UNIVERSIDAD POLITÉCNICA DE MADRID

ESCUELA TÉCNICA SUPERIOR DE INGENIEROS
DE TELECOMUNICACIÓN

**ENERGY AND ECONOMIC OPTIMIZATION OF
PV HYBRID SYSTEMS TO SUPPLY BUILDINGS
HVAC DEMAND: BATTERY MODELING AND
CONTROL STRATEGIES**

TESIS DOCTORAL

Juan Carlos Solano Jiménez

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Dedication

*A la memoria de Neptalí, Tulio y Martha,
quienes me vieron emprender este camino,
pero no culminarlo.*

Juan Carlos

*Por aquella educación que me dieron desde
niño, por apoyarme en cada etapa de mi
vida, por su infinito amor y por cuidarme
hasta cuando estoy lejos, por todo eso,
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*«Por más diplomas, cargo o dinero que
tengas, como tratas a las personas es lo que
define tu educación»*

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Abstract

The main objective of this research is to assess the potential of PV hybrid systems to supply the electrical consumption in the Heating, Cooling and Air-Conditioning (HVAC) systems of buildings.

The hypothesis of this thesis suggests that a PV hybrid system is capable of supplying the necessary energy to maintain the comfort conditions inside a building, while this system is technically and economically profitable from the point of view of the consumer.

In order to fulfil the proposed objective and contrast the hypothesis, a Battery Energy Storage System (BESS) has been coupled to a PV system already existing in the prototype of the nearly zero-energy building, so-called ‘Magic Box’ at the Instituto de Energía Solar - Universidad Politécnica de Madrid. Likewise, two heat pumps to maintain the comfort conditions inside the house, sensors of temperature, relative humidity and concentration of CO₂, have been installed.

In the PV hybrid system, control algorithms have been implemented, which are capable of managing the power generated by the PV system, the charge and discharge battery power, and the imported and exported electricity grid, in such a way that the electrical consumption of the heat pumps is always supplied. By means of these algorithms, two control strategies have been implemented (optimizing the PV self-consumption and peak-shaving) and two modes of operation (the battery supplies all loads, or the battery only supplies the HVAC specific load).

With the data collected after an extensive measurement programme, a model was developed that reproduces the control strategies implemented in the PV hybrid system, with an error lower than 10%. This model served as the basis for the development of a simulation software tool that allows one to evaluate — for various case studies — the main parameters of the system (PV generation, power exchange

with the BESS, power exchange with the utility grid and the battery state of charge). This tool, called *PVbat* also implements a detailed economic analysis, levelized cost of electricity, payback-time, and various sensitivity analyses (billing saving, self-consumption, self-sufficiency and battery lifetime), which allow one to determine whether the PV hybrid system is profitable or not.

By applying this model in two case studies (in Spanish and Ecuadorian scenarios), the starting hypotheses of the thesis have been demonstrated. A third case study also was evaluated (Portuguese scenario), where the economic impact of changing fixed charges in the bill electricity using PV-battery systems was analysed with total electricity consumption in a residential building, suggesting that the peak-shaving control strategy may lead to quite positive economic performance of PV-battery systems especially when the bill structure is based on fixed (power) charges.

The thesis is divided into four parts: the first part is the introduction, which details the research problem, the object of research, the hypotheses and the objectives. In the second part, a review of the state of the art of the fields related to this thesis is conducted. The third part presents the methodology used, the experimental stage, the battery control strategies and the validation of the grid-connected PV-battery systems model. The fourth part presents the results of the three case studies, the conclusions of this thesis, the publication of papers and international congresses, and finally, defines future lines of research that may arise from this Thesis.

Resumen

El objetivo principal de este trabajo de investigación es evaluar el potencial que tienen los sistemas híbridos fotovoltaicos para suministrar la potencia eléctrica necesaria a los sistemas de climatización en edificios.

Los sistemas de climatización, o también llamados HVAC por sus siglas en inglés (*Heating, ventilation and air-conditioning*), son utilizados a nivel mundial tanto en edificios comerciales, como residenciales para el acondicionamiento ambiental. En particular, estos sistemas representan entre el 40% y 60% del total de la demanda eléctrica de los edificios.

La hipótesis que se plantea en esta Tesis, sugiere que un sistema híbrido fotovoltaico, es capaz de suministrar la energía necesaria para mantener las condiciones de confort al interior de un edificio, a la vez que este sistema es rentable técnica y económicamente desde el punto de vista del consumidor.

Para cumplir el objetivo planteado y contrastar la hipótesis, se ha instalado y monitorizado un sistema de almacenamiento eléctrico acoplado a un sistema fotovoltaico ya existente en el prototipo de vivienda de consumo de energía casi nulo llamado ‘Magic Box’ del Instituto de Energía Solar de la Universidad Politécnica de Madrid. Así mismo, se ha instalado dos bombas de calor que mantienen las condiciones de confort dentro de la vivienda y sensores de temperatura, humedad relativa y concentración de CO₂.

