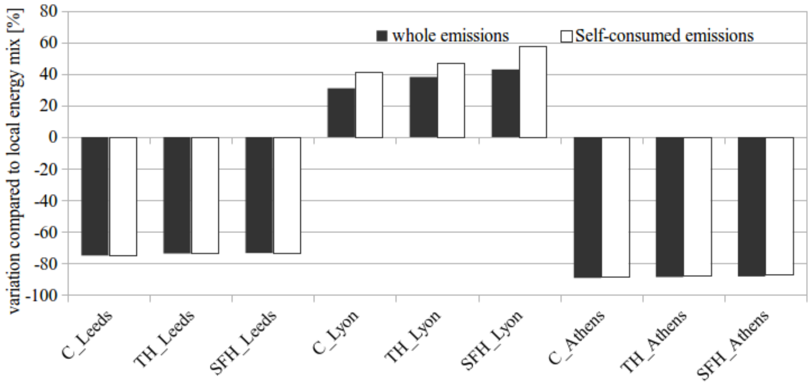


Figure 40: Every country where the optimization has been carried out has different specific CO_2 equivalent emissions: the emissions calculated for the BIPV system (Fig.39) have been compared with the local energy mix, the chart shows the emissions of each BIPV system compared to the energy mix of the country where is located. The emissions of the local energy mix are taken from [144]

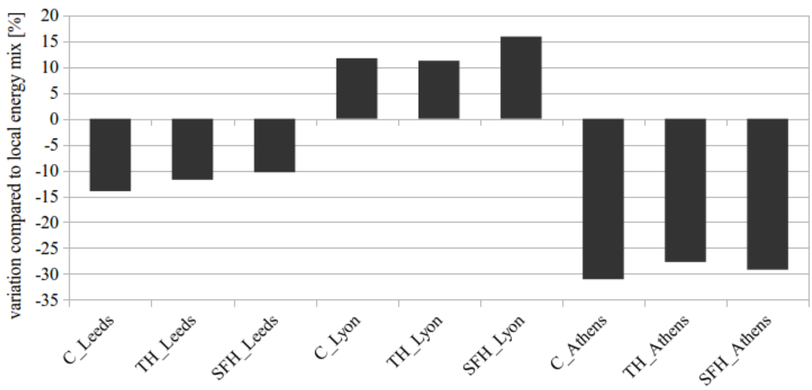


Figure 41: Considering the self-sufficiency reached in each combination of building-weather, the impact [%] on the total emissions of the building have been considered and is shown in the chart for C (Condominium), TH (Town House), SFH (Single Family House).

emission and the other types still above a 25% reduction. The levelized specific emission considered for the results shown in Fig.41 are those considering only the self-consumed fraction of the electricity. For this reason an amount of emission free electricity can be considered available if adequately exploited using demand side management or electricity sharing.

5.4 Profitability of the façade:

One recurrent theme in the BIPV literature is the possibility of using the photovoltaic material in the façade: the fact that façades have a lower annual yield [kWh/kWp] compared to the roof often makes them to be perceived as unprofitable or even a so called "green-washing"* , the truth tough can be very different if the load-matching (i.e. the contemporaneity between consumption and production) is taken into account. This section reports the results and the analysis of the study [87], which was performed adopting the technique under study in this thesis. The study argues that regarding building integrated photovoltaics, the maximization of the annual cumulative production is not always the best strategy. In this example installing photovoltaic modules on the façade can be economically advantageous even if the roof area is not fully occupied by PV. Actually, the study shows that the advantage generated by the façade integration is rather small and subject to uncertainty given the stochastic nature of the input (see [87]), but the important message carried by the presence of this improvement is that it is surely not a loss compared to the roof integration only. In order to apply the optimization algorithm, because part of the electric demand consists in the power absorption of the heat pump for the heating and cooling of the building, the first stage is the complete definition of the thermodynamic performance of the building under consideration. In fact, a detailed model of the thermo-dynamic behavior of the building is a key element given the importance of the form and size of the electric power demand as an input in this methodology. Such a model can be achieved with different already existing tools, but in the case study presented, the TRNsys environment was used. Appliances and lighting demands are added to the electric consumption of the HVAC system to obtain the overall demand. The hourly electric consumption of the building is crucial in determining the optimal PV capacity: if a PV system is too small it has no impact on the demand profile (hence on the NPV), if it is too big most of the electricity produced is not self-consumed. At the time of [87] * was still not possible to insert a different PV cost for different façades within the building, in other words the unitary price [€/kWp] was the same for the PV on the roof and on the façade. This parity might seem like an advantage for the façade integrated PV because a premium due to aesthetics

*i.e. a form of spin in which green PR or green marketing is deceptively used to promote the perception of a building as environmentally friendly

* the paper results published in 2019 but the review process was very long, actually the calculations are from 2017

and technological integration might be expected, nevertheless the price of a comparable façade cladding should be removed from the PV system in façades to account for multi-functionality [145]. If for example a system added on the roof has a total cost (modules, cables, inverters, mounting structure) of 1500 [€/ kWp] it could be price-comparable to a façade integrated system of ca. 3000 [€/kWp]. This is due to the assumption that the façade BIPV substitutes another material for a ventilated façade and the structure should be built regardless of the choice of PV or another material. With a back-of-the-envelope calculation we can calculate the price per square meter of the 3000 [€/kWp] system: assuming an efficiency of 15%, the cost of the BIPV ventilated facade would be 450 [€/m ^{2}]. Subtracting a price of a ventilated façade system (mounting structure plus cladding) of 225 €/m ^{2} the increase in price due to PV functionality would be 225 [€/m ^{2}], hence 1500 [€/kWp]. The real price of BIPV is a complicated matter due to the high level of customization of the single project and relative scarcity of industrial solutions, this paper does not include an adequate study about pricing, therefore the price of PV is considered as façade independent (i.e. purely the cost of PV, neglecting façade-specific structures or discounts due to replacements of other materials).

Description of the case study: The case study is a new school building designed on the area of an old one damaged by an earthquake in 2012. It is located in Novi di Modena, a small municipality in the Northern part of Italy. This study focuses on one of the school blocks. The building has a linear layout with the long façades being North-East and South-West. The classrooms characterized by large south-facing windows, receive direct sunlight during the most part of the day and require to be protected by a shading system to reduce the cooling load. The structure for the shadings is attached to the South-West side of the building and is not perfectly vertical (it has a tilt angle of 60 $^\circ$ to the horizontal), all the shadings can in theory be made of PV material, therefore all the south screen area is part of the area available for PV (see input section at Pag. 25). The TRNsys v.17 [146] software has been used for building thermal simulation. TRNsys is a graphically based software environment used to simulate the behavior of transient systems focused on assessing the performance of thermal and electrical energy systems. In the specific case the building simulation model has been used to derive the electrical energy loads [kW] of the building. The software allows the calculation on hourly basis of the electrical consumption to satisfy the heating and cooling demand. The geometry of the building is designed with TRNsys 3d (a sketch up plug in for TRNsys). The overall geometry of the modelled building is shown in Fig.42. The thermal

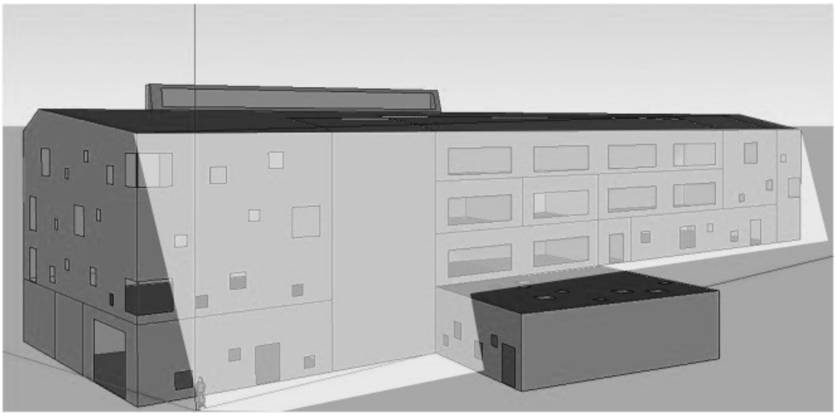


Figure 42: the picture shows a screen-shot of the school building taken from the TRNsys 3D Sketch-Up plug in. The shading screen where the PV system can be inserted is represented in translucent white on the South-West facade

building simulation output defines the heating and cooling energy demand. To calculate the final energy consumption it is assumed that the building works with an electrical air-to-water heat pump system with a mean COP (coefficient of performance) equal respectively for winter and summer season to 3.0 and 3.5. To calculate the overall electrical energy demand the electrical energy consumption of the appliances has been considered as well. To perform the optimization, the following inputs (Table 4) were used. The presence of net metering schemes was not considered and sold electricity was not valued. This choice was made to focus on the economic viability of PV without the use of the grid as a storage option and to see which level of self-consumption can be achieved with this conservative assumption. Please note that the price of the electric storage is assumed as 0: this choice was made because the objective of the study is not to study the profitability of some specific batteries with the present prices, but the effect that storage have on the capacity and positioning of PV installed and to identify at which price storage can become economically viable. Furthermore, the maximum cost of stored electricity to be profitable can be found by evaluating the positive impact on the NPV of the PV system. In the paper four storage hypothesis are compared: NS (with NO storage), WS (With Storage: 87 kW h), 1/3 WS (1/3 of the WS storage: 29 kW h) and 2/3WS (2/3 of the WS storage: 58 kW h) the quantity of PV installed is examined in relation to that. The surfaces available for PV are located on almost the entirety of the roof and the sun-screen on the façade, each point represents an area A of 3.6 m^2. Considering an efficiency of 15%, the potential capacity of the roof is ca. 95 kWp and of the façade is ca. 43 kWp, with an overall potential capacity of 138 kWp. The size of the

Table 4: list of techno-economic input used in the optimization.

Input:	value	
Efficiency of the modules in the PV system [%]	15	
Performance ratio of modules at STC [12] [%]	80	
Time horizon for NPV [years]	25	
Cost of PV system [€/kWp]	1800	
Cost of electric storage [€/kWh]	0	
Private electricity cost [€/kWh]	0.2	
Revenues for energy sale [€/kWh]	0	
Input:	min	max
Growth of the power demand [%/year]	0	2
Growth of the price of electricity [%/year]	-1	1
Discount rate [%]	0	6
Costs for maintenance (including inverter change) [€/kWp year]	18	36
Degradation efficiency losses [%/year]	0.3	0.8
Battery installed [kWh]	0	87

battery for the WS storage hypothesis was taken to accommodate the maximum daily over-production over one year of the biggest possible system (138 kWp) with a resulting usable capacity of 87 kWh.

Results: considering the climate condition, the building design technology and the intensity uses, the total electrical final energy consumption for the demo building in one year is equal to 182 MWh corresponding to 52.87 kWh/m^2. The major share of energy is due for heating, 76% of the total; followed by electrical appliances + lights (18%) and cooling (6%). Analyzing the irradiation over the two available surfaces (i.e. roof and south facade) (Fig. 43), it is visible how, despite having a slightly lower annual cumulative irradiation, the façade presents a higher solar radiation during the heating season. This irradiation pattern shows a better matching to the monthly electric demand, this is the main reason why the load matching procedure was considered in the optimization. The load matching (LM) procedure is different from a mere capacity optimization (CO) because it enables the use of surfaces with a lower annual cumulative irradiation. This feature is computationally expensive, but can be used when the least irradiated surface (the façade in this case) presents a higher irradiation in some HOY. The relation between NPV and capacity of the system is shown in Fig. 44. It is visible how the NPV grows linearly for smaller capacities, then grows at a slower pace until eventually starts to shrink. This phenomena is mainly caused

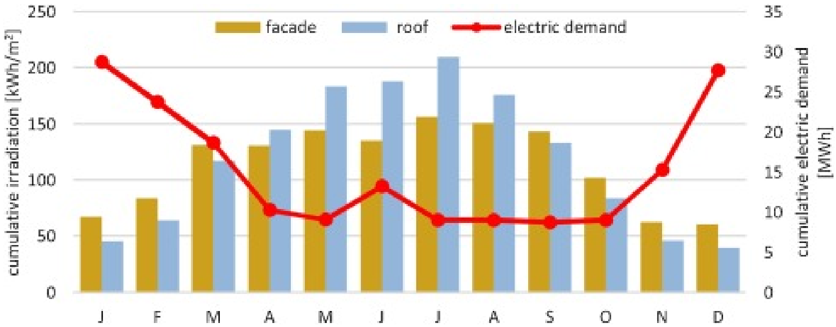


Figure 43: the chart,from [87], shows the cumulative electric demand of the building super-imposed over the monthly cumulative irradiation over the roof or the façade. Even tough the façade has a lower annual cumulative irradiation it gets more irradiation during the winter months.

by the rate of self-consumption: while 100% of the electricity produced by a small system is instantaneously self-consumed, this percentage decreases to 83% at the peak NPV of the NS system. In the four charts of Fig. 44 the WS and the NS systems are compared, the higher NPV of the WS system is due to a higher level of self-consumption. In these calculations the price for electricity fed into the grid is 0, which corresponds to a 100% curtailment (i.e. electricity is available from PV but nobody within the grid is willing to buy it). This input is an extreme consequence of the reduction of the value of PV electricity caused by an increase in its penetration (see [70]), it is a conservative assumption but it might really happen at some point in the future. The concept of negative prices for the electricity should not be considered as the inverters can regulate the power output of the PV system in a way that is always below or equal to the demand of the building/district. The charts in Fig. 44 also show that the highest NPV yielding capacity (i.e. the suggested capacity) is shifted on larger systems when the storage is added, the plateau "MP" in the curve in "a" (NS) is in fact on a capacity of ca. 62 kWp, while in "b" (WS) is located around 78 kWp. The larger capacity of the WS system, combined with the ability to store part of the excess solar electricity, can cover 42% of the cumulative electric consumption against a 32% brought by the NS system (both the values are calculated at the first year). The increase in optimal capacity is another effect of a higher flexibility for self-consumption and gives reason to believe that the penetration of urban PV will increase thanks to a foreseen increase in storage capacity. The increase in expected peak NPV by virtue of 87 kWh of storage is 28 k€, thus for such a large storage to be profitable the cost per kWh (for 25 years) should fall below 320 €(see Table 5). Such a figure is still too low, although according to [147] it will likely be reached between 2027 and 2040(if a life-span of 25 years is assumed).

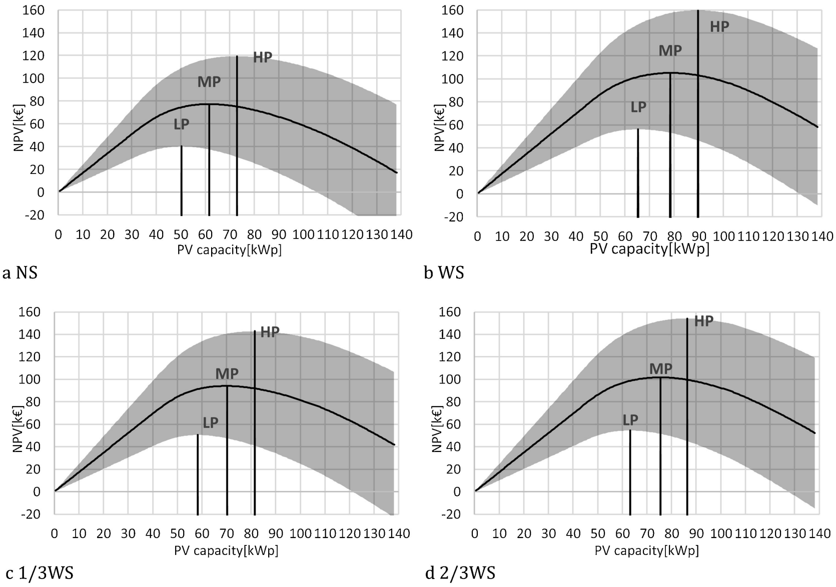


Figure 44: NPV in relation to the installed capacity, the grey area represent the possibilities between 25 and 75 percentile. a)no storage (NS) b) with storage (WS) c)1/3 of WS capacity (1/3WS) d) 2/3 of WS capacity (2/3WS). The picture is taken from [87]

By design, such a large system would always be under-utilized (in fact is designed to store the whole production of the sunniest day in the year), the optimal balance of PV/storage capacities is ultimately function of the relative prices of the two. Smaller storage system would be profitable with lower tough still unrealistic prices as shown in Table 5. Analyzing the demand profile of the building (Fig. 43) is visible how the electric demand is lower in summer. This prevents the full discharge of the battery in periods where the overproduction from PV is large and there is not enough demand to consume it. The electric storage should not be viewed simply as a physical support, it can be a service offered from a third party provider, this way a better use of the overcapacity can be envisioned. This approach would strongly mitigate the excess capacity of the battery in seasons where the demand is low, provided that there is enough "mixité" [148] in the low/medium voltage grid. If the storage is seen as a service and its capacity as a maximum guaranteed capacity, the maximum price that can be charged [€/kWh] can be obtained dividing the cumulative electricity exchanged by the difference in NPV with respect to the baseline storage hypothesis (NS). The cumulative energy provided by a WS storage in the first year is 9.3 MWh (Table 5), assuming a stable figure during its lifetime, the battery would provide ca 233 MW h. Considering the expected NPV gain of 28 k€generated by the presence of the storage, the battery levelized cost of stored electricity

Table 5: Dimensions correlated with the electric storage capacity, the table shows data for the peak NPV cases at each storage level.

	no storage (NS)	29 kWh (1/3WS)	58 kWh (2/3WS)	87 kWh (WS)
Optimal capacity [kWp]	61.6	70.2	75.6	78.3
Self-production (year 0) [%]	32.3	37.7	40.6	42
Self-consumption (year 0) [%]	83.3	82.4	82.4	82.4
NPV (25 year) [k€]	77.3	94.1	101.8	105.2
Stored energy (year 0) [MWh]	–	5.4	8	9.3
Cost of stored energy [€/kWh]	–	0.1239	0.1219	0.12
Profitability threshold price [€/kWh]	–	576.3	419.8	319.5