En el sistema híbrido, se ha implementado algoritmos de control, que son capaces de gestionar la potencia generada por el sistema fotovoltaico, la potencia de carga y descarga de la batería, y la energía importada y exportada de la red eléctrica, de tal manera que el consumo eléctrico de las bombas de calor siempre esté suministrado. Mediante estos algoritmos se ha logrado implementar dos estrategias de control (aumento del autoconsumo fotovoltaico y disminución de los picos de demanda de la red) y dos modos de funcionamiento (que la batería

abastezca toda la demanda de la vivienda, o que la batería actúe sólo para abastecer la demanda específica de climatización).

Con los datos recopilados luego de una extensa campaña de mediciones, se desarrolló un modelo matemático que reproduce las estrategias de control implementadas en el sistema híbrido, con un error menor al 10%. Este modelo sirvió de base para el desarrollo de una herramienta de simulación que permite evaluar —para diversos casos de estudio— los principales parámetros del sistema (generación fotovoltaica, intercambio de potencia con el sistema de almacenamiento, intercambio de potencia con la red eléctrica y el estado de carga de la batería). Esta herramienta, denominada *PVbat* también implementa un detallado análisis económico (costo de la energía generada y retorno de la inversión) y diversos análisis de sensibilidad (ahorro económico, autoconsumo, autosuficiencia y tiempo de vida de las baterías), que permiten determinar las condiciones para las cuales el sistema es rentable.

La tesis está dividida en cuatro partes, la primera parte es la introducción, en donde se detalla el problema de investigación, el objeto de estudio, las hipótesis y los objetivos de este trabajo. En la segunda parte se hace una revisión del estado del arte de los distintos temas y estudios relacionados con esta investigación. En la tercera parte se presenta la metodología utilizada, el detalle de la etapa experimental, la descripción de las estrategias de control y la validación el modelo propuesto para sistemas fotovoltaicos con almacenamiento eléctrico conectado a la red. La cuarta parte presenta los resultados de los tres casos de estudio mencionados, las conclusiones de esta Tesis, las publicaciones realizadas en revistas científicas y congresos internacionales y, finalmente, define futuras líneas de investigación que puedan surgir a partir de esta Tesis.

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Glossary

AC	Alternating Current
ADSM	Active Demand Side Management
AGM	Absorbed Glass Mat
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BAPV	Building Attached Photovoltaic
BESS	Battery Energy Storage System
BIPV	Building Integrated Photovoltaic
BMS	Battery Management System
BPIE	Buildings Performance Institute Europe
CB ECS	Commercial Buildings Energy Consumption Survey
CENELEC	European Committee for Electrotechnical Standardization
CO ₂	Carbon dioxide
COM	Communication from the European Commission
COP	Coefficient Of Performance
CoP	Conference of the Parties
CTE	Spanish Technical Building Code
DC	Direct current
DES	Distributed Energy Storage
DG	Distributed Generation
DGS	German Solar Energy Society
DSM	Demand Side Management
EA	Euro Area
EC	European Commission
EEG	German Renewable Energy
EER	Energy Efficiency Ratio
EHPA	European Heat Pump Association
EIA	U.S. Energy Information Administration
EN	European standard
ESS	Energy Storage Systems

EU	European Union
FiT	Feed-in Tariff
HVAC	Heating, Ventilation and air-conditioning
IDAE	<i>Instituto para la Diversificación y Ahorro de la Energía</i>
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IES	<i>Intituto de Energía Solar</i>
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
LCOD	Levelized cost of discharged electricity
LCOE	Levelized Cost of Electricity
LCOS	Levelized Cost of Storage
MAPE	Mean Absolute Percent Error
MPC	Model Predictive Control
NEM	Net-metering
NPV	Net present value
NREL	National Renewable Energy Laboratory
nZEB	Nearly Zero-Energy Buildings
PEB	Positive Energy Buildings
PMV	Predicted Mean Vote index
PPA	Power Purchase Agreements
PPD	Predicted Percentage of Dissatisfied
PV	Photovoltaic
PVbat	Grid-connected PV-battery systems simulator
PVPS	Photovoltaic Power Systems
RD	Spanish Royal Decree
RECS	Residential Energy Consumption Survey
RES	Renewable Energy Sources
RMSE	Root Mean Square Error
SBU	Sunny Backup
SHC	Solar Heating and Cooling
SMAPE	Symmetric Mean Absolute Percent Error
SMES	Superconducting magnetic energy storage
SSP	<i>Scambio Sul Posto</i>
ToU	Time-of-use
UNE	Spanish Association for Standardization
UNEF	<i>Unión Española Fotovoltaica</i>
UPM	<i>Universidad Politécnica de Madrid</i>
UPS	Uninterruptable Power Supply
VNM	Virtual net-metering
VRLA	Valve Regulated Lead-Acid
WBCSD	World Business Council for Sustainable Development
WEC	World Energy Council

Nomenclature

A_{sc}	Absolute self-consumption, [kWh]
B	Annual electricity bill of consumer, with no PV-battery system, [€]
B_{pv}	Annual electricity bill of prosumer, with PV-battery system, [€]
C	O&M costs and equipment replacement costs of the PV-battery system, €
C_b	Heat exchange by convection during breathing, [W/m ²]
CF_i	Cycles to Failure
CF	Correction factor
C_{deg}	Capacity loss by degradation, [0 — 1]
C_n	Nominal capacity of the battery bank, [Ah]
C_{pv}	O&M costs and equipment replacement costs of the PV system, [€]
C'_{pv}	Annual O&M costs of the PV system, [€]
C_s	O&M costs and equipment replacement costs of the BESS, [€]
C'_s	Annual O&M costs of the BESS, [€]
$coef$	Charge coefficient, [-1 — 0]
d	Degradation rate for PV modules, [%/year]
DoD	Battery depth of discharge, 1 = empty; 0 = full
e_t	Residual error
$E'_{discharge}$	Annual energy discharged from the battery, [kWh]
E'_{pv}	Annual PV electricity generated by the PV system, [kWh]
E_{hvac}	HVAC electrical energy consumption, [kWh]
E_{LoL}	Energy consumption not supplied by the system, [kWh]
E_b	Evaporative heat exchange during breathing, [W/m ²]
E_{charge}	PV electricity charged into the battery, [kWh]
$E_{discharge}$	Electricity discharged from the battery, [kWh]
$E_{exported}$	PV electricity exported into the grid, [kWh]
$E_{imported}$	Electricity imported from the grid, [kWh]
E_{load}	Loads electricity consumption, [kWh]
E_{pv}	PV energy, [kWh]
E_s	Heat exchange by evaporation on the skin, [W/m ²]

f_{cl}	Clothing area factor (ratio of clothed/nude surface area)
G_{hrz}	Global horizontal irradiance, [W/m ²]
h_c	Convective heat transfer coefficient
H	Sensitive heat losses from the skin by radiation and convection, [W/m ²]
I	Initial investment of the PV-battery system, [€]
I_d	Discharge current, [A]
I_{pv}	Initial investment of the PV system, [€]
I_s	Initial investment of the BESS, [€]
k_c	Efficiency coefficients of the inverter in charge, [0 – 1]
k_d	Efficiency coefficients of the inverter in discharge, [0 – 1]
L_{charge}	Losses in the battery inverter (charge), [%]
$L_{discharge}$	Losses in the battery inverter (discharge), [%]
LF	Load factor, [%]
LoL	Percentage of energy consumption not supplied by the system, [%]
m	Total number of samples
M	Metabolic heat generation rate, [W/m ²]
n	Discrete time sample
NPV	Net present value, [€]
p_a	Partial water vapour pressure in Pascals, [Pa]
$P_{inverter}$	Nominal power of the inverter, [W]
$P_{bat,0}$	Battery power before inverter, [W]
P_{bat}	Battery power after inverter, [W]
P_{hvac}	Power HVAC electrical consumption, [W]
P_{load}	Power consumed by loads, [W]
P_{LoL}	Power demand not supplied by the PV-battery system, [W]
P_{grid}	Exported or imported grid power, [W]
P_{max}	Maximum power imported from the grid, [W]
P_{pv}	PV power generation, [W]
$P_{remaining}$	Power that can be extracted from the battery, [W]
$P_{required}$	Power required to complete charge's battery, [W]
$P_{surplus}$	PV surplus power, [W]
r	Discount rate, [%]
r_e	Annual increase in electricity price for consumers, [%]
R	Annual revenues of the prosumer, [€]
RH	Relative humidity, [%]
S_B	Annual billing saving, [€]
SoC	Battery state of charge, 0 = empty; 1 = full
SoC_{low}	Lower limit state of charge, [0 — 1]
SoC_{max}	Maximum state of charge, [0 — 1]
SoC_{min}	Minimum state of charge, [0 — 1]
SoC_{up}	Upper limit state of charge, [0 — 1]
t	Year, $0 \leq t \leq T$
t_a	Ambient air temperature, [°C]
t_{cl}	Surface temperature of clothing, [°C]

t_r	Mean radiant temperature, [°C]
T	Lifespan of the PV-battery system, [year]
T_c	Condensation temperature, [°C]
T_{comf}	Indoor comfort temperature, [°C]
T_E	Evaporation temperature, [°C]
T_{indoor}	Indoor temperature, [°C]
$T_{outdoor}$	Outdoor temperature, [°C]
V_{dc}	Nominal voltage of the battery bank, [V]
V_n	Nominal voltage of the battery element, [V]
W	External work, [W/m ²]
WF	Weighting factor
Z_i	Number of charge/discharge cycles
Δt	Time interval, 0 — 1 [hours]
ε_{sc}	Self-consumption, [%]
ε_{ss}	Self-sufficiency, [%]
η	Efficiency
ρ	Economic compensation for PV electricity exported into the grid, [€/kWh]
σ_e	Standard deviation
τ	Iteration of years, $0 \leq \tau \leq T$

Part I

Introduction

Chapter 1

Introduction, Object, Hypothesis and Objectives

1.1. Introduction

Personal motivation

To become a university professor in Ecuador, my country, was my main motivation in starting my doctorate studies. I had worked in the academic world before, and because of this, I felt the need to learn the skills of academic research, in order to contribute new knowledge and innovation wherever I might go in the future.