LCOS could fall below 0.12 [€/kWh]. Table 5 clearly shows the need to include the optimization of the storage system as next step. It also shows that the smallest storage system considered in this study would be profitable at a final price of 576 €/usable capacity. This price is at close reach looking at learning curves of storage shown in [149] (year 2022 for residential Li-ion battery system price with a learning curve of 15%). The NPV charts are not a defined value but they present an uncertainty due to the stochastic variables. In the four charts the expected value is shown within a range sweeping from 25 to 75 percentile. Observing the plateau in the ranges (Fig. 44), a sliding toward higher capacities becomes visible when more optimistic scenarios are applied (LP < MP < HP). The dimensioning of the PV system can be done with a conservative or an optimistic mindset, the actual NPV of the system is maximized when the real scenario reflects the expectations. If a designer decides to install the capacity (WS) suggested by the pessimistic scenario (i.e. LP = 65.3 kWp), the system is under-dimensioned in the case the optimistic scenario happens: it should have had the optimistic capacity (i.e. HP = 89.6 kWp). Fig. 45 shows that of the 78 kWp of the median scenario (WS), ca. 18 are to be installed on the façade despite not having used up all the potential on the roof. In the bar chart the roof capacity remain unaffected by the scenario used while the façade capacity is strongly variable. This happens because the order of profitability

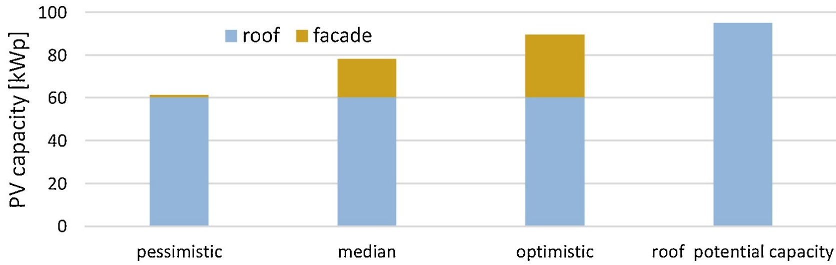


Figure 45: Capacities that maximize the NPV for scenario WS at point LP, MP and HP. The roof potential capacity is reported to show that the facade is occupied although there is still unoccupied space on the roof. The picture is taken from [87]

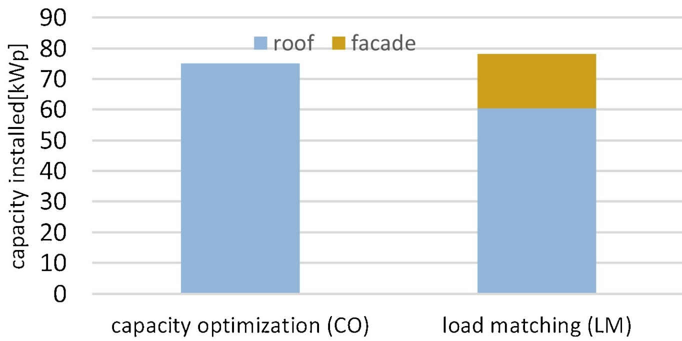


Figure 46: Capacities that maximize the NPV for scenario WS at point LP, MP and HP. The roof potential capacity is reported to show that the facade is occupied although there is still unoccupied space on the roof. The picture is taken from [87]

of the positions does not change with the scenario, what changes is the number of positions that are being occupied by PV modules. The optimization algorithm adds the modules in the same order, but while the pessimistic NPV is peaking, the median and optimistic NPV figure is still growing. The use of the pessimistic or optimistic NPV as a fitness function, in spite of the median, has a negligible effect on the optimal configuration, in this sense the order of profitability of the PV positions is not influenced by the scenario. Aside from the scenario, the capacity installed is affected by the use of load-matching. Fig. 46 shows the best performing (WS) NPV capacities obtained by merely optimizing the capacity and by performing load matching. In a pure capacity optimization (CO) the façade will not be used until the roof potential is completely covered because the façade has a lower annual cumulative irradiation. Fig. 17 shows that the overall capacity installed is higher for the optimal system where load matching (LM) is used (78 kWp against 75) although the roof capacity is ca. 15 kWp lower. The LM configura-

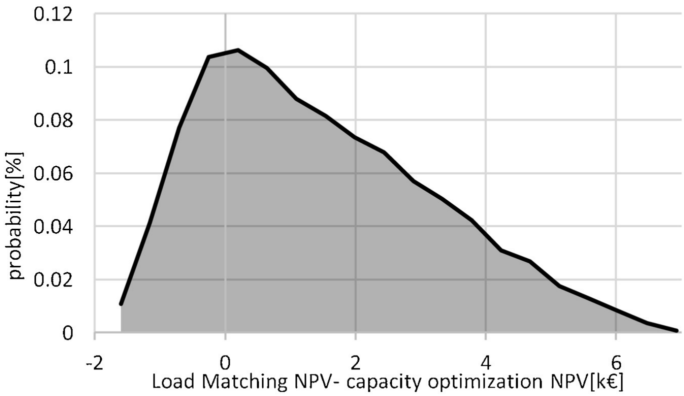


Figure 47: Probability of the NPV difference between the load matching (LM) configuration and the capacity optimization (CO) configuration for the WS storage hypothesis. The picture is taken from [87]

tion presents a slightly higher self-consumed cumulative energy over the life time (+3.3%), which would lead to an annual increase in revenues of 470–520 [€/year] over a baseline of 14'033–15'669[€/year] (at 0.2 €/kWh). Nevertheless the installation of an higher capacity carries an increased initial cost and higher risks in case of high maintenance costs or high discount rates. Despite this, the expected difference in NPV between the LM configuration and the CO is slightly positive as shown in Fig. 47. The expected gain between the two peaks in expected NPV, regardless of their capacity, is 1684 [€] equal to an NPV improvement of ca. 1.6% on the CO configuration. The chart in Fig. 47 was produced comparing the NPV of the LM and CO configurations for every scenario, note that LM does not guarantee a monetary gain as there are chances (26.8%) that LM produces a loss. This effect is partially due to the higher overall capacity of the LM configuration, there are in fact variables (i.e. initial cost, maintenance costs, discount rate) that put high capacities to disadvantage. Analyzing a single scenario the probability would collapse in a single value. For example using a degradation of 0.5, load growth of 1% (annual linear), a stable cost of electricity, no discount rate and a maintenance of 27 [€/kWp year], the NPV gain associated with LM would be equal to ca 4500€. If The NPVs are compared for each capacity (Fig. 48), the expected NPV gain of simply moving part of the modules from the roof to the façade can be measured. At the capacity of the peak CO (ca. 75 kWp) the expected NPV improvement for LM is small (1412 €), it is nevertheless interesting because it has been obtained without increase in the initial investment. If the NPV gain is spread to each kWp moved from roof to façade (ca 15 kWp) the expected gain is ca 97 €/kWp, which is ca. 5.4% of the initial cost. The highest gains provided by the LM are on systems of

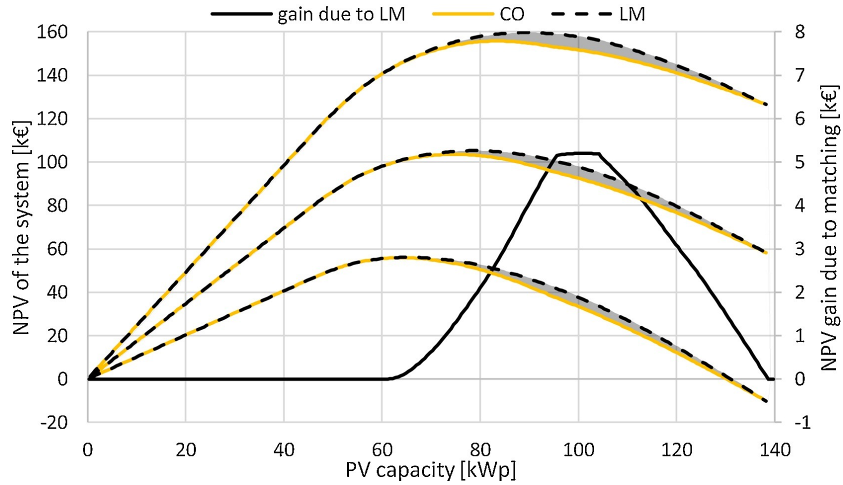


Figure 48: Expected NPV gain generated by load matching for each capacity in WS hypothesis: the colored areas for the capacities show the difference in expected NPV, the gain due to LM is represented for the expected case. The picture is taken from [87]

ca. 100 kWp with an expected gain above 5200 [€] equal to ca. 5.6% in NPV improvement. Given the current economics these capacities are slightly over-dimensioned, but are still hugely profitable and can nevertheless be chosen for environmental reasons. The chart in Fig. 48 shows a higher gain from load matching in case of optimistic scenarios, in terms of percentage of the NPV though the trend is the opposite. The reason for this is that the peak of NPV gain due to LM is independent from the scenario, while the peak of the sheer NPV tends to slide right for the optimistic ones. For example the NPV of a 100 kWp system, in a pessimistic scenario, increases of about 13% thanks to LM.

5.5 Effect of the electric storage on the optimal PV system:

In this paragraph a case study is examined with the methodology previously described, the paragraph reports the results and comments from [150]. Economic profitability aside, the visual impact of a BIPV system with real module dimensions can also be seen in this example, in fact the stage of the architectural design in this case study is more advanced than in others. In this case the PV system should be applied on the façades of a pre-existing building. The main factors influencing the output are the sunlight availability, its variation along the HOY (Hour Of the Year), the electric demand, the cost of different parts of the system and the cost of electricity. The method is applied on a group of three residential high-rise buildings in northern Italy, the system is optimized for maximum NPV(see fitness function in the section about the optimization algorithm at Pag. 30) or for a maximized self-sufficiency at prescribed payback time (see Pag. 33), the operation is repeated supposing different prices for the electric storage. The system has been sized using two different demand profiles: one from a well known building standard and a realistic one produced with a set of different individual curves from a stochastic generator and calibrated on a measured aggregated demand profile. Using the realistic curve the coverage of the electric demand of the optimized configuration goes beyond 20% for the optimal NPV configuration [150]. The case study presented in this paper is a city district composed by three high rise residential buildings (Fig. 49) located in Trento city, in the Province of Trento in northern Italy. Without measured data available, for the sake of a realistic example an electric demand profile was generated with LPG (Load Profile Generator [127]): 8 different type of family were stochastically simulated, and their prevalence was adjusted to fit as closely as possible an aggregated electric demand profile measured in a residential district in northern Italy. The population composition by type of family and their prevalence in cumulative electricity demand is shown in Figure 50. The optimization algorithm also needs meteorological data and an electric demand curve (see input section at Pag 25). The meteorological file is the one for the city of Trento taken from the Meteonorm database [71]. For the electric demand two different curves were used: one is the realistic demand of the building produced with LPG (Load Profile Generator), the other one is taken from the prEN16798-1 and ISO/FDIS 17772-1 Standards [151]. For the optimization the set of inputs from Table 6was used:

Results: Using diverse demand curves for the optimization process can lead to different results, in this section the difference in terms of average power between the two curves is shown. The difference between the standard and the realistic curve matters for us as much as it

Figure 49: 3-Dimensional representation of the buildings in the case study. The picture is taken from [150]

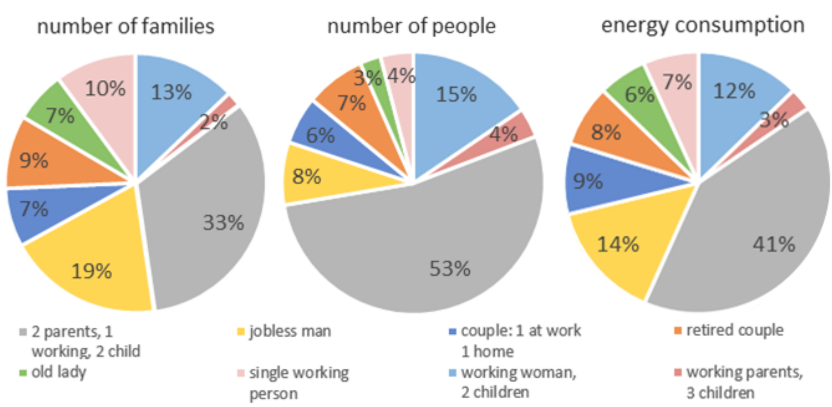


Figure 50: population and energy consumption make-up of the case study by type of family. The picture is taken from [150]

Table 6: list of techno-economic input used in the optimization.

Input:	value	
Efficiency of the modules in the PV system [%]	16.5	
Performance ratio of modules at STC [12] [%]	85	
Time horizon for NPV [years]	25	
Cost of PV system [€/kWp]	1800	
Cost of electric storage [€/kWh]	250	908
Private electricity cost [€/kWh]	0.2	
Revenues for energy sale [€/kWh]	0	
Input:	min	max
Growth of the power demand [%/year]	0	2
Growth of the price of electricity [%/year]	-2	2
Discount rate [%]	0	4
Costs for maintenance (including inverter change) [€/kWp year]	18	36
Degradation efficiency losses [%/year]	0.5	1
Battery installed [kWh]	0	87

affects the result of the optimization. Fig. 51 shows that in this example the curve from the standard suggests a lower electric demand (-26.7%), this would lead the optimization algorithm to choose a smaller capacity compared to the actual optimal one. The standard curve does not possess a seasonal variability, this feature is surely uncommon in real demand curves as the electric consumption for the lights is likely to have more intensity during the winter months. This aspect might praise excessively the annual cumulative irradiation over the irradiation in winter, advantaging the modules with a low tilt (e.g. those integrated in the roof) over the ones with a high tilt (e.g. those integrated in the facade). Looking at the demand curves along the day is possible to compare the average value of the realistic curve with those of the standard one (in the standard curve every day is the same, therefore the values are not averages but are the actual ones). It is visible how the realistic curve is more constant along the day (the reduction of the demand during the central hours of the day is lower) and both the demand peaks are shifted toward the central hours. In terms of effect on the optimization, the shape of the realistic curve turns out to be way more advantageous for PV: a strongly reduced demand during the central hours of the day (when the solar irradiation is higher) makes it easy for a large system to over-produce electricity sending part of it to the grid and thus reducing the potential savings in terms of energy. A demand curve with a strong reduction of the power during the central hours of the day would push the algorithm

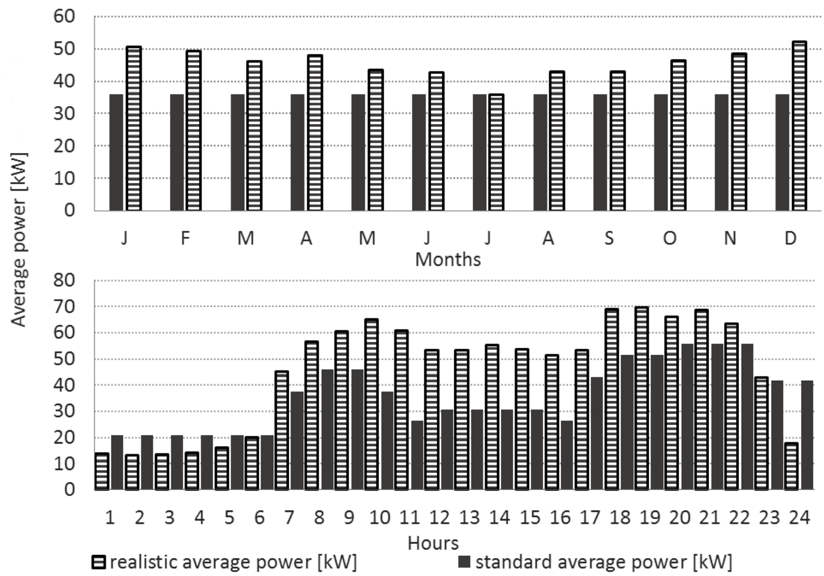


Figure 51: Comparison of the standard curve and of the realistic one along the month of the year and of the hour of the day. The picture reports the content of Fig. 5 and 6 of [150]

into choosing a smaller system, but also to install a larger part of the system in unconventional positions in order to get more energy in the early morning and in the late afternoon. Both these two effect would tend to disappear when the battery price is set very low (more battery capacity is installed). The optimization can bring diverse results because it is affected by the demand curve, by the fitness function and by the prices of the components. Table 7 collects the results in terms of capacity and of percentage installed in the southern façade for the two demand curves and the two fitness function. As expected from the analysis of the demand curve, the realistic load curve yields a higher capacity result compared to the standard one. The difference in result due to the shape of the curve is remarkable: being only 26.7% higher in terms of cumulative energy, the realistic demand produces a system that is more than 63% larger both with NPV and Max, Self-Sufficiency at prescribed payback time (i.e. at prescribed IRR). The relative stability of the realistic curve along the central hours of the day (i.e. a lower reduction of the daytime electric demand) allows the optimization algorithm to install a larger capacity without being forced to inject huge shares of the energy produced into the grid for little value. It is important to notice how the gain in capacity due to the load curve shrinks from 63% to 55% with the installation of larger batteries (see IRR row of Table 8). This effect is due to the mitigation effect, provided by the battery, of the strong drop

Table 7: optimal installed capacity for the two fitness functions. The table is taken from [150]

	East (%)	South (%)	West (%)	Total (kWp)
IRR (Batt. Cost 908 €/kWh)				
Standard load[151]	17	82	1	100
Realistic load	4	86	10	163
NPV (Batt. Cost 908 €/kWh)				
Standard load[151]	0	100	0	62
Realistic load	0	100	0	102
IRR (Batt. Cost 250 €/kWh)				
Standard load[151]	0	100	0	115
Realistic load	0	100	0	178

in intensity of the standard curve. Fig. 52 shows the change in optimized PV system from a maximum NPV fitness function to a maximum self-sufficiency at prescribed payback time, is visible that with both the load profiles the maximum self-sufficiency at prescribed payback time fitness function leads to a higher installed capacity. This is because the maximum NPV obtainable, if transformed to an IRR would lead to a higher rate than the 3.23. In this sense the fitness function based on IRR is less "greedy" then NPV and more "self-coverage oriented" (in fact it maximizes the energy self-consumed accepting lower earnings during the lifetime of the system, see description at Pag.33). The tendency of maximizing self-sufficiency in the IRR fitness function is also visible in the choice of PV modules in different facades: in Table 7 and Fig. 52 is possible to see how with both demand curves ca. 15% of the system is installed outside of the southern façade. It is interesting to notice how these east/west oriented parts of the plant are abandoned in favor of more irradiated southern portions when the electric storage get cheaper. An economic electric storage would allow to cover morning and evening demand peaks using electricity gathered during the central hours of the day. Table 8 and Table 9 show the system components capacities and the self-sufficiency (i.e. the coverage of electricity demand) for two different prices for the electric storage. In both the hypothesis, the max self-sufficiency fitness function causes a larger installation of batteries, although for the 908 €/kWh price the installed capacity is negligible. It is important to notice that the installation of batteries have a positive effect on the PV capacity installed (see also Fig. 53), for example the cost of battery equal to 250 €/kWh would cause a 9% and 15% increase in the IRR optimal PV capacity of the standard and the realistic pro-