Between 2010 and 2013 I had the opportunity to work on a research project related to renewable energies. Also, in 2011 I collaborated with a European company dedicated to the installation of photovoltaic plants around the world. This was my first introduction to solar energy and all its potential as an inexhaustible source of energy. In 2013 I won a scholarship to study for a doctorate, the area of knowledge to which I applied being, unsurprisingly, renewable energy, specifically solar PV. With this background I applied and was admitted to the programme of Solar Photovoltaic Energy at the *Instituto de Energía Solar - Universidad Politécnica de Madrid* (IES-UPM), starting my PhD in 2014.

I firmly believe in the potential of photovoltaic systems installed in buildings to supply their electricity demand. Innovations in photovoltaic and battery systems, efficiency improvements, new and innovative photovoltaic integration products in buildings and permanent price reductions make this technology, which will gradually replace conventional energy sources with the consequent reduction of CO₂ emissions in the atmosphere, a very attractive topic of investigation.

The research problem

Energy consumption in buildings

According to the International Energy Agency ([IEA, 2017](#)), total global energy consumption in 2016 was about 13500 million tonnes of oil equivalent (Mtoe), and according to the U.S. Energy Information Administration ([EIA, 2016](#)), this value has an annual increase of 1.4%, as shown in [Fig 1.1](#). In addition, the World Business Council for Sustainable Development ([WBCSD, 2016b](#)), indicates that the building sector alone represents approximately one-third of global energy consumption worldwide and over 20% of global man-made greenhouse gas emissions, meaning that in 2016 this sector consumed about 4500 Mtoe.

Figure 1.1: World energy consumption in 2016. Source: EIA, WBCSD, IEA.

Also in Europe, according to the European Union Directive 2010/31/EU ([EU, 2010](#)), buildings account for 40% of total primary energy use and 36% of total greenhouse emissions. The reduction of energy use in buildings is therefore significant to improving their energy performance in order to conserve energy and reduce environmental impact. However, the energy system in buildings is quite complex, as the types of energy and building vary greatly.

The most frequently considered building types are commercial, residential and industrial buildings, varying from small residential buildings to big structures. The energy behaviour of these buildings is influenced by many factors, such as location and weather conditions (especially temperature), their construction and the physical property of the materials used, as well as the behaviour of the building users.

According to the Annual Energy Outlook 2017 (EIA, 2017) and the last report of the Commercial Buildings Energy Consumption Survey (CBECS, 2012) and Residential Energy Consumption Survey (RECS, 2015), energy-consuming applications in buildings can be grouped into seven major groups (see Fig. 1.2). Heating, ventilation and air-conditioning systems (HVAC), the reports noted, are the main end use for all building types, with a weight close to 45%, followed by lighting at around 20% and appliances at between 5% to 25%.

Figure 1.2: Consumption by end use for different building types. Source: Compiled by author based on the Database of EIA-CBECS, EIA-RECS.

Ghaffarianhoseini *et al.*, (2013); Li, Yang *et al.*, (2013); Ellabban *et al.*, (2014); and Chel *et al.*, (2017), in their research on renewable energy technologies and sustainable development of energy-efficient buildings, suggest four broad ways to reduce the energy consumption of new buildings which ultimately result in mitigating emissions of CO₂. They are as follows:

- a) Comfort-passive building design.
- b) Low embodied energy materials for building construction.
- c) Optimised energy efficiency strategies.
- d) Building-integrated renewable energy technologies.

However, according to the National Renewable Energy Laboratory ([NREL, 2011](#)), reducing existing building energy consumption requires only the last two items; that is, reducing the need for energy implementing energy efficiency measures and, to offset the building's remaining energy needs, using renewable energy systems.

In order to support these short-, medium- and long-term approaches, global policies are being implemented in order to encourage an increased use of energy from renewable energy resources, in both developed and developing countries. For example, the ambitions of the Energy Efficiency in Buildings Project and of the Low Carbon Technology Partnerships initiative ([WBCSD, 2016a](#)) are that estimated energy use in buildings is reduced by 50% by 2030 through actions on energy efficiency that offer favourable economic returns, using today's best practices and technologies.

Similarly, the Renewable Energy Directive ([EU, 2009](#)) establishes an overall policy for the production and promotion of energy from renewable sources. It requires the EU to fulfil at least 20% of its total energy needs using renewables by 2020, so-called *Horizon 2020*, to be achieved through the attainment of individual national targets. On 30 November 2016, the European Commission ([EC, 2016a](#)) published a proposal for a revised Renewable Energy Directive to make the EU a global leader in renewable energy and ensure that by 2030 the target of at least 27% of the EU's total energy consumption is met through renewables.

The European Commission is also pushing the acceleration of energy innovation through the Mission Innovation Initiative ([EC, 2017](#)) which was launched at CoP¹ 21 and currently comprises 23 members who together account for the largest share of global CO₂ emissions² and clean energy efforts. This work programme calls for open innovation, open science and being open innovation, open science and openness to the world through activities focusing on a more bottom-up, user-centred energy system.

¹ Conference of the Parties - Climate Conference is more commonly known as CoP.

² United States, China and the European Union account for 54% of the world's CO₂ emissions.

Source: <https://data.worldbank.org/indicator/EN.ATM.CO2E.PC>. Date accessed: 30/08/2017.

Why HVAC?

According to American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE, 2016), HVAC systems are a combination of elements that enable environmental comfort variables inside buildings, such as temperature, humidity and fresh air, to be maintained at a desirable level. Their importance is obvious when compared with other end-uses (see Fig. 1.2), given that HVAC systems account for the largest share of energy usage in building systems in many countries. In fact, some research indicates that these systems represent between 40% and 60% of energy demand for buildings in Europe, more than 50% in the United States, and are of increasing importance in buildings worldwide (Fong *et al.*, 2010; Perez-Lombard *et al.*, 2011; Chua *et al.*, 2013).

The European Commission (EC, 2016b) has implemented policies to address this issue too, such as the COM (2016) 51, the so-called ‘EU Strategy on Heating and Cooling’, which seeks to achieve building decarbonisation through energy efficiency and renewable energy practices, supported by decarbonised electricity and district heating. The same document also states that ‘Buildings can use automation and controls to serve their occupants better, and to provide flexibility for the electricity system through reducing and shifting demand, and thermal storage’, which suggests that the building integration with renewable energies, in order to supply HVAC consumption, is a subject of great interest to be investigated.

Figure 1.3: Final energy consumption for HVAC in the 28 EU Member States. Source: COM (2016) 51.

Why renewable energies?

[Fig. 1.3](#) below depicts the share of renewables and non-renewable energy in each of the 28 EU Member States. It shows that fossil fuels heavily dominate the heating and cooling sector in most of them, except for a few Nordic countries. The values of [Fig. 1.3](#) can be grouped as follows: 45% of energy for HVAC in the EU is used in the residential sector, 37% in industry and 18% in services. Each sector has potential to reduce demand, increase efficiency and shift to renewable sources.

Conversion to an efficient building makes it possible to switch to new conditioning equipment that uses renewable energy technologies. For example, there are a number of highly efficient, innovative appliances that quickly approach market-readiness, such as reversible heat pumps ([Table 1.1](#)), widely used worldwide, suggesting that combining heat pumps with control strategies and renewable energies, have the highest energy-efficiency rating of all technologies defined nowadays.

Table 1.1: Efficiency rating of new space Heating appliances. Source: COM (2016) 51.

Efficiency rating	Best Available Technology class for heating
A+++	Combination heat pumps, temperature control and solar technology.
A++	Combination heat pumps with solar technology.
A+	Gas cogeneration
A	Condensing gas boilers
B	--
C	Non-condensing gas boilers.
D	Electric resistance.

Before selecting an appropriate renewable energy technology to apply to a building and ultimately to supply its HVAC demand, it is important to consider many factors, as the NREL notes in its report ([NREL, 2011](#)):

- Available renewable energy resource at or near the building site.
- Available area for siting of the renewable energy technology.
- Cost of electricity purchased from the grid provider for the building.
- Available incentives for offsetting the installation cost of the renewable energy.
- Local regulations affecting renewable energy systems.
- The desire to preserve or not alter existing architectural features.
- Characteristics of the energy profiles to be offset by the renewable energy installation.

Following this, renewable energy technologies that can be incorporated into building energy systems include: solar electric, or photovoltaic (PV) systems; solar thermal, including solar hot water; heat pumps³; wind turbines; and, biomass systems. The solar technologies —both PV and thermal— are widely used in the residential and commercial environment, being the PV the most easily to be incorporated into existing HVAC systems.

Why PV?

The price reduction of PV modules, by around 85% in the last seven years (IEA PVPS, 2017) (see Fig. 1.4), and the innovation of new building-integrated photovoltaics (Yang *et al.*, 2016; Biyik *et al.*, 2017), coupled with increasing end-consumer electricity prices —around 40% in the last 9 years (see Fig. 1.5) — have substantially modified the profitability of this technology, and therefore, its use in little known applications such as HVAC in buildings.

Figure 1.4: Evolution of PV modules prices in USD cents/kWh. Source: IEA-PVPS.

In fact, the IEA-Solar Heating and Cooling Programme (IEA-SHC, 2016) has shown a special interest in this technology, particularly within its Task 53, the main objective of which is to analyse the use of solar systems for cooling and heating, including PV-driven systems, from both technical and economic points of view.

³ Only if heat pumps are adjusted to the definitions of Directive 2009/28/EC and Directive 2013/114/EU, that is to say, if the Seasonal Performance Factor (SPF) is higher than 2.5.

Figure 1.5: Evolution of EU-28 and Euro Area (EA) electricity prices for household consumers in EUR/kWh. Source: EUROSTAT.

Although the SHC programme uses the solar resource, both solar thermal and solar electric, several studies have been carried out to determine which solution is more effective technically and economically. For example, (Eicker *et al.*, 2014) compared the economic efficiency of two solar energy-based HVAC systems: an electric (compression) powered by a PV system, and a thermal (absorption) powered by a solar thermal system, working in three different climates corresponding to Palermo, Madrid and Stuttgart. The results showed that the use of PV can achieve savings of up to 50% in terms of primary energy, while the savings provided by the solar thermal system can reach a maximum of 37%.