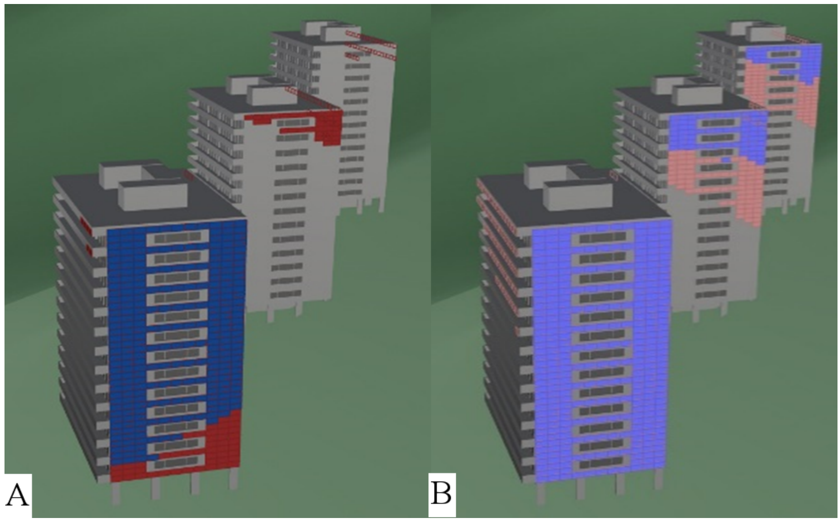


Figure 52: 3D representation of the optimal PV system for standard load (A) and realistic load (B). The modules in red represent those that are installed for a max. self-sufficiency but not for the maximum NPV fitness function. The picture is taken from [150]

Table 8: PV, battery capacity and performance for a 908 €/kWh battery. The table is taken from [150]

	PV capacity (kWp)	Battery capacity (kWh)	Self-sufficiency (%)
IRR			
Standard load[151]	100	0.5	20
Realistic load	163	0.4	26
NPV			
Standard load[151]	62	0	16
Realistic load	102	0	20

Table 9: PV, battery capacity and performance for a 250 €/kWh battery. The table is taken from [150]

	PV capacity (kWp)	Battery capacity (kWh)	Self-production (%)
IRR			
Standard load[151]	115	130	27
Realistic load	178	179	33
NPV			
Standard load[151]	65	6	16
Realistic load	107	16	21

Table 10: variation of KPIs from a standard load optimized system to a realistic load optimized system in a realistic load economic simulation. The table is taken from [150]

	Optimized by standard	Optimized by realistic	Variation [%]
PV capacity [kWp]	62	102	-39
Self-production [%]	15	21	-29
NPV (25 years) [€]	42995	65193	-34

file respectively. A larger improvement for the standard load profile is not a surprise as the shape of this curve is less favorable for PV and can therefore benefit more by the installation of batteries. In case of new construction or in case there is not the time to measure the electric demand of the building, a designer would rely on a standard demand curve to proceed in the optimization of the BIPV system. In this study we cannot estimate the average error made by the use of these demand curves as we do not have a large set of examples out of which extrapolate general conclusions. Nevertheless is possible to evaluate what type of economic and energy loss would have happened in this specific case had the designer chosen to apply the standard demand. Table 4 shows the variation in KPIs caused by the use of a standard load if the realistic load happens. In other words a perfectly predictive optimization case is compared with the optimization case based on the standard curve available today.

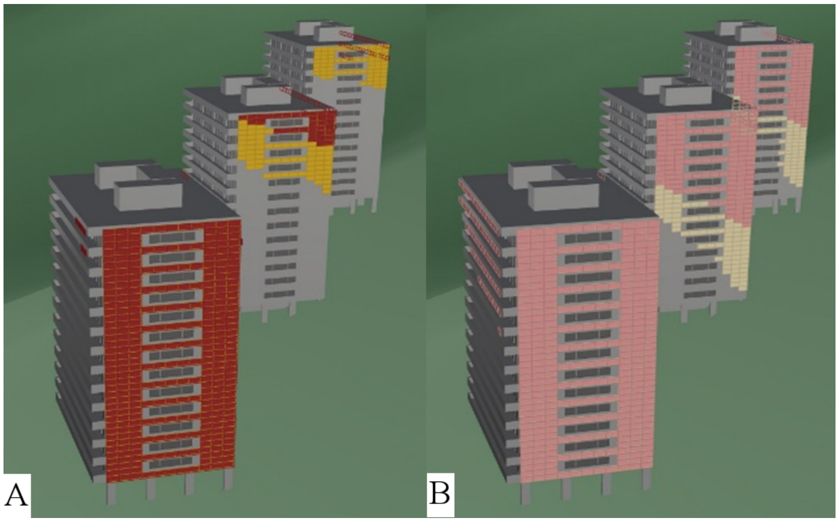


Figure 53: 3D representation of the increase of PV installation due to drop in electric storage price. The optimal system are represented for the standard curve on the left (A), and for the realistic one on the right (B). The picture is taken from [150]

5.6 Impact of a growing penetration of EVs on the KPI of the system:

This section is based on an excerpt from the paper [152] where the tool described in this thesis is applied on a group of three residential multi-family houses in Sweden. This demo site was built in 1970/1973, it is comprised of 48 apartments over three floors, most of the apartments have one or two bedrooms. The total façade surface gross area of the complex is 2146 m^2, the total roof surface gross area is 1750 m^2, and the total heated area is 3861 m^2. The energy consumption of the cluster is 165 kWh/(m^2 year), including operational electricity but not including electricity used in the flats for appliances and lighting. These buildings will be improved by a series of renovation plans including installation of PV, thermal energy storage, DC micro grid, EVs and heat pump systems [152]. The EV load is generated by using the Grahn-Munkhammar model [153]. It simulates the EV home-charging based on standard settings of 0.2 kWh/km electricity use (including losses) and 24 kWh battery capacity available for trips, and a total distance driven per year of about 12,200 km as a Swedish average scenario. The model adopted considers the EV battery charging process as related to household activities (i.e. away, sleeping, etc.). For example, the EV owners usually charge the EVs after returning home from work, and thus charging process is usually activated in this period. The household activities are first computed by a discrete Markov-chain model, then the usage of EVs

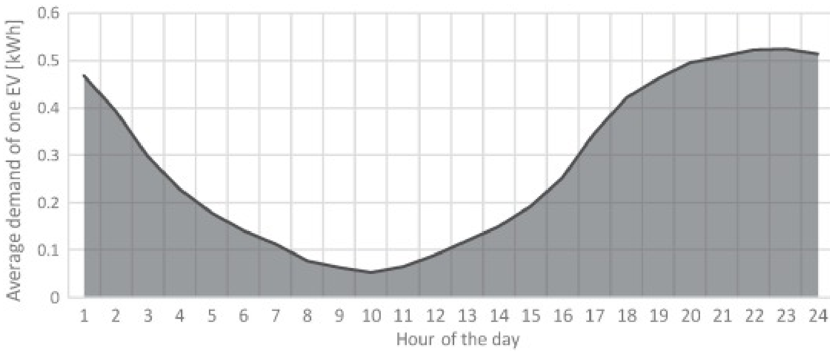


Figure 54: Average EV charging load in one day. The picture is taken from [152]

and the charging load profiles are calculated according to the obtained household activities. The state of charge ($SOC_{i+1,j}$) of the j^{th} EV battery in the $(i + 1)^{th}$ time interval is calculated by Equation 11.

$$SOC_{i+1,j} = \begin{cases} SOC_{i,j} - \gamma(v, C_{S,i})\Delta t, & if consuming \\ SOC_{i,j} + CP\Delta t, & if charging \\ SOC_{i,j}, & else \end{cases} \tag{11}$$

When the EV is being used, the electricity consumption is calculated based on the EV velocity (**v**) and the season (represented by a seasonal coefficient $\mathbf{C}_{\mathbf{S,i}}$ which changes along the season and the hour of the day). When the EV is being charged, the SOC of the battery will increase at a constant charging rate (i.e. 2 kW used in this study). Δt is the time step for calculating the EV battery SOC. To prolong the service life of battery, full charging/discharging cycles should be avoided when using it, and thus the batteries in the EVs are subject to a maximum DOD as well as a CL in accordance to the home electric storage system (see the section about the behaviour of the electric storage from Pag.44). Fig. 54 shows the hourly EV charging load in a typical day. The charging load is small during daytime and reaches the minimum during 9:00 11:00, while it reaches the maximum at night during 22:00 24:00. Note that in peak demand time (i.e. between 22:00 and 24:00) the EV demand is still lower than the charging power of the EV plug (i.e. 2 kW), this is due to the fact that the EV are not always charging contemporaneously. The optimization was performed in this case on a building owned by the company LudvikaHem AB Bobutiken which provided the set of input used in the optimization and reported in the following table (table 11). Fig. 55 represents the variation of electric demand due to the EVs on an annual basis and for the average day. The EV charging load is not much affected by the season in terms of cumulative demand, shown in Fig. 55 (a). This is because of two reasons: (1) the low operation temperature

Table 11: list of techno-economic input used in the optimization.The table is taken from [152]

Input :	value	
Module efficiency	17.4%	
Performance ratio of the system at STC	80%	
Price of electricity sold to the grid [€]	0.05	
Price of electricity bought from the grid [€]	0.16	
Time horizon [years]	15	
Cost of the finished PV system [€/kWp]	1420	
Cost of the storage system [€/kWh]	670	
Input :	min	max
Costs for maintenance (excluding inverter change) [€/kWp year]	0	15
Linear annual growth of the electrical load	0	2
Linear annual efficiency losses	0.5	1
Annual discount rate	0	2
Linear annual growth of bought electricity	0	3
Linear annual growth of sold electricity	-1	0

in winter will reduce the battery capacity, which can lead to reduced ranges. However, by increasing the charging frequency (i.e. how often the battery is charged) or the average depth of discharge, the overall cumulative charging loads (which can be considered approximately proportional to the product of ranges and charging frequency) are still likely to be stable [152]. (2) For the EVs used in cold regions, large amount of electricity is needed for heating the interior of the car, leading to reduced available amount of battery-stored electricity for EV motion. However, in Sweden such amount of electricity is partly provided by the buildings (i.e. the heating process occurs in the car park before the EV usage), and the battery in the car does not need to supply heat to heat up the car before a journey. Since most of the electricity stored in the EV battery is still used for motion in winter seasons, the EV ranges will not be greatly reduced because of the increasing heating needs in Sweden. Please also note that even with assumptions that lead to a significant amount of heating by the car battery (greater winter EV charge demand), the results of the study would not change as this increased demand occurs only during the months with very little PV production, and when all PV can be used for other loads [152].In annual cumulative terms, each EV absorbs little over 1MWh so that the aggregated demand of 23 EVs requires an amount of energy that is almost equal to 30% of the baseload. In the hourly average load over the year, displayed in Fig. 55 (b), it is

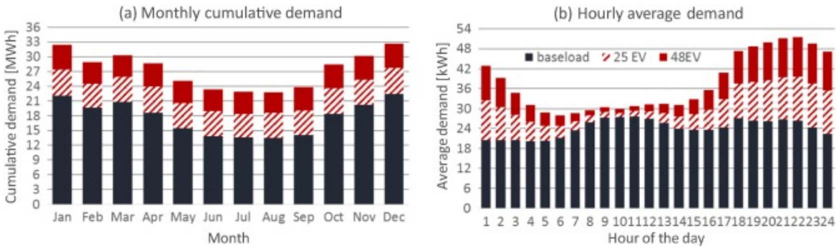


Figure 55: Variation of building electric demand with EV demand considered (a) on annual basis and (b) in the average day (i.e. hourly average values over the year). The demand is considered at two levels of penetration of EVs (i.e. 24 and 48 EVs which are equal to 1 EV every two households or one for each respectively). The picture is taken from [152]

visible that the EVs are adding their demand mostly at night, and the additional load thins out during the daytime (especially during the late morning). In general, the annual behaviour of the EV demand can be considered advantageous for the PV installation, because the PV produces proportionally more during the summer months when the rest of the load demand is the least. Nevertheless, the prevalence of the load at night risk to render the PV less useful unless electric storage is installed. On the other hand, an electric storage is extremely unlikely to be profitable as there is probably no over-production of PV electricity during the winter months (thus forcing the storage to have idle time and therefore reducing its profitability). PV optimization gives different results with the impact of variations of EV as shown in Fig. 56 and table 12. The southern portion of the roof is the first one to be occupied by the PV system because it is the most irradiated part. With increasing presence of EVs, it is visible how the PV system grows in size. Despite having slightly higher irradiation compared to the façades, the east and west portions of the roof are not entirely utilized for the application of PV by the algorithm, the southern façades are used instead. The reason for this noticeable behaviour lies probably in it having a better performance during winter months, when the sun angles are closer to the horizontal and the electric demand is more prominent, the façade integration results therefore to be more profitable, thus prioritized by the algorithm. Table 12 shows various KPIs at the three levels of EV presence. Despite a noticeable growth in the installed capacity, the larger growth of the demand forces the share of PV electricity to go down. There is a slight increase in self-consumption (not surprising considering that the whole system shifts towards larger load and larger capacity), thus a small reduction in the LCOE of the self-consumed electricity. The results from this study are consistent with other similar analysis in Sweden. For instance, in [154] under different scenarios of PV capacities and EV penetrations,

Table 12: Various KPIs at the three levels of EV presence. The table is reported from [152]

KPI	2 EV	25 EV	48 EV
Installed capacity [kWp]	79.2	88.3	96
Installed storage capacity [kWh]	0.4	0.2	0.1
Expected self-consumed-LCOE [€cent/kWh]	17.7	17.7	17.6
Self-consumption [%]	79.4	80.3	80.9
Self-sufficiency [%]	25.1	21.8	19.8
Annual cumulative demand [MWh]	213	274	330

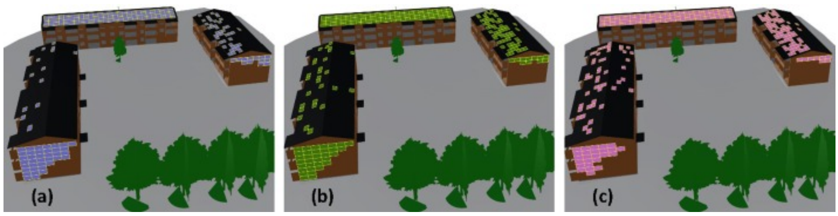


Figure 56: PV visualization with impact of variation of EV (a) two EV case; (b) 25 EV case; (3) 48 EV cases. The picture is taken from [152]

the self-sufficiency values vary within 20% 30%, which is close to the values calculated in this study [152].

5.7 The benefit of energy sharing:

This section reports the results and the relative descriptions shown in [155], it deals with the advantage given by the possibility to aggregate both electric demand and areas available for the PV system, it also lay the grounds for a future research on the business models for the shared Photo-Voltaic systems. The use of urban photovoltaic systems for the generation of on-site electricity in residential application was known primarily for single households in the past. Today a proliferation of emerging technologies in disparate fields of research and industry promise to shift urban photo-voltaics from single pro-sumers to integrated prosumer communities. These comprise, mini grids, smart meters, district scale storage and block-chain markets which are gaining significant momentum. This section shows the quantitative advantage of a shared vs. a solitary cost-optimal system in terms of installed capacity, economic benefit, self-sufficiency rate and LCOE (Levelized Cost of Electricity). The study has been conducted on 16 single family houses characterized by their geometry and their hourly electricity demands, a techno-economic optimization of capacity and positions of photovoltaic system and capacity of storage was performed with two different reward functions: to maximize the NPV (Net Present Value) and minimize LCOE while guaranteeing 27% of self-sufficiency. The same optimization procedure was performed on each home separately and on different sets of homes aggregated, the comparison of the results is shown and discussed. The electrical demand curve of a single household is often characterized by a strong variability between baseload and peak consumption, in some instances the baseload is actually 0. This makes the use of PV electricity very difficult as it forces the system to shove all its power down the grid while the peaks in electric demand remain almost unaffected. The results of dimensioning an urban PV system with a techno-economic optimization algorithm based on self-consumption are strongly impacted by the shape (and obviously the sheer size) of the electrical demand. The following example shows how self-sufficiency can be improved by the aggregation of diverse households. Furthermore it advocates the use of electricity sharing technology as a complement to the electric storage for solving the contemporaneity issues connected with large penetration of PV electricity. In [152],[87], and [156] the authors showed how BIPV (Building Integrated Photo Voltaic) systems could be dimensioned and positioned over the envelope of a building or district using optimization techniques. Recently, similar techniques have been independently used by diverse studies such as [66], [157] and [67], suggesting that consensus is growing over the need for such a workflow in the urban PV planning practice. The results of the optimization in numerous residential case studies shows that a PV penetration above 20% of the cumulative electricity demand is commonly achieved. This share is way beyond the country with the largest penetration of PV in the world (i.e. Honduras at 12.5% [158]),yet is notably below the typical 3 kWp installation of a single family household (which is quite common in Italy) system (in this paper an average of < 1kWp per household achieves 20%). The reason for this apparent paradox lies in the fact that, though the houses with PV installation have 3 times what is needed or more, the houses that do have any PV are still less than 1/3. Is the electricity community the next step? Can owning a small share of a medium sized PV plant increase the use of overall urban PV while generating profit?

inputs: The electric demand used for the optimization consists of a sub-sample of energy consumption readings for a set of London Households that took part in the UK Power Networks led Low Carbon London project between November 2011 and February 2014 available at [159]. This database was chosen because is freely available online and it contains a large number of measured electric demands for household appli-

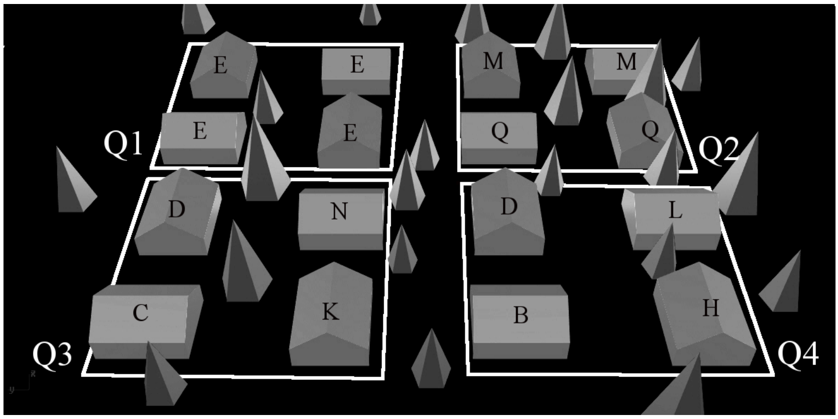


Figure 57: 3D geometry of the group of 16 homes divided by ACORN classification: the houses are divided in 4 quarters(Q1,Q2,Q3,Q4),The whole block contains a well assorted socio-economic layout comprising the ACORN groups B, C, D, E, H, K, L, M, N and Q (see explanation below).

ances. The household demands are classified according to the ACORN consumer classification [160]. The whole group of 16 houses contains a well assorted socio-economic layout comprising the ACORN groups B, C, D, E, H, K, L, M, N and Q. The quarters (groups of 4 houses, see Fig. 57) have been chosen in a way to form two well assorted quarters (q3 ”C,D,K,N” and q4 ”D,H,L,Q”) and two socio-economically homogeneous ones (q1 “E” and q2 ”N,Q”).