Many studies simulating PV systems coupled to HVAC equipment have been published (Williams *et al.*, 2012; Daut *et al.*, 2013; Thygesen *et al.*, 2014; Turner *et al.*, 2015), demonstrating the interest in using PV electricity to condition the indoor climate of buildings, despite it not having been validated experimentally. Other studies have presented experimental results, such as (Aguilar *et al.*, 2014) that analysed the operation and energy behaviour of an air conditioner simultaneously connected to the grid and a PV system. However, this system did not use a storage system, making it impossible to use the system in absence of solar radiation. In another work, (Li *et al.*, 2015), the performance of a solar photovoltaic-driven air conditioner was experimentally analysed in the hot summer and cold winter zone in Shanghai, China. However, the research did not include control strategies or a model in a dynamic regime, which would have allowed system behaviour to be determined under other operating conditions.

Why electrical storage?

Battery Energy Storage Systems (BESS) can be developed using many different types of technologies. However, for PV systems, the only technology that is in wide use is the electrical storage battery, which uses the potential energy of electrochemical reactions to store electricity. In recent years, the inclusion of batteries in grid-connected PV systems has gone through dynamic development in countries like Germany, United States, Japan and Australia (Hoppmann *et al.*, 2014; Kairies *et al.*, 2015).

In this context, the battery is generally considered an effective means of decoupling PV generation from and consumption, thereby increasing the self-consumption rate and reducing grid demand. It has won the struggle to provide stored energy over many other competing technologies thanks to its energy density, its safety profile and its cost as indicated by the World Energy Council (WEC, 2016), which has estimated that the costs of electrochemical battery technologies will have fallen by as much as 70% by 2030 compared to today's cost.

In the field of grid-connected PV hybrid systems (PV systems with electrical storage), several simulation-based studies have been conducted (Achaibou *et al.*, 2012; Poullikkas, 2013; Weniger *et al.*, 2014; de Oliveira e Silva *et al.*, 2016), showing the benefits of using a BESS to reduce grid electricity consumption. However, these studies present neither experimental data nor control strategies based on PV generation, load condition and battery state of charge. Remarkable contributions involving control strategies in PV-battery systems have been published and validated with experimental data (Purvins *et al.*, 2013; Quoilin *et al.*, 2016; Salpakari *et al.*, 2016; Linssen *et al.*, 2017); nevertheless, because their focus is on maximising PV self-consumption they have not used control strategies to decrease the contracted power of the grid.

As regards the economic viability of PV-battery systems, significant studies such as (Eicker *et al.*, 2014; Hoppmann *et al.*, 2014; Ciez *et al.*, 2016; Linssen *et al.*, 2017) have been carried out. However, these studies aimed at supplying overall building's electricity demand and not a specific load such as HVAC equipment, and they do not provide information on the economic savings of PV-battery systems compared with that of other grid connection scenarios.

In the second part of this thesis, a more detailed state of the art of all points discussed in this introduction (PV in the building environment, BESS for PV systems, HVAC, and economic viability of PV hybrid systems) is presented.

1.2. Object of the research

Despite the importance of HVAC systems in the energy balance of buildings, the review previously done in [Section 1.1](#) demonstrates that specific strategies for combining local PV generation and electricity storage with HVAC equipment powered by electricity (especially reversible heat pumps) are still under study.

In the context above, this thesis seeks to investigate the technical and economic benefits of using a grid-connected PV hybrid system in combination with optimised control strategies to supply HVAC consumption in buildings, as shown in [Fig. 1.6](#) below:

Figure 1.6: Object of research outline.

To meet this goal, this thesis is based on an extensive experimental campaign that has allowed data to be obtained of the different variables involved in the HVAC system (see [Fig. 1.7](#)). In addition, two heat pumps configured to maintain comfort conditions inside the experimental building have been installed. The power required

for the heat pumps comes from a grid-connected PV hybrid system. In this hybrid system, an algorithm has been developed to establish different control strategies in order to optimise the use of the battery so that it can provide energy and power benefits.

The strategies are based on a previously developed model for PV hybrid systems that calculates the main electricity flows, battery status and overall system performance in terms of self-sufficiency and self-consumption (see [Fig. 1.7](#)).

The model —implemented in a simulation tool called *PVBat*— also performs an economic analysis and sensitivity analysis, providing the billing savings that the PV hybrid system would produce in comparison with a conventional grid-only supply. Likewise, the projected levelized cost of electricity (LCOE) and the investment payback-time can be calculated by considering the initial costs of both the PV system and the BESS, as well as battery lifetime, equipment changes and current electricity pricing. Three case studies with real or estimated data on PV generation and electrical consumption have been analysed using *PVBat*, allowing the optimum dimensions of a PV-battery system to be sized from a technical or economic point of view, according to the users' needs.

1.2.1. Main parameters

To analyse the behaviour of the PV hybrid system, the following parameters were considered.

- P_{pv} : Power produced by the PV system.
- P_{load} : HVAC electricity consumption.
- P_{grid} : Exported/imported grid power.
- P_{bat} : Charge/discharge battery power.
- ϵ_{sc} : Self-consumption, and ϵ_{ss} : Self-sufficiency.
- *Economic analysis*: LCOE, payback-time, and billing saving.

In [Fig. 1.7](#), a diagram of the input variables and main parameters is shown; and, in the third part of this thesis a detailed explanation of the modelling and experimental work, as well as the different case studies analysed, will be provided.

Figure 1.7: Flowchart of the model developed: main parameters and variables.

1.3. Hypothesis

Next, the research hypothesis (H1) and the null hypothesis (H0) are presented:

Research hypothesis:

A grid-connected PV hybrid system is able to supply HVAC consumption in a building in such a way that it is profitable from the technical and economic point of view.

Null hypothesis:

A grid-connected PV hybrid system is able to supply HVAC consumption in a building, but it is not profitable from a technical or economic point of view.

H1 and H0 are divided into two distinct parts, the first being common to both. *A priori*, the quick response to this premise is ‘yes’, because any of the elements of the system —PV or BESS— can be oversized, allowing HVAC consumption always to be supplied.

The second part of the research hypothesis indicates that the system is technically and economically profitable. In order to test this premise, it is necessary to determine the optimised sizes of each of the components of the system so that it is attractive and competitive compared with traditional electricity distribution grid.

The technical point of view involves variables such as self-consumption, self-sufficiency, sizing of the PV system and the BESS, equipment characteristics and expected lifetime. The optimised sizing of these parameters will determine whether it is technically feasible to install a grid-connected PV hybrid or conventional PV and, ultimately, whether the loads can be disconnected from the utility grid.

The economic point of view involves many variables, such as: the price of PV system and BESS, cost of electricity generated by the system, current and future electricity prices, inflation, discount rate, cost of operation and maintenance, etc. The economic analysis will show whether the cost of electricity generated by the PV hybrid system is competitive compared with the retail electricity price, and whether or not payback of the investment will be achieved.

Research questions

Hence, to check the research hypothesis and the null hypothesis this thesis attempts to answer the following research questions:

- a. What is the electricity demand of maintaining comfort conditions inside a building?
- b. Is the electricity generated by a PV system installed in a building capable of supplying HVAC consumption?
- c. To what extent can a BESS increase energy savings in a building with a grid-connected PV system?
- d. Is it possible to implement battery control strategies leading to high PV self-sufficiency levels in power and energy terms?
- e. What is the influence of the control strategies on the batteries lifetime?
- f. What are the economic savings, and under what conditions is the financial investment profitable when installing PV hybrid systems to supply the HVAC consumption in a building?

1.4. Objectives

1.4.1. General objective

To technically and economically optimise PV hybrid systems to supply HVAC consumption in buildings through battery control strategies.

1.4.2. Specific objectives

1. To install and monitor an HVAC system based on heat pumps in the experimental house, in order to evaluate the electricity consumption necessary to maintain comfort conditions inside the building.
2. To implement control strategies in order to high PV self-sufficiency levels in power and energy terms.
3. To develop appropriate models and software tools in order to simulate the behaviour of grid-connected PV hybrid systems in different scenarios.
4. To experimentally validate the models and control strategies used, through an extensive measurement campaign in the test building.
5. To perform a technical-economic analysis of case studies under realistic operation conditions, in order to evaluate the profitability of the system in each case.

1.5. Thesis structure

This thesis is divided in four parts: *i*) Introduction, *ii*) State of the art, *iii*) Methodology and validation, and *iv*) Results and conclusions. Every part groups together several chapters that are related to each other.

The State of the art is composed by [Chapters 2, 3 and 4](#). [Chapter 2](#) describes the PV systems in building environments, including main definitions and categories of PV self-consumption schemes. [Chapter 3](#) presents a review of electricity storage systems currently used in conjunction with distributed PV generation. [Chapter 4](#) provides an overview of buildings climate control, heat pumps technology, and thermal comfort in buildings.

The methodology is presented in Part III, which is composed by [Chapters 5, 6 and 7](#). [Chapter 5](#) presents the experimental stage and the measuring instruments description in detail. In [Chapter 6](#), the grid-connected PV-battery systems

modelling is explained in detail along with the two battery control strategies presented in this thesis. This Chapter also presents the validation of the model compared with the experimental campaign carried out. [Chapter 7](#) presents the formulation used in order to determine the economic viability of PV-battery systems.

Part IV is constituted by [Chapters 8](#) and [9](#). [Chapter 8](#) shows the results of this thesis, grouped in three case studies. These studies were submitted to scientific journals. Finally, in [Chapter 9](#), the main findings are summarized, and conclusions are drawn together with proposals of future works.

For a better understanding of the thesis structure, a schematic representation of the chapters is shown in the figure below.

Figure 1.8: Thesis structure.

Part II

State of the art

Chapter 2

PV in the building environment

2.1. Introduction

Generally speaking, electricity systems have traditionally consisted of large power stations (coal, gas, hydropower, nuclear, etc.) that inject the energy produced into the transmission and distribution grid and finally into consumers' electric grid. The energy flow is unidirectional, and the generation plants are usually far from the final consumption. In contrast to this model, distributed generation⁴ (DG) is being implemented widely throughout the world ([Bollen *et al.*, 2011](#); [Adefarati *et al.*, 2016](#); [Bansal, 2017](#); [Swayne *et al.*, 2017](#)), in which generation plants are relatively small⁵ —compared to big central power stations— and connected directly to the distribution grid. Grid interconnection and extension costs are significant factors for integrating Renewable Energy Sources (RES) generation technologies into an existing electricity grid ([Bhatia, 2014](#)).