- **B,C** affluent achievers
- **D,E** rising prosperity
- **H** comfortable communities
- **K,L,M,N** financially stretched
- **Q** urban adversity

Fig. 57 shows the 3D representation of the group of houses under study, the hourly irradiation was simulated over the roof of the houses. The results determined that,in terms of irradiation, the impact of the trees is minimal but there is a very strong difference in pattern between the North-South and the East-West oriented roofs. The irradiation was calculated from numerous measuring points using the reverse ray-tracing software RADIANCE [94](see section about calculation of irradiation at Pag. 43). The weather file, from which the hourly series of irradiation and temperature are taken, was downloaded from the database METEONORM [71] and refers to the measured data of a weather station located in London (51.517,-0.117). The following table (Table 13)

Table 13: list of techno-economic input used in the optimization.

Input:	**value**	
Efficiency of the modules in the PV system [%]	18	
Performance ratio of modules at STC [12] [%]	80	
Time horizon for NPV [years]	30	
Cost of PV system [€/kWp]	1200	
Cost of electric storage [€/kWh]	670	
Private electricity cost [€/kWh]	0.2	
Revenues for energy sale [€/kWh]	0	
Input:	**min**	**max**
Growth of the power demand [%/year]	0	2
Growth of the price of electricity [%/year]	-2	2
Discount rate [%]	0	4
Costs for maintenance (excluding inverter change) [€/kWp year]	0	15
Degradation efficiency losses [%/year]	0.5	1

contains all the techno-economic inputs used for the PV system optimization. The unitary cost of the inverter has been assumed equal to 350 €/kWp of system and must be substituted every 10 years, this cost is added to the maintenance costs reported in the table.

results and discussion: The optimization procedure was repeated using two different fitness functions: in the first round the NPV was maximized (see fitness function at page 30) while in the second one the LCOE was minimized while guaranteeing 27% electricity from PV (see fitness function at page 34) as mandated by the original target of the 2030 climate and energy framework of the European commission for renewable energies. As seen in the relative section (Pag. 30)and in previous examples, the first reward function is designed maximize the economic benefit that can be extracted by a PV system in the whole district, the installation and maintenance costs of the system are proportional to the capacity of its components (i.e. PV system and electric storage) as shown in Equation 1, while the economic benefit is due only to the self-consumed quota of the electricity (the revenues are set to 0 as shown in Table 13). In terms of economic yield (€saved/ €invested) a very small system is the optimum as its productivity never exceed the demand of the building/district ensuring that no electricity is wasted or given for free to the grid, nevertheless the impact of such a system on the whole energy consumption is negligible, hence its NPV is much lower than the highest obtainable. For this reason a “healthy” level of over-production

Figure 58: average PV capacity per house without energy sharing capability, or with sharing capability within varying level of aggregation. No electric storage was installed at this price tag with the first fitness function

is required by an NPV optimal system. Fig. 58 shows the average PV capacity installed for every house in the district. If each single house installs the optimal capacity for its own consumption without the possibility of sharing electricity there is a tolerably large variability among the different houses (as shown by the round individual dots in Fig. 58). This result is not surprising as the load profiles are diverse themselves both in shape and size as a result of diverse number of family members, different behaviours, customs and socio-economic situation. It is visible how the optimal capacity has, on average and therefore in absolute numbers, a huge increase when the electricity sharing is taken into account: the ability to share electricity among four neighbours would increase the optimal capacity of a whopping +118%, on top of this the ability to share the electricity among 16 would provide an additional +3.3%. Figure 3 also shows that the variability in optimal capacity is greatly reduced from single houses to groups of four: this suggests that while the design of a single family system is highly subject to stochastic features of the electric demand, the design of a system for four households could be predictable and therefore be determined with higher confidence. Fig. 57 shows how the houses are arranged according to two possible alignments(i.e North-South or West-East). Not only the capacity of the sum of the PV systems has increased, but the positions where the different PV modules have been positioned are changed as well. It is interesting to notice how the algorithm, if given the possibility, preferentially uses the south slope of the roof, this is done in order to maximize the yield [kWh/kWp]. If the houses are optimized singularly the east and west sides of the roof should be used because some houses only have those alignments available. In the optimization that act over a group of houses (i.e. 4 or 16 houses)in fact the East-West orientations are selectively excluded from the installation of PV modules. The reason appears to be that the relatively low yield of the PV system, derived from high latitude,

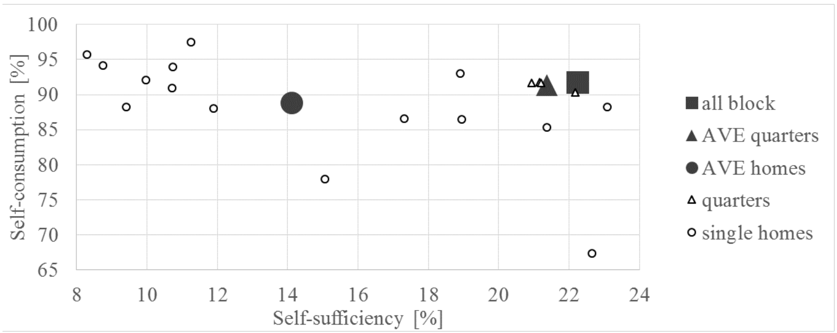


Figure 59: self-consumption V.S. self-sufficiency at varying level of aggregation.

forces the algorithm to fall back on a very high self-consumption ratio (see Fig. 59) as it cannot afford to lose precious electricity to the grid. The high self-consumption ratio means that the overall system is small enough that there is not much over-production, hence not much premium in an East-West orientation for a better matching. Fig. 59 shows the performance in terms of self-consumption and self-sufficiency: as in Fig. 58 it is shown how the KPI varies wildly among the single households while they become far more constant in the case of electricity sharing. In practice, the shape and size of the electric demand is strongly determinant of the PV performances in an optimized single household, while the aggregation of at least 4 households guarantees a more predictable level of optimal performance. This feature is interesting for the potential it has in the simplification of the design process (e.g. in case a "universal" aggregated household demand is found which only depends on the annual cumulative consumption). Fig. 59 also shows that both self-consumption and self-sufficiency can simultaneously improve amid growing aggregation: while self-consumption only shows a modest growth (the baseline disaggregated is already kept pretty high), the self-sufficiency manifests a powerful increase + 51% from single to shared among 4 and an additional 4.2% from 4 to 16. This result is not surprising as a similar level of self-consmption and a larger optimal capacity are consistent with an increase in the energy consumed on-site, which is in turn consequence of a better sourcing of the consumer for the electricity produced. Last but certainly not least: Table 14 shows the sum of individual NPVs against the aggregated and the global one with percentage variation. With the other reward function (see Pag. 34), contrary to the previous one, a mandatory level of performance is required for a solution to be considered. The equations in the section about the LCOE minimization at page 34 in the section about the optimization algorithm shows how the fitness function is heavily penalized whenever

Table 14: cumulative NPV of the whole district and its variation amid different levels of aggregation.

	Sum houses	Sum quarters	whole district
NPV [€]	3636	13170	14143
variation[%]		262.2	7.4

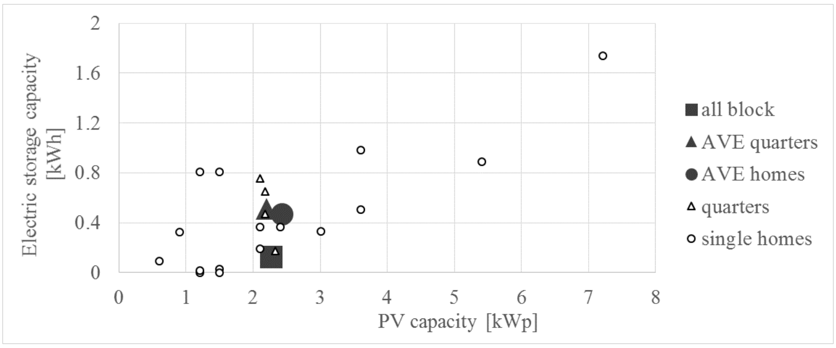


Figure 60: PV and electric storage capacities at different levels of aggregation.

the condition of 27% self-sufficiency is not met. The mandatory self-sufficiency turns the KPI of installed capacity on its head: while a larger capacity was an advantage in obtaining a higher NPV, here the highest fitness function is obtained with a smaller capacity, as it takes a higher effectiveness in guaranteeing the same requirement while using a leaner system. The average capacity per house stays relatively the same amid aggregation of the load suggesting that it is not feasible to reach such result with a smaller PV system, the average per house electric storage capacity instead drops sensibly (from a total of 7.4 kWh, 0.46 per house, in the single houses to less than 2 kWh, 0.12 per house, in the whole district)(see Fig. 60). Fig. 60 also shows that the relative capacities of PV and storage system follow a non-linear path along the process of aggregation of more households, the quarters show in fact a bit of storage more than the single houses and a bit of PV less than the whole district. Despite the seemingly confuse variation of PV and storage capacity at increasing aggregation level(see Fig. 60), Fig. 61 demonstrates how both LCOE and LCOEself are consistently decreasing over an increase in the level of aggregation. This shows the clear impact of the possibility of sharing in the economic performance of the PV system in the district. As in the previous reward function, also here the results show a lower dispersion at increasing aggregation, nevertheless the quarters show a certain scattering along the capacity of storage (see Fig. 60) that is then reflected in the asymmetric dispersion of LCOEself

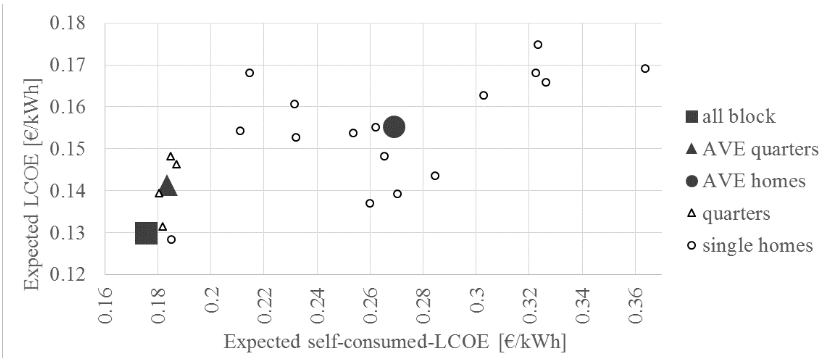


Figure 61: LCOEself and LCOE at different levels of aggregation.

against LCOE in Fig. 61. The storage capacity in fact does not produce any electricity, hence its presence has a huge and negative impact on the LCOE while not necessarily impacting the LCOEself(for which the storage boost both the cost and the cumulative energy produced). The result have shown that a system which covers more than 27% of the electric demand of a single house is slightly too expensive for the benefit it generates, the initial cost of the system and the final losses in the NPV are in fact almost linearly correlated. Conversely, when the load is aggregated, the system achieves economic sustainability: an aggregation of 4 household is sufficient, in fact very little improvement is achieved with an aggregation of 16 households compared to it. Despite the differences shown in Fig. 60 in the proportion between PV and storage capacity, both cost and NPV of the quarter's system turn out to be similar.

6 Sensitivity analysis and impact of input values

In this section the relation between the different value of inputs and the output of the optimisation is explored. In this way the inputs that have a major impact on the result of the optimisation can be understood and their value determined with the most effort. Observing the charts included in this section a designer who used this methodology can understand in general terms the level of accuracy of the results provided. The sensitivity analyses is based on an optimization performed on a baseline case which is then repeated changing different inputs one by one, in this way the individual share of impact by every different input can be evaluated separately. The error can be caused by a wrong input from the designer but also by an inherent inaccuracy of the software. For example the turn-key PV system can be considered cheaper or more expensive because of an error in the price forecast, while the overall performance ratio of the system can be underestimated or overestimated

Table 15: list of techno-economic input used in the baseline case.

Input:	**value**	
Efficiency of the modules in the PV system [%]	16.5	
Performance ratio of modules at STC [12] [%]	80	
Time horizon for NPV [years]	30	
Cost of PV system [€/kWp]	1500	
Cost of electric storage [€/kWh]	670	
Private electricity cost [€/kWh]	0.2	
Revenues for energy sale [€/kWh]	0	
Input:	**min**	**max**
Growth of the power demand [%/year]	-1	2
Growth of the price of electricity [%/year]	-2	2
Discount rate [%]	2.8	3.8
Costs for maintenance (excluding inverter change) [€/kWp year]	0	30
Degradation efficiency losses [%/year]	0.5	1

because of a precision error embedded in the calculation (which is a simplified one as explained in the relative section at Pag.40). The set of input used for the baseline case are reported in table 15, to generate different cases each input is increased or decreased by 20% of its baseline value. The sensitivity analysis is repeated for a maximization of the NPV (see Pag.30) and for a maximization of the self-sufficiency over the life-time of the system (see Pag.33), in case of self-sufficiency maximization the lifetime is considered 20 years instead of 30. As no major differences in the sensitivity results have been noticed, for the sake of brevity and clearness, only the results of maximization of NPV are reported. For the optimization, the number of inhabitants is considered zero, but this does not mean that that building is empty, instead a standard residential curve was used in every iteration of the process without generating it with the stochastic noise by the Gamma distribution function (explained at Pag. 54). Contrary to the section "Current BIPV profitability", starting at Pag. 61, where the objective was to assess generally the profitability of bipv in a variety of situations, in this section only the condominium type of residential building was used and the whether file used was that of the city of Trento. A change in weather patterns over a long period of time or a change of the electric demand in the building are not addressed in this session. These issues involve other different scientific disciplines and, despite being of the uttermost importance, they have not been tackled within this doctoral thesis. The study of the impact of the future variation in weather or in consumption pattern within

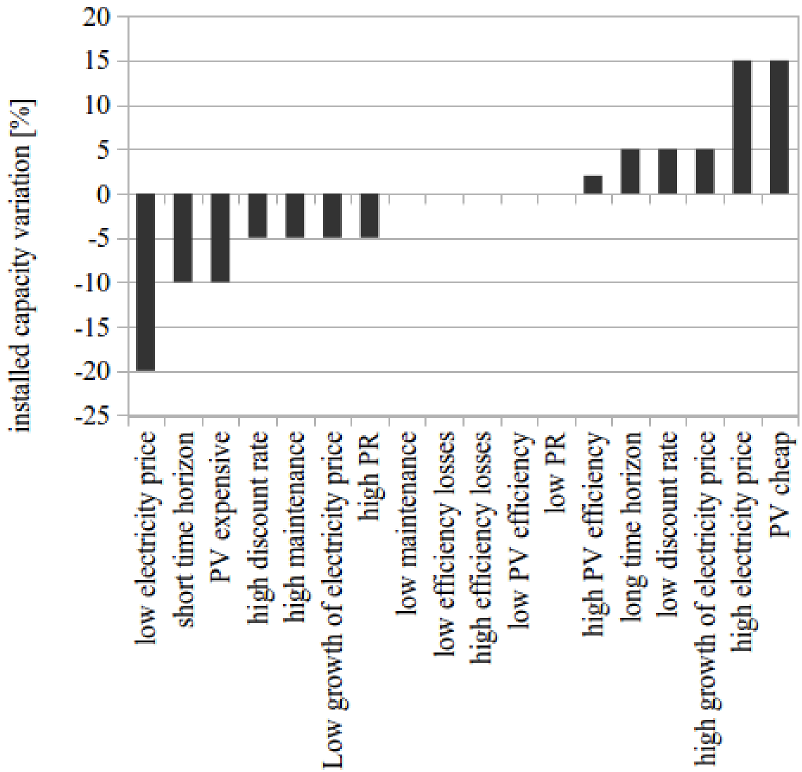


Figure 62: sensitivity of the optimal capacity to the variation of + or - 20% of the baseline value for a set of inputs.

future residential buildings is strongly recommended as future area of research. As the primary scope of the method and tool discussed in this thesis is that of determining capacity and positions of the PV modules over the envelope of the building, and considering that in this specific example all the modules are positioned over the roof surface, the main output of the optimization is that of suggesting the capacity of PV to be installed. Fig.62 shows the impact, in terms of percentage of variation of the optimal capacity for a maximum NPV system, of a variation of plus or minus 20% in the values reported over the "x" axis. The variation that affect the optimal capacity the most (in absolute terms) is a low price for the electricity by the consumer: in fact a reduction from 20 to 16 €cents per kWh would cause a reduction of 20% in the optimal capacity installed, Conversely an increase of 20% of the electricity price for the consumer, albeit slightly less effective, would still cause an increase of 15% in the optimal capacity. This result suggests not only that the price of the electricity should be estimated carefully (as every% point in error would almost cause a % point of over/under-estimation in the optimal capacity), but also that major variation of the price of the electricity (i.e. more than 10%) in the future are a major concern for the investment in photovoltaic technology. For the mitigation of this phenomena the long-term forecast of the price of electricity at local and global scale should be investigated if and as much as possible, furthermore the impact and capacity of modification of the system during its lifetime should be considered. In the section "Effect of the electric storage on the optimal PV system" at Pag. 90 is shown how a reduction of the price of electric storage (with consequent increase of the optimal storage capacity), has a positive impact on the optimal PV capacity: for this reason the later addition of electric storage systems could possibly be a mitigation strategy for an over-sized PV system in case of electricity price drop. In the case of a future sharp rise in the electricity price, the addition of new PV array should be considered, for this reason research is needed to guarantee the flexibility of BIPV systems both in terms of technological and electrical integration. A very strong effect, albeit smaller, is induced by the turn-key cost of the PV system: a variation of 20% of the initial value of 1500 €/kWp to either 1200 or 1800 €/kWp can generate a fluctuation in the order of (-10%,+15%). Another quite significant role is played by the time horizon for the investment where a variation of 20% (i.e. 6 years) caused a variation of (-10%,+5%) in optimal capacity. Fig.62 shows that not only the price of electricity itself, but also its growth over time can have a noticeable impact (+ or - 5%)on the final optimal capacity of the system. The regular interval of price variation (which is a stochastic input, see input section at Pag. 30) is comprised between -2 and 2 (see Table 15), it has therefore neutral effect in terms of effect on the optimal capacity but it is considered to affect the uncertainty of the result (see Fig.44 at Pag. 85 for example). When a variation of 20% is applied, the interval can shift to[-1.6,2.4] or to[-2.4,1.6] causing an increase or decrease in the optimal capacity. A variation of 20% of the initial 2% each year (which is to say 0.4% per year)would lead to an overall growth or shrink equal to the 12% of the initial price, the gradual variation of the price and the effects due to the discount rate are such that the optimal capacity receives a variation of 5% as shown in Fig.62. A similar impact is represented by a variation of the annual discount rate (which is assumed as an interval centered around 3.3% as forecasted as real world growth rate by the IMF [143]), the variation of the discount rate in the baseline is assumed + or - 0.5% forming an interval of [2.8%,3.8%]. The central value of 3.3 is increased or decreased of 20% to reach either [2.14%,3.14%] or [3.46%,4.46%], also in this case the variation has a compound effect over time and leads to a noticeable variation in optimal capacity (i.e. + or - 5%). The PR of the system has a counter-intuitive effect, in fact a high PR (i.e. 96% instead of the initial 80%) reduces the optimal capacity of the system.

This effect is due to the fact that a highly performing system causes many hours of over-production over the year so to overwhelm the positive effect of increased self-sufficiency (see Fig.65). If the estimation of the PR is too low (64% in this case) no effect on the optimal capacity has been shown in the optimization process, this is a great news because it shows that a simplified calculation method such as the one described in this thesis (see Pag. 4.2) can be trusted in determining the optimal PV capacity as long as the PR values are kept on the conservative side. Similarly to the PR, the maintenance costs have an a-simmetric effect on the optimal capacity if they are under or over-estimated: in the baseline case the typical maintenance costs (which do not include the costs due to substitution of inverters and electric storages if present) are assumed between 0 and 30 [€/kWp year] (which is to say 25, to 55 €/kWp year including the costs for the inverter change), the variation of 20% is applyed to the half-interval (i.e. 15 [€kWp year]) centering it around either 12 or 18, thus [-3,27] or [3,33]. If the maintenance costs are low the optimal capacity does not show variation compared to the baseline case, when the maintenance costs are 20% higher the optimal capacity is shown to be 5% lower. Little to no impact are found for PV efficiency and efficiency losses over time, these parameters obviously have impact over the NPV and the gross electricity production of the system. The PV efficiency might indeed have an impact in situations where the shading of PV modules constitutes a strong limit to the maximum dimension of a PV array such as the Town-House example in the profitability section (see Fig.25 at Pag.65 where the optimal capacity is the same both in Lyon and in Athens due to the limit imposed by shading despite the different level of irradiation). Another chiefly important output of the optimization is the NPV of the investment. looking at the Fig. 63 it can be noticed that the results are much more well graded compared to the previous figure (Fig. 62). in this chart the effect on the net present value are not directly caused by the variation in parameters: in fact, the effects on the NPV also take into account the factor played on the optimal capacity installed. In this sense, the previous chart influence this one because the solutions that have a larger capacity show an NPV that results from the techno-economic performance of a larger capacity. in terms of Net present value, the variable which affect the most the results is the electricity price: the effect, which is probably amplified by the variation in capacity seen in the previous chart, can generate an NPV variation of almost 60 per cent in both directions. Another aspect that has a huge impact on the NPV is the performance ratio of the system, this aspect, despite having low effect on the optimal capacity installed for the reason explained before, can contribute to almost 40 % on the final net present value of the investment. This is likely because the performance ratio changes the productivity of the system without changing the nom-

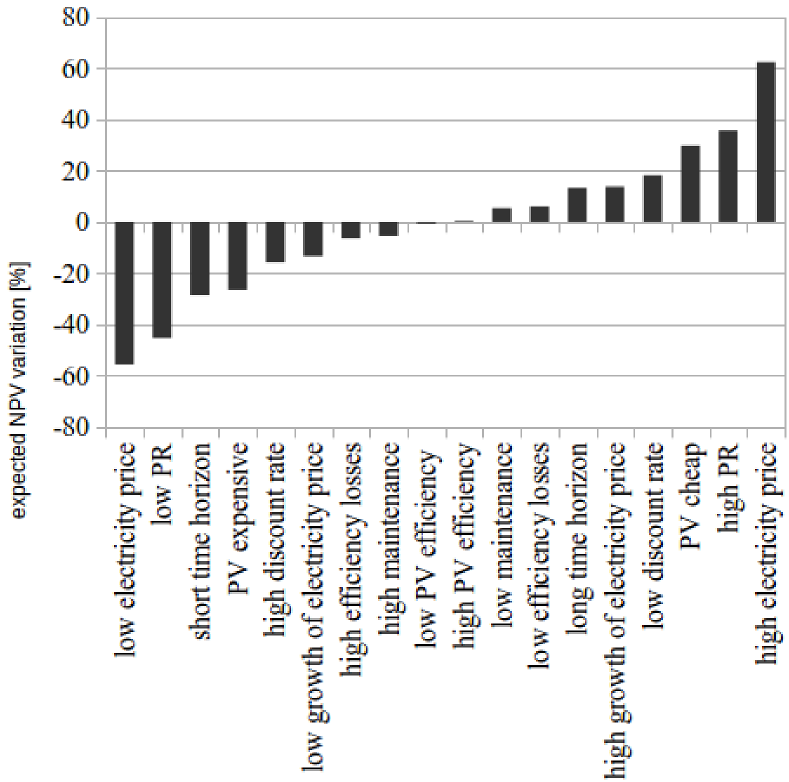


Figure 63: sensitivity of the maximum NPV to the variation of + or - 20% of the baseline value for a set of inputs.

inal capacity, which is the main factor ininfluencing investment price and maintenance costs. The time horizon shows to have a particularly a-symmetric effect: if a short time horizon is particularly penalizing for the NPV (i.e. more than 20 percent lost), a longer time horizon is not equally advantageous. Possibly the effects of the time horizon are such that earlier years of the investment, when the effects of degradation and the discount rate on the earnings are lower, can exert a major contribution compared to the ones from later on. Another contributing factor is that the inverter is changed after every ten years and therefore a longer time horizon creates one additional substitution of the inverter with a negative effect on the NPV. The initial investment cost of the turnkey system is also very important as input factor: aside the effect that it has on the optimal capacity, it also have an even larger effect on the net present value. The opposite is true for the discount rate that, while having a moderate impact on the optimal capacity, shows to have a variation of almost 20 % on the net present value in both directions. Surprisingly, a little growth of electricity price shows a much more moderate effect on the final NPV. The reason might be again that its effect are stronger in the later years of the investment when the discount rate and the degradation had a major effect on the techno-economic output of the system. Moderate but still noticeable effect is caused by the maintenance cost and the degradation of the system over time, while the efficiency of the system has an almost neutral effect. in terms of LCOE, the distinction should be made between the levelized cost of electricity produced and that of the electricity produced and self-consumed within the building (see the output section at Pag. 35 or the optimization session in the paragraph about the minimization of the LCOE at Pag.34). In the chart the performance values are ordered according to the LCOE: at first sight, it can be noticed how most of the value have little effect over the LCOE, while there is a small fraction of inputs that have a large impact. The elephant in the room for this KPI is played by the PR, which although being a little less effective than its own variation when high, can cause a significant increase when too low. The LCOE self consumed is generally a little less affected by the variation in PR compared to that of the electricity produced, the reason for this phenomena might lie in the increase in self consumption shown in case of lower performance ratio. Unsurprisingly, the cost of the PV system also here plays a really important role, and for the same self consumption reason the LCOE self consumed is less affected by the cost. It's quite curious to see how a short time horizon has the ability to grow significantly the LCOE and $\text{LCOE}_{\text{self}}$ while a longer time horizon does not create a comparable improvement to the situation. As was shown before by the NPV chart, the effects of degradation, maintenance costs and discount rate are counter balancing the positive effect of a longer time horizon. All the other in-

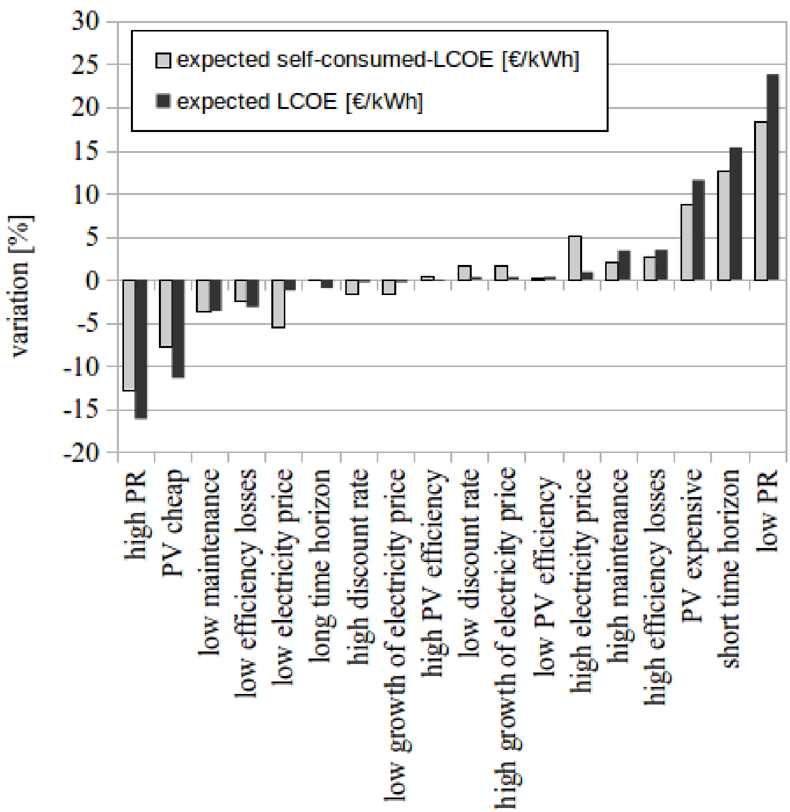


Figure 64: sensitivity of the minimum LCOE and $LCOE_{self}$ to the variation of + or - 20% of the baseline value for a set of inputs.

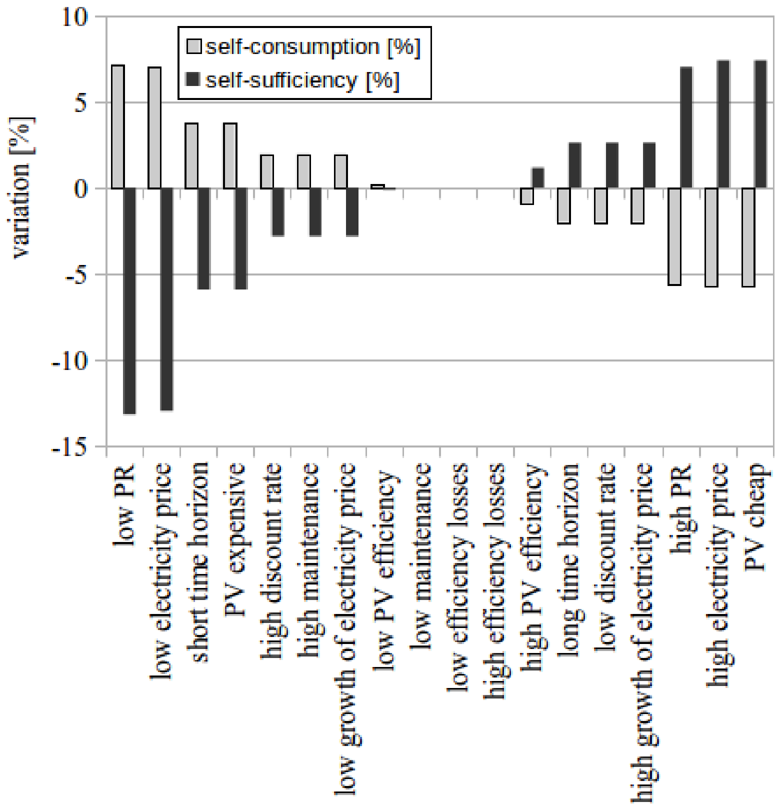


Figure 65: sensitivity of self-consumption and self-sufficiency to the variation of + or - 20% of the baseline value for a set of inputs.

puts considered have a rather negligible effect on the LCOE, although it should be noticed the relatively large impact of the electricity price on the $LCOE_{self}$. This is likely only caused by a smaller capacity installed with the consequential higher self consumption when the cost to electricity is low. Observing the effect of the inputs in self-consumption and self-sufficiency in Fig. 65 it is noticeable how the two key performance indicator are specular to each other in terms of sensitivity to the inputs. Avoiding the consideration of aspects related to load-matching using different facades of the building or use of electric storages (which are both absent from this optimization) a larger capacity necessarily mean a larger overproduction, therefore a smaller self-consumption, but also an increased self-sufficiency. In fact, while a larger capacity promotes more hours of overproduction during the year, it does not only create over production, but is also partially consumed on site increasing the self-sufficiency. Due to the large impact that the installed capacity has both on self-consumption and self-sufficiency these chart surely shares some commonalities with the previous one (Fig.62). The major difference, which is also an extremely prominent aspect, consists in the PR that, without affecting the capacity installed, has an extreme negative impact on the self-sufficiency. on the contrary a low electricity price, which causes a drop in self-sufficiency, is almost completely explained by the reduction in installed capacity. The same is true for the short time horizon, the initial cost of the system, the discounter rate, maintenance costs and the growth of the electricity price. Despite the negative impact on the installed capacity, an elevated PR has nevertheless a positive impact on the self-sufficiency. The riduction in self-consumption associated with increasing self-sufficiency is in fact the chief cause of the lower capacity installation associated with an high performance ratio. Specular to the values seen before, an high efficiency of the PV, a long time horizon, a low discount rate or high growth of the electricity price are almost entirely due to the higher capacity installation that these inputs promote. The efficiency losses does not show to have any impact, because they are measured at the first year after installation (differently from the LCOE which is averaged along the whole lifetime of the system).

Key takeaways from the sensitivity analysis: The optimization to maximise the NPV of the investment and that to maximize the self-sufficiency were performed on the condominium type of building (as in the three types shown in Fig.23 at Pag. 62) using the weather from the city of Trento (Italy). The optimization was then repeated changing the input parameters one at a time of an amount equal to 20% of their initial value. The result are reported for the maximum NPV only as no large difference were found compared to the maximum self-sufficiency, the KPI analized are the installed capacity (Fig.62 at Pag. 110), NPV (Fig. 63),LCOE (Fig. 64) and a comparison of self-consumption and self-sufficiency(Fig. 65). The main findings are reported as follows:

- The installed capacity is extremely sensible to the electricity price, a high price encourages a larger optimal capacity and vice-versa in case of a low price. There is a slight a-symmetry suggesting that further increases in the electricity price (e.g. +30%) would not be as effective, this is an expected phenomenon as the growing capacity spurs an excess of over-production that eventually prevents any further growth if no storage is installed. An even larger effect (+ or - 60%) is caused on the final NPV, this behaviour is in fact a result of the direct effect on the NPV itself and the indirect effect due to a larger/smaller capacity

- The growth of the electricity price is not as much effective as it represents 20% of an initial growth rate that is limited (see Table 15 at Pag.109). The efficacy of the current cost of electricity shows that large rises or drops in future costs will strongly affect the adequacy of the PV system.

- A slightly over-dimensioned system would be very effective in protecting a consumer from sudden rises in electricity price, it would also make the case for a later installation of electricity storage.

- The maintenance cost does not affect the capacity when low, but it reduces it when high, therefore it should be assessed carefully (at least in terms of its minimum / maximum interval).

- The discount rate is also shown to be quite effective in determining the ideal capacity (i.e. + or - 5 %). In this case, as for the growth of the electricity price, the result is affected by the initial baseline chosen (see Table 15), thus no accurate statement can be made about it. Unsurprisingly this parameter has a surprising impact on the final NPV (ca + or - 20 %).

- The P.R. of the system has been found to produce a counter-intuitive result, in fact a high P.R. encourages a lower optimal capacity. The result is likely due to the fact that a more efficient system, albeit increasing its profitability, increases the over-production occurrences by a larger margin rendering a larger system suboptimal. A low P.R. does not affect the optimal capacity, this is a good news for the accuracy of the capacity suggested as it can allow a simplified calculation to be reliable when applied on a conservative value. The effect of P.R. on the NPV is instead very high(second only to the electricity price), this is because it can boost the productivity of the system without altering the costs. For the same reason the P.R. show to have a large impact on the two LCOE values.

- The initial price of the PV system also has a huge impact, it is shown to be slightly a-symmetric in the sense that a cheap system gives a larger boost than the reduction caused by an expensive one. The reason for this is not clear, but most likely might lie in the relation between self-consumption and capacity of the system. In terms of NPV the initial investment cost has an impact of ca.(-25% +30%), in this case the a-symmetry is caused by the strong difference in capacity. In terms of LCOE the initial cost has a symmetric impact as costs and production are both linearly modified with the capacity. The $LCOE_{self}$ on the contrary shows a bias toward increasing as the low initial cost spurs a lower self-consumption.

- The lifespan of the system also shows to have a significant impact (from -10% to +5%), in this case the a-symmetry is mainly due to the increased cost for one additional inverter change for the longer lifespan. The inverter change also repeats the same a-symmetry in the expected NPV which is impacted in a similar way.

- The degradation rate does not show to have impact on the optimal capacity of PV to be installed but it certainly has an impact on the expected LCOE

- The LCOE presents two contradicting properties: for once it seems more prone to increase than decrease as a whole, this suggests that the set of values used as a default is in general a "lucky combination" and that changing one variable at a time likely results in an overall worsening of the situation. Conversely tough, circa half of the value examined have little to no impact on the KPI suggesting the realized LCOE as an attractor.

- SC show to mirror each other as a variation in capacity is invariably positively correlated with self-sufficiency and negatively correlated with self-consumption due to the lack of storage or PV on different facades.

7 Conclusions and knowledge derived from the experience

7.1 conclusions

Current economic and energetic BIPV profitability: The results shown in the sections simply and unequivocably tell that BIPV, under the conditions of cost,weather and electricity prices assumed, is profitable if installed in the correct capacities. The capacities obtained for the optimal NPV system, aside from being profitable over the lifetime of the system, are also quite modest when compared to building renovation costs. In a condominium for example, with a cost of less than 500 €per capita it would be possible to cut the electricity consumption by at least 20%. The weak spot of the self-consumption based business model appears to be the payback time: it is in fact always above 12 years, and in leeds can reach as long as almost 24 years. Considering that all the solutions showed a positive NPV, it is possible to conclude that the IRR of the system is easily higher than the real discount rate applyed of 2.8 to 3.8 % (See Table 3 at Pag. 64). The high IRR and the long payback time are a consequence of the type of payment that should be done almost 100% upfront for this type of systems. These characteristics, if a low risk for the investment can be demonstrated, could prove a desirable long term investment and, with the aid of financial institution, lead to a strong growth of the market and a reliable stream of revenues or savings. If the lifetime cumulative electricity balance is maximized (i.e. the electrictity self-consumed over the lifetime minus the electricity required to produce the BIPV system) instead of NPV, the capacities installed are far larger: this is an encouraging factor as the most stringent framework (the economic one in our case) is also the one that presents more improvement opportunities. In other words there is no risk of over-dimensioning the system given the economic optimum: if the economic optimum had produced larger capacities than the energetic one, there would have been a risk of excessive over-production(i.e. a wasteful system).

Specific CO_2 emissions of the systems: The solution which maximizes the NPV, retrieved from the three example cases of the previous section (i.e. Current BIPV profitability at Pag.61), is analyzed in terms of levellized CO_2 emissions during its lifetime. Given the assumptions made in the typical input values paragraph about the embedded CO_2 emissions (Pag. 59), the specific equivalent emissions that can be obtained with a BIPV system in the three residential types range from a minimum of 70 [kg CO_2 eq/MWh] for the whole electricity produced in a condominium system in Athens, to a maximum of 123 [kg CO_2

eq/MWh] for the self-consumed fraction of a single family house in Leeds. These levels of specific emissions tend to be much lower than those of present energy mix of most countries, for a reference, the specific emissions of the OECD countries are estimated to 432 [kg CO_2 eq/MWh](i.e. above 350% of the worst case scenario)in [144]. Because of this, BIPV can be considered a reliable and economically sustainable source of GHG emission reduction in most countries although it would probably worsen the situation in Costa Rica, France, Iceland, Norway, Sweden and Switzerland. The entity of the emission reduction (or increase) swings hugely from one case to another, with reduction cuts deeper than 70% in England and above 85% in Greece for the self-consumed fraction*. As expected the BIPV system always results in an increase of specific CO_2 equivalent emissions when applyed in France due to the outlier low specific emissions of this country, the system ranges from a +31% for the whole electricity produced in the condominium system to a + 58% for the self-consumed fraction in the single fammily house. Obviously these differences should be multiplyed by the self-sufficiency of each example as all the remainder electricity is simply taken from the standard energy mix of the country. After applying the self-sufficiency fraction (using the self-consumed specific emissions) the average variations of specific emissions of England, France and Greece are -12%, +13% and -29% respectively. All in all the results can be considered encouraging as the values of CO_2 equivalent emissions resulted are still vastly lower than the average of OECD countries or of the EU (between 60% and 80% lower compared to the energy mix of the EU). In other words, despite the non optimal placement of a BIPV system compared to a ground mounted, south oriented one, and despite the non-contemporaneity of production and consumption, the BIPV still easily outperforms the energy mix of most countries when optimized for maximum NPV. This means that it is possible to gain huge improvement in terms of carbon intensity while generating an economic benefit at the same time. Furthermore the reduction of the energy mix of PV producing countries would in turn lower the specific emissions of the photovoltaic material leaving some additional reduction potential in the future.

*even higher if the whole electricity produced is considered

Profitability of the façade: The research described in the paragraph at page 80 showed that the façade can be profitable in spite of having a lower annual cumulative irradiation: actually the improvement provoked by the movement of modules from the roof to the façade are negligible(as Fig. 48 at page 89 shows), nevertheless the fact that there are advantages at all (i.e. there are no losses) is remarkable. The notion that the façade is only an architectural choice (i.e. only due to aesthetics)is possibly due to the lack of early design optimization in the professional practice and in scientific literature. The optimization was repeated with four possible hypothetical storage capacities: from the absence of electric storage (NS), to the presence of ca. 87 kW h of storage (WS). The NPV optimal system turned out to be ambitious in terms of demand coverage. The NS (no storage) optimal system can in fact cover (i.e. guarantee a self-sufficiency of) 32.3% of the annual cumulative demand of the building in the first year of installation (Table 5 at page 86). Unsurprisingly higher percentages of demand are self-produced when electric storage is installed (up to 42% for the highest storage). This higher coverage from PV is not due uniquely to the higher flexibility provided by the storage, but also to higher installation of PV capacity when the storage is present. An interesting aspect is in fact the synergetic effect of PV and storage on each other. The presence of storage pushes higher the NPV optimal capacity of PV (from 62 to 78 kWp, see Table 5 at page 86), and keeps the self-consumption stable around 83%. The designer has the possibility to choose between a pessimistic and an optimistic scenario, even if the median one is more resilient to varying scenarios. The plateau of the pessimistic and optimistic curves are shifted in terms of capacities compared to the expected one (e.g. from 50 to 73 kWp in the NS case, see Fig. 15). The results are confronted for a mere capacity optimization or a load matching procedure (see input section at page 28), the latter more computationally expensive but interesting when the least irradiated surfaces have higher irradiation in some particular period of the year. Considering the installation of the PV modules, it has been highlighted that their position on the building envelope can be different from the usual and expected ones, thanks to the load matching LM procedure. Using the LM, an improvement of NPV is possible without variation of installed capacity (see Fig. 48 at Pag. 89) therefore without affecting the investment costs, but just moving the PV modules on the envelope. The entity of the NPV improvement is usually very small (5.6% gain for a system of 100 kWp in the expected scenario, see Fig. 19), but it can become important for ambitious systems in pessimistic scenarios (+13% for a 100 kWp system under pessimistic scenario).

Effect of the electric storage on the optimal PV system: The study presented in the section starting at page 90 gives reason to be optimistic about the future economic performance of BIPV as it suggests that a large PV installation on the façade of an high rise building is possible with present prices and technologies [150]. The study shows also that is possible to cover 26% of the cumulative electric demand of the case study without the need for storage and employing economically advantageous solutions. The demand profile taken from the standard, being slightly lower in magnitude (-27%), led as a result a much smaller system (-63%) compared to the actual optimum. This aspect shows that the shape of the curve along the day, and probably along the seasons, has a strong effect on the size of the optimal BIPV system. This study, being based on a single example, cannot conclude that the standard is too low in magnitude nor give indications on any specific correction that can be done on its shape (e.g. decrease the prevalence of the daytime drop in power demand). Nevertheless it provides a principle to evaluate the demand curves: with growing measured data, the variability of the load profiles will be gradually probed, and the features impacting the optimal solution will be known. It seems therefore feasible to find, at least for what concerns residential buildings, one or more standardized demand curves able to lead to an economically effective system. A set of curves that, though not identical to the real demand of a building, do not differ with this in such a way to cause significant differences in the optimal solution. For what concerns the example presented in the section, the standard curve taken from [151] is significantly affected in terms of performance, it in fact leads to losses about 30% on both lifetime self-sufficiency of electricity and NPV of the investment. The optimization has to be run with more examples to assess the real usefulness of the standard curve and ultimately accept it or discard it for our method. Statistical studies on various demand profiles and on their effect over the result of the optimization would lead to propose new ones more fit for the purpose. A higher level of confidence on the input data for this method would lead to more accurate results, therefore to more profitable BIPV system and hopefully a higher penetration of this technology [150]. gible. It is important to notice that the installation of batteries have a positive effect on the PV cap acity installed (see also Fig. 53 at Pag. 97), for example the cost of battery equal to 250 €/kWh would cause a 9% and 15% increase in the IRR optimal PV capacity.

Impact of a growing penetration of EVs on the KPI of the system: With increased EV penetration, the cost-optimal PV capacity will also increase due to the increased electrical demand. Increasing the number of EVs will lead to a slight increase in the SC, as the whole system shifts towards larger load and larger capacity. The EV profiles used have only a small seasonal variation. This is not always correct for the cold Swedish winter climate, when a significant amount of heating is required for the interior of the car, which increases the amount of electricity used for a given journey. How large this heating demand is depends on the duration of the journey and not its distance. The electricity demand of the buildings used includes electrical heating for cars in the car park before use, as is common practice in Sweden, so the battery in the car does not need to supply heat to heat up the car before a journey. For the location of the cluster, there is no traffic congestion along the usual routes and thus the energy use for motion will be prevailing compared to that for heating, even in winter. Additionally, in the winter the electric load is far greater than the PV production, so any differences of EV load at this time of year would have very little impact on the results. In each hour of a day, the charging demand varies dramatically, reaching peaks at night and valleys during daytime. Such daily EV demand profiles have an opposite trend as the PV power generation, which reaches peak in the daytime and becomes zero at night. Thus, the increase of EV numbers will not promote a higher contemporary self-consumption rate for PV electricity. In the residential area of Sweden the interaction between PV and EVs results quite unfavourable suggesting to replicate the optimization process in other building clusters, instead of those composed only of residential buildings. The relation between PV and EVs could be more synergic in offices and commercial activities due to the better contemporaneity of production and demand, as EV's used for commuting can be charged during the working hours. This study did not consider the scenario in which EV batteries are allowed to deliver energy to the grid in order to alleviate the grid stress in the peak-demand hours [161]. In such scenario, EVs are used as mobile electrical energy storage which can be charged in buildings with surplus renewable production and discharged in places or times of insufficient renewable supplies [162]. If this additional function is considered and a more varied cluster is provided, the deployment of EVs can help further increase the renewable energy self-consumption at the building cluster level.

The benefit of energy sharing: The optimization shown at Pag. 101 used the method explained in [87] and [156], it was applied on a small residential district: the procedure was repeated for each household independently, for each quarter (i.e. group of 4 households) and for the whole district using two different fitness functions. For both the fitness functions the aggregation of households caused a generalized improvement of all the KPI measured. The installed capacity (+118%), the NPV (+262.2%) and the self-sufficiency(+51%) improved when the NPV was maximized, while both LCOE and LCOEself became lower (16->14->13 and 27->18->18 €cent/kWh respectively) when the 27% of self-sufficiency was guaranteed. The main result of this study lies in the quantitative benefit of the electricity sharing among residential households. It is shown, albeit still in a single case study, that the optimal PV capacity, LCOE (both of whole produced or consumed only electricity), self-sufficiency and NPV can simultaneously improve despite a reduction of the optimal capacity of the electric storage. The aggregation of the load of a modest number of households can create a locally balanced pro-sumer community that does not need to sell any electricity to the grid for its business model (Revenues for energy sale [€/kWh] = 0). It is already feasible to reach a 27% self-sufficiency as mandated by the original target climate and energy framework in terms of share of renewables without economic losses, with PV only and with 2019 technology and costs; the foreseeable reduction in electric storage costs suggests that huge improvements are about to be unlocked. The small variability in results among aggregated demands may signify that a simplified design strategy is possible (i.e. one that does not need the use of hourly load but can work with the cumulative one). This result is by no means conclusive, it bags more questions indeed: is this feature still visible for less than 20 households if simulated at lower time resolution? What are the business models that can enable the actual financing and operation of the optimal PV system (P2P market, local PV energy provider, PV shareholders)? Can the presence of free electricity (during over-production time) kick start new practices or forms of storage? How much impact can the reduction in storage price have on the optimal storage capacity? And on the optimal PV capacity? The preliminary results are encouraging and a plethora of research endeavors is open on the topic, new research can bring interesting news for the benefit of all.

knowledge derived from the experience: Relevant concerns when it comes to the installation of photovoltaic system in buildings is the fear of wasting money in a poorly performing technology that does not have a relevant impact on the actual energy consumption of the building. A neglected phenomenon is that the performance of the BIPV system strictly depends on its scale relative to the electric demand of the building and on the positions of the active material on the different facades. The performance of the BIPV system ultimately comes down to the quantity of electricity that it produces during its lifetime and on the fraction of this electricity that is directly used in the building. Energy performance aside, it is also important to ensure that a BIPV system is profitable, or at least that it does not realizes a loss of money [150].As it is easy to imagine, the economic profitability of the BIPV system is strongly dependent on its scale relative to the electric consumption of the building: in other words, to make a building totally energetically independent is way more expensive than having a fraction of a specific load covered by PV. The economic performance of a BIPV system ultimately depends on the relative capacities of its components amid electricity prices, electric demand, availability and orientation of surfaces, presence of shading bodies and so on. Provided that BIPV is an environmental asset, if the adoption of a BIPV system is economically advantageous, is there a reason not to adopt it? The method developed and described in these pages has the aim of increasing the BIPV market, for this reason its use has been envisioned in a large array of situations: new buildings, retrofit of existing ones, in combination with heat pumps or EVs, based on single dwellings or communities. The versatility of this methodology, and of similar ones that arose independently, makes it useful for the analysis of different combination of technologies in different weathers and regulatory framework, for this reason it has the potential to become a staple of the BIPV design practice. There are potentially new and unexplored reward functions that can be used to Dimension a PV system although high care shoould be taken to choose the correct KPI to form a reward function. KPIs such as LCOE or IRR are very interesting for assessment purposes, but did not work when used as a fitness function for a BIPV system in an economic regime of self-consumption. The main reason for this is that on a building, where the irradiation is uneven, the minimum LCOE is available only in the very spot where the annual cumulative irradiation is the highest, therefore minimizing LCOE would suggest a rather small system. The same drawback holds true when IRR is maximized or payback time is minimized. Furthermore, IRR and PT are best when the self-consumption is 100% (as the revenues/cost ratio depends on rate of self-consumption), and would suggest an insignificant system whenever there is a seasonal drop in the electric demand (such as periods in which large portions of the population is on holiday elsewhere). Fitness functions based on IRR and LCOE are feasible but require some further constraints: for example self-consumption can be maximized while requiring a specific IRR, LCOE can be minimized but requiring a minimum self-production [87].The method is developed with the goal to support conceptual/preliminary design with a technical-economic optimization. However the current work-flow for the modelling, simulation and analysis and the need to know in detail some information such as the hourly electric consumption are still fragmented, specialist and likely time-consuming. This could represent a limit in early design. The idea is presented in this thesis as a concept and the advantages of this approach are shown and discussed, nevertheless much improvements are needed to realize the potential of this technique, ideal would be the integration of this method as a plug-in in a dynamic simulation software, possibly BIM based [87].

Reading through the results with the curiosity of what is the technical, and in some regards environmental, potential of BIPV, the reader will probably be comforted by the large untapped potential still left for the growth of this technology. In an extremely rainy and poorly irradiated location such as Leed, on a single family house (i.e. without the possibility to aggregate the load), on a roof that does not have a south slope (i.e. in a deeply sub-optimal context where the matching is not needed due to low yield), for a residential electric load (i.e. characterized by whorse contemporaneity factor compared to offices, schools and factories), the NPV optimal BIPV system reaches a self-sufficiency above 14%. According to the latest IEA report [163] the country with the most self-sufficiency due to PV is Honduras at 13.26%, followed, with an ample gap, by Germany at 7.47%: the self-sufficiency of the world according to the same report is 2,14%. The results indicate that there is a staggering untapped economical potential for this technology. According to the results the installation cap sits at a monumental height and therefore is possible to cut aboundant chops of the current electric demand without the need of economically harmful solutions with present day technology and costs. The results deriving from an optimization for life-time cumulative electricity self-consumed indicated that the energetic optimum is usually larger than the economic one, therefore optimal levels of electricity generated and self-consumed can be attained even at levels of self-sufficiency that would normally be considered severely inefficient (i.e. from 66% in Leeds to 54% in Athens). This result is encouraging as cost reduction is still ongoing along production and installation of photovoltaic systems and the economic optimum is bound to increase over time. In numerous optimizations presented, the value of the excess PV electricity has been considered equal to 0, this means that low level of self-consumption are correlated to large excesses of PV electricity at times, therefore to the presence of aboundant quantities of free electricity during hours of overproduction: this availability of free energy could act as a stimulating factor for the diffusion of electric storage technologies. The results show to be positive overall if the GHG emissions are taken into account as well, in fact the specific CO_2 emissions can swing from ca. 70 [g CO_2 eq/kWh] to ca. 123[g CO_2 eq/kWh] in front of an EU average of more than 300 [g CO_2 eq/kWh]. Truth be told there are some countries where the energy mix is presently so low that adding more BIPV would result in higher emissions, but these are outlyer low examples and on average important reduction can be made. The notion that only the highest yielding surface of the building should be used did not hold true in all the examples considered, there are in fact examples where it makes sense to install part of the system on a surface invested by lower irradiation but with a better production profile, other examples still can increase the reward function adding part of the system on a lower irradiation surface when the topmost one has been completely occupied. In terms of electric storage the prices for now are not so to guarantee a profitable business model based on self-consumption with significant capacities installed, huge storages were only installed for cases in which the self-sufficiency was maximized and future prices were considered (i.e. 250 €/kWh in the example about the effect of the electric storage on the optimal PV system at

Pag 90). The installation of large storage capacities, by increasing the value of PV electricity, encouraged the installation of larger PV system proving the strong sinergies between these two technologies, the price reduction foreseen for the electric storage technology leaves room for a moderate optimism, especially considering that sources of revenues or savings could come from grid-regulation services and reduction of the baseline costs of the electric contract thanks to peak demand reduction. The use of BIPV in combination of EV produced mixed results in terms of performance, despite increasing self-consumption and capacity installed it lowered slightly the self sufficiency due to large addition of electric demand at night-time hours of the day. Although not experimented in this thesis, which is mainly focussed on residential buildings, it would be interesting to repeat the EV optimization using work-place related charging patterns to see what impact it could have on the self-sufficiency of a work-place. Finally, the aggregation of the load has been shown to improve the NPV of an impressive + ca. 270% while increasing capacity and improving self-consumption and self-sufficiency at the same time. Most of the gain was found in the aggregation of 4 houses compared to one, but noticeable improvements were found also for the aggregation from 4 to 16 houses in the example considered.

7.2 limitations

7.3 future development

The work presented in the previous pages is by no means conclusive, the optimization technique can still be employed with hugely diverse weather conditions, sets of input, prices and regulatory frameworks. The versatility of the technique can make it into a stepping stone for a broader research endeavour, the technique can be associated with a more accurate algorithm for the estimation of PV production and used at a later stage of the architectural design to refine the characteristics of the system. Other aspects could be added to the optimization algorithm such as dynamic building simulation tools for the correct design of BIPV devices having impact on comfort and building energy use (e.g. semi-transparent PV,PVT or PV shadings).The tool presents synergies with other research fields either because it can provide an insight to them or because they can improve the data and the results of it. Urban renewable energy assessment could be used to process large quantity of consumption data, running the optimization over an urban geometry it would be possible to estimate the PV potential of a district or a city. The use of sensors in the building and the production of real-time models such as the so called "digital-twins" would greatly improve the quality of the imput data for the optimization greatly reducing the economic risk for the investment. Perhaps the most interesting application of the tool is to use it as a starting point for the study of PV related business models: in fact, if the system design is such to guarantee the maximum NPV, the focus can be shifted to the financial and energy distribution aspects of the PV deployment. In this sense peer to peer energy sharing, local energy providers and energy communities can be explored as earning schemes for urban PV systems both with direct investment from the shareholder and with financial institution purchasing it in a mortgage based solution. The economic simulation of energy communities would also require some degree of modelling of a micro-grid as the communities can either use the existing infrastructure (that should tough be kept locally balanced in terms electricity production and consumption) or install a private micro-infrastructure such as a dc ring. Another crucial aspect of this type of optimization is the impact that storage technologies have on it, in this sense the method can be used as an analysis tool to monitor improvements in cost reduction, higher efficiency and prolonged lifetime or reduced degradation of new electric or thermal storage systems. Another aspect that needs deeper investigation is the impact of renewable-savvy control strategies for electrical applyances or electricity based heating systems, this in fact is very likely to increase the optimal PV capacity to be installed.

References

[1] Global Energy Trends. Technical report, Enerdata, May 2019.

[2] E. U. Commission. EU energy,transport and GHG emissions trends to 2050. Technical report, European Commission, 2013.

[3] Mariano J. guillen. Solar Skins: an opportunity for greener cities. Technical report, Solar Power Europe & PV ETIP.

[4] Susan Solomon, Dahe Qin, Martin Manning, Kristen Averyt, and Melinda Marquis. *Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC*, volume 4. Cambridge university press, 2007.

[5] E. U. Commission. A 2030 framework for climate and energy policies, March 2013.

[6] Fatih Birol. Renewables 2018: Market analysis and forecast from 2018 to 2023. Technical report, IEA (international energy agency), October 2018.

[7] IEA-PVPS T15-04: 2018 Subtask C–International framework for BIPV specifications. Technical report, IEA-PVPS T15, August 2018.

[8] The Energy Performance of Buildings Directive: buildings performance factsheet. Technical report, European Commission, January 2019.

[9] Bill Prindle, Maggie Eldridge, Mike Eckhardt, and Alyssa Frederick. The twin pillars of sustainable energy: synergies between energy efficiency and renewable energy technology and policy. *Washington, DC: American Council for an Energy-Efficient Economy*, 2007.

[10] Momir Tabakovic, Hubert Fechner, Wilfried Van Sark, Atse Louwen, George Georghiou, George Makrides, Eliza Loucaidou, Monica Ioannidou, Ingrid Weiss, Sofia Arancon, and others. Status and outlook for building integrated photovoltaics (BIPV) in relation to educational needs in the BIPV sector. *Energy Procedia*, 111:993–999, 2017.

[11] ECSE. EN 50583-1 photovoltaics in buildings -part 1: BIPV modules, 2016.

[12] ISO. ISO FDIS 18178:GLASS IN BUILDING - LAMINATED SOLAR PHOTOVOLTAIC GLASS FOR USE IN BUILDINGS, September 2016.

[13] IEC. IEC 61730-1:2016, August 2016.

[14] Marco Lovati, Jennifer Adami, Giuseppe De Michele, Laura Maturi, and David Moser. A Multi Criteria Optimization Tool for BIPV Overhangs. In *6AV.5.15*, June 2016.

[15] Francesca Frasca, Marco Lovati, Cristina Cornaro, David Moser, and Anna Maria Siani. Use of photovoltaic modules as static solar shadings: Retrofit of a paleontological site in Rome. Bern, Switzerlnd, October 2017.

[16] IEC. IEC TS 61836:2016 , Solar photovoltaic energy systems - Terms, definitions and symbols, December 2016.

[17] LV Fang, Xu Honghua, and Wang Sicheng. National Survey Report of PV Power Applications in China. Technical report, International Energy Agency, July 2013.

[18] Henk Kaan and Tjerk Reijenga. Photovoltaics in an architectural context. *Progress in Photovoltaics: Research and Applications*, 12(6):395–408, 2004.

[19] T Schoen, D Prasad, D Ruoss, P Eiffert, and H Sørensen. Task 7 of the IEA PV power systems program–achievements and outlook. In *Proceedings of the 17th European Photovoltaic Solar Conference*, 2001.

[20] Laura Maturi and Jennifer Adami. *Building integrated photovoltaic (BIPV) in Trentino Alto Adige*. Springer, 2018.

[21] Igor Sartori, Assunta Napolitano, and Karsten Voss. Net zero energy buildings: A consistent definition framework. *Energy and buildings*, 48:220–232, 2012.

[22] Marta Maria Sesana and Graziano Salvalai. Overview on life cycle methodologies and economic feasibility for nZEBs. *Building and Environment*, 67:211–216, 2013.

[23] European Parliament & Council . Directive 2010/31/EU on the Energy Performance of Buildings (EPBD), May 2010.

[24] European Parliament and European Council. Directive 2009/28/CE on renewable energy sources (RES), April 2009.

[25] M Mandalaki, S Papantoniou, and T Tsoutsos. Assessment of energy production from photovoltaic modules integrated in typical shading devices. *Sustainable Cities and Society*, 10:222–231, 2014.

[26] Giacomo Bizzarri, Mark Gillott, and Vittorino Belpoliti. The potential of semitransparent photovoltaic devices for architectural integration: the development of device performance and improvement of the indoor environmental quality and comfort through case-study application. *Sustainable Cities and Society*, 1(3):178–185, 2011.

[27] Erika Saretta, Paola Caputo, and Francesco Frontini. A review study about energy renovation of building facades with BIPV in urban environment. *Sustainable Cities and Society*, 2018.

[28] Satu Paiho, Isabel Pinto Seppä, and Christel Jimenez. An energetic analysis of a multifunctional façade system for energy efficient retrofitting of residential buildings in cold climates of Finland and Russia. *Sustainable cities and society*, 15:75–85, 2015.

[29] Ilaria Vigna, Roberta Pernetti, Wilmer Pasut, and Roberto Lollini. New domain for promoting energy efficiency: Energy Flexible Building Cluster. *Sustainable cities and society*, 38:526–533, 2018.

[30] E. U. Commission and others. *Directive of the European Parliament and of the council on the promotion of the use of energy from renewable sources (recast)*. Brussels, 2016.

[31] Søren Østergaard Jensen, Anna Marszal-Pomianowska, Roberto Lollini, Wilmer Pasut, Armin Knotzer, Peter Engelmann, Anne Stafford, and Glenn Reynders. IEA EBC Annex 67 Energy Flexible Buildings. *Energy and Buildings*, 155:25–34, November 2017.

[32] KO Aduda, T Labeodan, W Zeiler, G Boxem, and Y Zhao. Demand side flexibility: Potentials and building performance implications. *Sustainable cities and society*, 22:146–163, 2016.

[33] Rebecca Jing Yang. Overcoming technical barriers and risks in the application of building integrated photovoltaics (BIPV): hardware and software strategies. *Automation in Construction*, 51:92–102, 2015.

[34] Patrick Heinstein, Christophe Ballif, and Laure-Emmanuelle Perret-Aebi. Building Integrated Photovoltaics (BIPV): Review, Potentials, Barriers and Myths. *Green*, 3(2):125–156, 2013.

[35] RME Valckenborg, W van der Wall, W Folkerts, JLM Hensen, and A de Vries. ZIGZAG STRUCTURE IN FAÇADE OPTIMIZES PV YIELD WHILE AESTHETICS ARE PRESERVED.

[36] Laure-Emmanuelle Perret-Aebi, Jordi Escarré, Heng-Yu Li, Laurent Sansonnens, Federico Galliano, Gianluca Cattaneo, Patrick Heinstein, Sylvain Nicolay, Julien Bailat, Sébastien Eberhard, and others. When PV modules are becoming real building elements: White solar module, a revolution for BIPV (Presentation Recording). In *SPIE Optics+ Photonics for Sustainable Energy*, pages 95630Q–95630Q. International Society for Optics and Photonics, 2015.

[37] P. Jayathissa, M. Luzzatto, J. Schmidli, J. Hofer, Z. Nagy, and A. Schlueter. Optimising building net energy demand with dynamic BIPV shading. *Applied Energy*, 202(Supplement C):726–735, September 2017.

[38] Lars Broman. On the didactics of renewable energy education — drawing on twenty years experience. *Renewable Energy*, 5(5):1398–1405, August 1994.

[39] Rosaria Ciriminna, Francesco Meneguzzo, Mario Pecoraino, and Mario Pagliaro. Rethinking solar energy education on the dawn

of the solar economy. *Renewable and Sustainable Energy Reviews*, 63:13–18, September 2016.

[40] Liangliang Sun, Lin Lu, and Hongxing Yang. Optimum design of shading-type building-integrated photovoltaic claddings with different surface azimuth angles. *Applied Energy*, 90(1):233–240, February 2012.

[41] Chen Kian Wee, Patrick Janssen, and Arno Schlueter. Performance Driven Design Optimisation with Scientific Workflow System. In *International Conference on Green Buildings and Optimization Design (GBOD 2012)*. ASME Press, 2012.

[42] Morgan D. Bazilian and Deo Prasad. Modelling of a photovoltaic heat recovery system and its role in a design decision support tool for building professionals. *Renewable Energy*, 27(1):57–68, September 2002.

[43] Anatoli Chatzipanagi, Francesco Frontini, and Alessandro Virtuani. BIPV-temp: A demonstrative Building Integrated Photovoltaic installation. *Applied Energy*, 173(Supplement C):1–12, July 2016.

[44] Shady Attia, Mohamed Hamdy, William O'Brien, and Salvatore Carlucci. Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design. *Energy and Buildings*, 60:110–124, May 2013.

[45] WM Pabasara U Wijeratne, Rebecca J Yang, Eric Too, and Ron Wakefield. Design and development of distributed solar PV systems: Do the current tools work? *Sustainable cities and society*, 2018.

[46] PVSITES software [Online] Available: http://www.pvsites.eu/software/.

[47] Valentin Software https://www.valentin-software.com.

[48] PVSyst general features [Online] Available: http://www.pvsyst.com/en/software/functionalities.

[49] SolarGis [Online] Available: https://solargis.info/pvplanner.

[50] Nate Blair, Aron P Dobos, Janine Freeman, Ty Neises, Michael Wagner, Tom Ferguson, Paul Gilman, and Steven Janzou. System advisor model, sam 2014.1. 14: General description. Technical report, National Renewable Energy Laboratory (NREL), Golden, CO., 2014.

[51] G Lobaccaro, F Fiorito, G Masera, D Prasad, and others. Urban solar district: a case study of geometric optimization of solar façades for a residential building in Milan. In *50th Annual Conference, Australian Solar Energy Society (Australian Solar Council)*, pages 1–10. Australian Solar Energy Society, 2012.

[52] Gabriele Lobaccaro, Francesco Frontini, Gabriele Masera, and Tiziana Poli. SolarPW: A new solar design tool to exploit solar potential in existing urban areas. *Energy Procedia*, 30:1173–1183, 2012.

[53] Taeyon Hwang, Seokyoun Kang, and Jeong Tai Kim. Optimization of the building integrated photovoltaic system in office buildings—Focus on the orientation, inclined angle and installed area. *Energy and Buildings*, 46:92–104, March 2012.

[54] Karoline Fath, Julian Stengel, Wendelin Sprenger, Helen Rose Wilson, Frank Schultmann, and Tilmann E. Kuhn. A method for predicting the economic potential of (building-integrated) photovoltaics in urban areas based on hourly Radiance simulations. *Solar Energy*, 116:357–370, June 2015.

[55] A. G. Imenes and J. Kanters. 3d solar maps for the evaluation of building integrated photovoltaics in future city districts: A norwegian case study. In *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, pages 3141–3146, June 2016.

[56] D. L. Talavera, E. Muñoz-Cerón, J. de la Casa, M. J. Ortega, and G. Almonacid. Energy and economic analysis for large-scale integration of small photovoltaic systems in buildings: The case of a public location in Southern Spain. *Renewable and Sustainable Energy Reviews*, 15(9):4310–4319, December 2011.

[57] Daniel Kurt. Net Present Value - NPV, November 2003.

[58] Brandon Rodriguez. The power of creative constraints, June 2017.

[59] Bernard Rudofsky. *Architecture without architects: a short introduction to non-pedigreed architecture*. UNM Press, 1964.

[60] H. Al-Hinai, W. J. Batty, and S. D. Probert. Vernacular architecture of Oman: Features that enhance thermal comfort achieved within buildings. *Applied Energy*, 44(3):233–258, January 1993.

[61] T. Tassiopoulou, P. C. Grindley, and S. D. Probert. Thermal behaviour of an eighteenth-century Athenian dwelling. *Applied Energy*, 53(4):383–398, April 1996.

[62] Manoochehri Hossein. *Kermaan City (and Maahaan Town): A Visual Journey To Main Features of- (The Indigenous (or Traditional) Architecture in Historic Cities of Iran*. April 2013.

[63] Jeffrey Horn, Nicholas Nafpliotis, and David E Goldberg. A niched Pareto genetic algorithm for multiobjective optimization. In *Evolutionary Computation, 1994. IEEE World Congress on Computational Intelligence., Proceedings of the First IEEE Conference on*, pages 82–87. Ieee, 1994.

[64] Scott Kirkpatrick, C Daniel Gelatt, Mario P Vecchi, and others. Optimization by simulated annealing. *science*, 220(4598):671–680, 1983.

[65] Marco Dorigo, Mauro Birattari, and Thomas Stutzle. Ant colony optimization. *IEEE computational intelligence magazine*, 1(4):28–39, 2006.

[66] S. Freitas, C. Reinhart, and M. C. Brito. Minimizing storage needs for large scale photovoltaics in the urban environment. *Solar Energy*, 159:375–389, January 2018.

[67] Christoph Waibel, Georgios Mavromatidis, Andrew Bollinger, Ralph Evins, and Jan Carmeliet. Sensitivity analysis on optimal placement of façade based photovoltaics.

[68] J. H. Wong, M. Royapoor, and C. W. Chan. Review of life cycle analyses and embodied energy requirements of single-crystalline and multi-crystalline silicon photovoltaic systems. *Renewable and Sustainable Energy Reviews*, 58:608–618, May 2016.

[69] Gabriele Lobaccaro, Aoife Houlihan Wiberg, Giulia Ceci, Mattia Manni, Nicola Lolli, and Umberto Berardi. Parametric design to minimize the embodied ghg emissions in a zeb. *Energy and Buildings*, 167:106–123, 2018.

[70] Lion Hirth. Market value of solar power: Is photovoltaics cost-competitive? *IET Renewable Power Generation*, 9(1):37–45, December 2014.

[71] Jan Remund. Accuracy of Meteonorm 7.1.6, October 2015.

[72] Thomas Huld. PVMAPS: Software tools and data for the estimation of solar radiation and photovoltaic module performance over large geographical areas. *Solar Energy*, 142:171–181, January 2017.

[73] Francesco Frontini, Pierluigi Bonomo, and Robert Hecker. Photovoltaic glass in building skin. A tool for customized BIPV in a BIM-based process.

[74] Apeksha Gupta, Alexandra Cemesova, Christina J. Hopfe, Yacine Rezgui, and Tracy Sweet. A conceptual framework to support solar PV simulation using an open-BIM data exchange standard. *Automation in Construction*, 37:166–181, January 2014.

[75] Hang-Jung Kuo, Shang-Hsien Hsieh, Rong-Chin Guo, and Chi-Chang Chan. A verification study for energy analysis of BIPV buildings with BIM. *Energy and Buildings*, 130:676–691, October 2016.

[76] Gui Ning, Li Junnan, Dong Yansong, Qiu Zhifeng, Jia Qingshan, Gui Weihua, and Deconinck Geert. BIM-based PV system optimization and deployment. *Energy and Buildings*, 150:13–22, September 2017.

[77] Anne Gerd Imenes. Performance of BIPV and BAPV installations in Norway. In *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, pages 3147–3152. IEEE, 2016.

[78] A. Al-Otaibi, A. Al-Qattan, F. Fairouz, and A. Al-Mulla. Performance evaluation of photovoltaic systems on Kuwaiti schools' rooftop. *Energy Conversion and Management*, 95:110–119, May 2015.

[79] Jae Bum Lee, Jae Wan Park, Jong Ho Yoon, Nam Choon Baek, Dai Kon Kim, and U. Cheul Shin. An empirical study of performance characteristics of BIPV (Building Integrated Photovoltaic) system for the realization of zero energy building. *Energy*, 66:25–34, March 2014.

[80] Xinfang Wu, Yongsheng Liu, Juan Xu, Wei Lei, Xiaodong Si, Wenlong Du, Chunjiang Zhao, Yunbo Zhong, Lin Peng, and Jia Lin. Monitoring the performance of the building attached photovoltaic (BAPV) system in Shanghai. *Energy and Buildings*, 88:174–182, February 2015.

[81] Xinjing Zou, Bian Li, Younghui Zhai, and Liqing Zhou. Performance of a grid-connected BIPV system at Jiangsu Province, China. In *2012 Asia-Pacific Power and Energy Engineering Conference*, pages 1–4. IEEE, 2012.

[82] Cristina S. Polo López, Francesco Frontini, Gabi Friesen, and Thomas Friesen. Experimental Testing under Real Conditions of

Different Solar Building Skins when Using Multifunctional BIPV Systems. *Energy Procedia*, 48:1412–1418, January 2014.

[83] Nuria Martín-Chivelet, Juan Carlos Gutiérrez, Miguel Alonso-Abella, Faustino Chenlo, and José Cuenca. Building Retrofit with Photovoltaics: Construction and Performance of a BIPV Ventilated Façade. *Energies*, 11(7):1719, July 2018.

[84] Stephen Wittkopf, Selvam Valliappan, Lingyun Liu, Kian Seng Ang, and Seng Chye Jonathan Cheng. Analytical performance monitoring of a 142.5kwp grid-connected rooftop BIPV system in Singapore. *Renewable Energy*, 47:9–20, November 2012.

[85] Nils H. Reich, Bjoern Mueller, Alfons Armbruster, Wilfried G. J. H. M. van Sark, Klaus Kiefer, and Christian Reise. Performance ratio revisited: is PR > 90% realistic? *Progress in Photovoltaics: Research and Applications*, 20(6):717–726, 2012.

[86] Robert Hooke and Terry A Jeeves. "Direct Search"Solution of Numerical and Statistical Problems. *Journal of the ACM (JACM)*, 8(2):212–229, 1961.

[87] Marco Lovati, Graziano Salvalai, Giulia Fratus, Laura Maturi, Rossano Albatici, and David Moser. New method for the early design of BIPV with electric storage: A case study in northern Italy. *Sustainable Cities and Society*, 48:101400, July 2019.

[88] Robert W Andrews, Joshua S Stein, Clifford Hansen, and Daniel Riley. Introduction to the open source PV LIB for python Photovoltaic system modelling package. In *Photovoltaic Specialist Conference (PVSC), 2014 IEEE 40th*, pages 0170–0174. IEEE, 2014.

[89] David John Gagne, Amy McGovern, Sue Ellen Haupt, and John K Williams. Evaluation of statistical learning configurations for gridded solar irradiance forecasting. *Solar Energy*, 150:383–393, 2017.

[90] Elke Lorenz, Thomas Scheidsteger, Johannes Hurka, Detlev Heinemann, and Christian Kurz. Regional PV power prediction for improved grid integration. *Progress in Photovoltaics: Research and Applications*, 19(7):757–771, 2011.

[91] Marco Pierro, Francesco Bucci, Matteo De Felice, Enrico Maggioni, Alessandro Perotto, Francesco Spada, David Moser, and Cristina Cornaro. Deterministic and Stochastic Approaches for Day-Ahead Solar Power Forecasting. *Journal of Solar Energy Engineering*, 139(2):021010, 2017.

[92] Wendelin Sprenger, Helen Rose Wilson, and Tilmann E. Kuhn. Electricity yield simulation for the building-integrated photovoltaic system installed in the main building roof of the Fraunhofer Institute for Solar Energy Systems ISE. *Solar Energy*, 135:633–643, October 2016.

[93] S.M.O Solution: An Innovative Design Approach to Optimize the Output of BIPV Systems Located in Dense Urban Environments. *Energy Procedia*, 91:945–953, June 2016.

[94] Greg Ward Larson and Rob Shakespeare. *Rendering with Radiance: the art and science of lighting visualization*. Booksurge Llc, 2004.

[95] Laura Maturi, Giorgio Belluardo, David Moser, and Matteo Del Buono. Bipv system performance and efficiency drops: overview on pv module temperature conditions of different module types. *Energy Procedia*, 48:1311–1319, 2014.

[96] Richard Perez, Pierre Ineichen, Robert Seals, Joseph Michalsky, and Ronald Stewart. Modeling daylight availability and irradiance components from direct and global irradiance. *Solar Energy*, 44(5):271–289, January 1990.

[97] Galen Barbose and Naim Darghouth. Tracking the Sun IX: the installed price of residential and non-residential photovoltaic systems in the united states. Technical report, August 2016.

[98] Ran Fu, David Feldman, and Robert Margolis. US solar photovoltaic system cost benchmark: Q1 2018. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), November 2018.

[99] Fernando M. Camilo, Rui Castro, M. E. Almeida, and V. Fernão Pires. Economic assessment of residential PV systems with self-consumption and storage in Portugal. *Solar Energy*, 150:353–362, July 2017.

[100] Renewable Power Generation Costs in 2018. Technical report, International Renewable Energy Agency, 2019. ISBN 978-92-9260-126-3.

[101] Bruno Burger, Klaus Kiefer, Christoph Kost, Sebastian Nold, and Simon Philipps. Photovoltaics Report. Technical report, Fraunhofer ISE, March 2019.

[102] Renewable Energy Report: gli scenari futuri delle rinnovabili in italia. Technical report, Politecnico di Milano, 2018.

[103] Ronald Wilson and Alan Young. The embodied energy payback period of photovoltaic installations applied to buildings in the U.K. *Building and Environment*, 31(4):299–305, July 1996.

[104] Kazuhiko Kato, Akinobu Murata, and Koichi Sakuta. An evaluation on the life cycle of photovoltaic energy system considering production energy of off-grade silicon. *Solar Energy Materials and Solar Cells*, 47(1):95–100, October 1997.

[105] Kazuhiko Kato, Akinobu Murata, and Koichi Sakuta. Energy pay-back time and life-cycle CO2 emission of residential PV power system with silicon PV module. *Progress in Photovoltaics: Research and Applications*, 6(2):105–115, 1998.

[106] P. Frankl, A. Masini, M. Gamberale, and D. Toccaceli. Simplified life-cycle analysis of PV systems in buildings: present situation and future trends. *Progress in Photovoltaics: Research and Applications*, 6(2):137–146, 1998.

[107] E. A Alsema and E Nieuwlaar. Energy viability of photovoltaic systems. *Energy Policy*, 28(14):999–1010, November 2000.

[108] K. Knapp and T. Jester. Empirical investigation of the energy payback time for photovoltaic modules. *Solar Energy*, 71(3):165–172, January 2001.

[109] Jyotirmay Mathur, Narendra Kumar Bansal, and Hermann-Joseph Wagner. Energy and Environmental Correlation for Renewable Energy Systems in India. *Energy Sources*, 24(1):19–26, January 2002.

[110] Erik Alsema and Mariska J. de Wild. Environmental Impact of Crystalline Silicon Photovoltaic Module Production. *MRS Online Proceedings Library Archive*, 895, 2005.

[111] Niels Jungbluth, Christian Bauer, Roberto Dones, and Rolf Frischknecht. Life Cycle Assessment for Emerging Technologies: Case Studies for Photovoltaic and Wind Power (11 pp). *The International Journal of Life Cycle Assessment*, 10(1):24–34, January 2005.

[112] R. Kannan, K. C. Leong, R. Osman, H. K. Ho, and C. P. Tso. Life cycle assessment study of solar PV systems: An example of a 2.7kwp distributed solar PV system in Singapore. *Solar Energy*, 80(5):555–563, May 2006.

[113] T Muneer, S Younes, N Lambert, and J Kubie. Life cycle assessment of a medium-sized photovoltaic facility at a high latitude location. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 220(6):517–524, January 2006.

[114] EA Alsema, MJ de Wild-Scholten, and VM Fthenakis. Environmental impacts of PV electricity generation-a critical comparison of energy supply options. In *21st European photovoltaic solar energy conference*, pages 3201–07, 2006.

[115] Roberto Dones, Christian Bauer, Rita Bolliger, Bastian Burger, M Faist Emmenegger, R Frischknecht, T Heck, N Jungbluth, A Röder, and Matthias Tuchschmid. Life cycle inventories of energy systems: results for current systems in Switzerland and other UCTE countries. *Final report ecoinvent data v2. 0*, 5, 2007.

[116] Vasilis M. Fthenakis, Hyung Chul Kim, and Erik Alsema. Emissions from Photovoltaic Life Cycles. *Environmental Science & Technology*, 42(6):2168–2174, March 2008.

[117] Mariska de Wild-Scholten. Energierücklaufzeiten für PV-module und systeme energy payback times of PV modules and systems. In *Workshop Photovoltaik-Modultechnik*, volume 26, page 27, 2009.

[118] L. Lu and H. X. Yang. Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong. *Applied Energy*, 87(12):3625–3631, December 2010.

[119] Masakazu Ito, Keiichi Komoto, and Kosuke Kurokawa. Life-cycle analyses of very-large scale PV systems using six types of PV modules. *Current Applied Physics*, 10(2, Supplement):S271–S273, March 2010.

[120] Vasilis Fthenakis, Rick Betita, Mark Shields, Rob Vinje, and Julie Blunden. Life cycle analysis of high-performance monocrystalline silicon photovoltaic systems: energy payback times and net energy production value. In *27th European Photovoltaic Solar Energy Conference and Exhibition*, pages 4667–4672, 2012.

[121] Byung-ju Kim, Ji-yong Lee, Kyung-hwan Kim, and Tak Hur. Evaluation of the environmental performance of sc-Si and mc-Si PV systems in Korea. *Solar Energy*, 99:100–114, January 2014.

[122] Matteo Giacomo Prina, Matteo Lionetti, Giampaolo Manzolini, Wolfram Sparber, and David Moser. Transition pathways optimization methodology through energyplan software for long-term energy planning. *Applied Energy*, 235:356–368, 2019.

[123] Matthias Leuthold. Energy storage technologies: Battery storage for grid stabilization. In *IEA EGRD Workshop on Energy Storage*, 2014.

[124] Electricity IRENA. storage and renewables: costs and markets 2030. *Abu Dhabi.: Int Renew Energy Agency*, 2017.

[125] Eero Vartiainen, G Masson, C Breyer, and D Moser. Improving competitiveness of solar pv with electricity storage. In *Proceedings of the 33rd European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam, The Netherlands*, pages 25–29, 2017.

[126] Mattia Dallapiccola, Marco Lovati, Jennifer Adami, and David Moser. Early Design Tool For PV + Battery Sizing: An Approach To Maximize The Economic Outlook Of BIPV By Increasing Self-Consumption. Rome, April 2019.

[127] Noah Pflugradt and Urs Muntwyler. Synthesizing residential load profiles using behavior simulation. *Energy Procedia*, 122:655–660, September 2017.

[128] Gamma distribution function [Online] Available: https://en.wikipedia.org/wiki/Gamma_distribution.

[129] Household electricity prices [Online] Available: https://ec.europa.eu/eurostat/.

[130] David D. Hsu, Patrick O'Donoughue, Vasilis Fthenakis, Garvin A. Heath, Hyung Chul Kim, Pamala Sawyer, Jun-Ki Choi, and Damon E. Turney. Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation. *Journal of Industrial Ecology*, 16(s1):S122–S135, 2012.

[131] Paolo Frankl, Emanuela Menichetti, and Giacomo Prennushi. Deliverable n 11.2-RS Ia "Final report on technical data, costs and life cycle inventories of PV applications".

[132] N Jungbluth, M Stucki, R Frischknecht, and S Buesser. Photovoltaics. *et al., Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Ecoinvent report*, (6-XII), 2009.

[133] Sergio Almeida Pacca. *Global Warming Effect Appliedd to Electricity Generation Technologies*. PhD Thesis, University of California, Berkeley, 2003.

[134] E. A. Alsema. Energy pay-back time and CO2 emissions of PV systems. *Progress in Photovoltaics: Research and Applications*, 8(1):17–25, 2000.

[135] Vasilis Fthenakis and Erik Alsema. Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004–early 2005 status. *Progress in Photovoltaics: Research and Applications*, 14(3):275–280, 2006.

[136] Hiroki Hondo. Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy*, 30(11-12):2042–2056, 2005.

[137] M Lenzen, C Dey, C Hardy, and M Bilek. Life-cycle energy balance and greenhouse gas emissions of nuclear energy in Australia. Report to the Prime Minister's Uranium Mining, Processing and nuclear energy review (UMPNER). *Sydney, Australia: Integrated Sustainability Analysis, University of Sydney*, 2006.

[138] Sergio Pacca, D Sivaraman, and GA Keoleian. Life cycle assessment of the 33 kW Photovoltaic system on the Dana building at the University of Michigan. *Michigan, USA*, 2006.

[139] Martin Pehnt. Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renewable energy*, 31(1):55–71, 2006.

[140] Achim Bubenzer and Joachim Luther. *Photovoltaics guidebook for decision-makers: technological status and potential role in energy economy*. Springer Science & Business Media, 2002.

[141] A Stoppato. Life cycle assessment of photovoltaic electricity generation. *Energy*, 33(2):224–232, 2008.

[142] Y. Tripanagnostopoulos, M. Souliotis, R. Battisti, and A. Corrado. Performance, cost and life-cycle assessment study of hybrid PVT/AIR solar systems. *Progress in Photovoltaics: Research and Applications*, 14(1):65–76, 2006.

[143] World Economic Outlook. Technical report, International Monetary Fund, April 2019.

[144] National inventory submissions to the united nations framework convention on climate change (unfccc, crf tables), and replies to the oecd state of the environment questionnaire. Technical report, 2019.

[145] Guus Verberne, Pierluigi Bonomo, Francesco Frontini, MN van den Donker, Anatoli Chatzipanagi, K Sinapis, and Wiep Folkerts. BIPV Products for Facades and Roofs: a Market Analysis. 2014.

[146] Solar Energy Laboratory. TRNSYS: A transient simulation program. 1990.

[147] Oliver Schmidt, Adam Hawkes, Ajay Gambhir, and Iain Staffell. The future cost of electrical energy storage based on experience rates. *Nature Energy*, 2(8):17110, 2017.

[148] Robert E Best, Forest Flager, and Michael D Lepech. Modeling and optimization of building mix and energy supply technology for urban districts. *Applied energy*, 159:161–177, 2015.

[149] Eero Vartiainen, Gaëtan Masson, and Christian Breyer. PV LCOE in Europe 2015–2050. In *Proceedings of the 31st European Photovoltaic Solar Energy Conference, Hamburg, Germany*, pages 14–18, 2015.

[150] Marco Lovati, Jennifer Adami, and David Moser. Open source tool for a better design of bipv+ battery system: an applied example. Brussels, September 2018.

[151] Kaiser Ahmed, Ali Akhondzada, Jarek Kurnitski, and Bjarne Olesen. Occupancy schedules for energy simulation in new prEN16798-1 and ISO/FDIS 17772-1 standards. *Sustainable Cities and Society*, 35:134–144, November 2017.

[152] Pei Huang, Marco Lovati, Xingxing Zhang, Chris Bales, Sven Hallbeck, Anders Becker, Henrik Bergqvist, Jan Hedberg, and Laura Maturi. Transforming a residential building cluster into prosumers in Sweden using Energy-Matching concepts: optimal design and sensitivity analysis of a coupled 'PV-heat pump-thermal storage-electric vehicle' system.

[153] Pia Grahn, Joakim Munkhammar, Joakim Widén, Karin Alvehag, and Lennart Söder. Phev home-charging model based on residential activity patterns. *IEEE Transactions on power Systems*, 28(3):2507–2515, 2013.

[154] Joakim Munkhammar, Pia Grahn, and Joakim Widén. Quantifying self-consumption of on-site photovoltaic power generation in households with electric vehicle home charging. *Solar energy*, 97:208–216, 2013.

[155] Marco Lovati, Jennifer Adami, Mattia Dallapiccola, Grazia Barchi, Laura Maturi, and David Moser. FROM SOLITARY PRO-SUMERS TO ENERGY COMMUNITY: QUANTITATIVE ASSESMENT OF THE BENEFITS OF SHARING ELECTRICITY. Marseille, France, September 2019.

[156] Marco Lovati, Rossano Albatici, Laura Maturi, David Moser, and others. EFFECT OF MODULE ORIENTATION AND BATTERIES ON PERFORMANCE OF BUILDING INTEGRATED PHOTOVOLTAIC SYSTEMS. In *33rd European Photovoltaic Solar Energy Conference and Exhibition*. WIP Wirtschaft und Infrastruktur GmbH & Co Planungs KG, 2017.

[157] Ali Mohammad Shirazi, Zahra S Zomorodian, and Mohammad Tahsildoost. Techno-economic BIPV evaluation method in urban areas. *Renewable Energy*, 143:1235–1246, 2019.

[158] Trends in photovoltaic applications. Report IEA PVPS T1-30:2016 21, IEA (international energy agency), 2016.

[159] "SmartMeter Energy Consumption Data in London Households" [Online] Available: https://data.london.gov.uk/publisher/uk-power-networks.

[160] The Acorn user guide [Online] Available: https://acorn.caci.co.uk/downloads/Acorn-User-guide.pdf.

[161] Yanyi Sun, Hong Yue, Jiangfeng Zhang, and Campbell Booth. Minimisation of residential energy cost considering energy storage system and ev with driving usage probabilities. *IEEE Transactions on Sustainable Energy*, 2018.

[162] G Barone, A Buonomano, F Calise, C Forzano, and A Palombo. Building to vehicle to building concept toward a novel zero energy paradigm: Modelling and case studies. *Renewable and Sustainable Energy Reviews*, 101:625–648, 2019.

[163] Snapshot of global photovoltaic market. Report IEA PVPS T1-33:2018 21, IEA (international energy agency), 2018.

Marco Lovati was born near Milan in 1987, after high school he completed a Master in Architectural Engineering at the University of Pavia. In 2016 he started a PhD in the department of Civil, Environmental and Mechanical Engineering at the University of Trento which was financed by the EURAC research center. Marco developed a method and a software tool for the sizing of building integrated photovoltaic systems in a self-consumption based, incentive free economic setup. From 2017 to 2019 Marco was WP leader in the H2020 EnergyMatching project. In the project his design methods were applied to the design of 3 BIPV systems as part of the retrofit of the same number of buildings in different European countries, the systems are now under construction. Marco wishes that his present research will shed light on the financial and economic instruments to realize an optimally designed BIPV system.