⁴ The term 'distributed generation' (DG) refers to the production of electricity (electric power generation units) connected directly to the distribution network or connected to the grid on the customer site of the meter.

⁵ DG can vary between a couple of kilowatts to up ~300 MW, according to the following categories: micro: $\sim 1 \text{ W} < 5 \text{ kW}$; small: $5 \text{ kW} < 5 \text{ MW}$; médium: $5 \text{ MW} < 50 \text{ MW}$; and, large: $50 \text{ MW} < \sim 300 \text{ MW}$ ([Ackermann, 2001](#); [Prakash *et al.*, 2016](#); [Theo *et al.*, 2017](#)).

In the field of the PV modules installed in buildings ([German Solar Energy Society \(DGS\), 2013](#); [IEA-SHC, 2013](#); [CENELEC, 2016](#); [Biyik *et al.*, 2017](#)) PV systems can be classified into two main groups: Building Attached Photovoltaic (BAPV) and Building Integrated Photovoltaic (BIPV), as shown in [Figure 2.1](#). BAPV is a PV system added on the building and has no direct effect on the structure's functions. On the other hand, in the BIPV systems, the PV modules can be integrated in the building envelope (into the roof or façade) by replacing conventional building materials. Therefore, BIPV systems have an impact on the building's functionality and can be considered as an integral part of the energy system of the building. In a BIPV scheme, PV modules can be naturally blended into the design of the building, creating a harmonious architecture ([Henemann, 2008](#)). For the purpose of this thesis, both terms BAPV and BIPV will be used interchangeably like BIPV or grid-connected PV systems or PV systems on buildings, where the installed PV power and the annual PV electricity generation are the most important parameters to consider.

Figure 2.1: a) Example of BAPV: Grid-connected PV system set up on the terrace at IES-UPM. b) Example of BIPV: Grid-connected PV system on façade of a Near Zero Energy Buildings prototype called ‘Magic-Box’ at IES-UPM.

Although grid-connected decentralized PV installations are the fastest growing power generation technology —with around 30% of the total PV installations in 2016 ([IEA PVPS, 2017](#))—, rules and procedures for governing the penetration of the PV generation into the utility grid system are still under discussion at international level and in each region and country ([IEA PVPS, 2017](#)).

Two additional concepts should be distinguished among grid-connected PV systems: *i*) Nearly Zero Energy Buildings (nZEB), where energy consumption is reduced but still a negative balance, and *ii*) Positive Energy Buildings (PEB), where PV systems produce more energy than the building consumes ([Directive 2010/31/EU](#); [Kolokotsa *et al.*, 2011](#); [Salom *et al.*, 2011](#)). In both cases, the PV electricity not self-consumed is therefore exported into the grid.

Grid interconnection of the PV systems

Grid interconnection of a PV system has the advantage of more effective utilization of the generated power (Eltawil *et al.*, 2010). However, the technical requirements from both the utility grid side and the PV system side need to be satisfied to ensure the safety of the PV user and the reliability of the utility grid.

The main elements of a grid-connected PV system are shown in Figure 2.2. The inverter may fix the DC voltage at which the PV array operates, or —more commonly— uses a maximum power point tracking function to identify the best operating voltage for the array and then convert it to AC voltage. The inverter operates in phase with the utility grid and it is generally delivering as much power as it can, depending on the available sunlight and temperature conditions. Grid-connected PV systems can be found in different sizes and power levels for different needs and applications, ranging from a single PV module of around 200 W to more than a million modules for PV plants over 300 MW (Ackermann, 2001; Braun *et al.*, 2010; Kouro *et al.*, 2015; Prakash *et al.*, 2016; Theo *et al.*, 2017).

Figure 2.2: Grid-connected PV system general scheme.

Grid-connected PV systems standards

The main international standard is IEC 60364-7-712 ([IEC, 2017a](#)), which is formally entitled: ‘Low voltage electrical installations: Part 7-712: Requirements for special installations or locations, solar PV power supply systems’. This standard is applied in electrical installations of PV systems in order to supply all or part of building electrical demand. The equipment of a PV installation, like any other item of equipment, is dealt with only so far as its selection and application in the installation is concerned.

Other relevant standards —according to international organizations: IEC (International Electrotechnical Commission), EN (European standard) and UNE (Spanish Association for Standardization)— are:

- IEC-EN-UNE 62446-1 ([IEC, 2016b](#)): Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance – Part 1: Grid-connected systems – Documentation, commissioning tests and inspection.
- IEC-EN-UNE 61727 ([IEC, 2004](#)): Photovoltaic (PV) systems - Characteristics of the utility interface.
- IEC-EN-UNE 61140 ([IEC, 2016a](#)): Protection against electric shock – Common aspects for installation and equipment.
- IEC-EN-UNE 61277 ([IEC, 1995](#)): Terrestrial photovoltaic (PV) power generating systems - General and guide.
- IEC-EN-UNE 61724 ([IEC, 2017b](#)): Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis.
- UNE-EN 50583-2 ([AENOR, 2016](#); [CENELEC, 2016](#)). Photovoltaics in Buildings - Part 2: BIPV Systems.

2.2. Self-consumption and Self-sufficiency

The electricity from a PV system that can be consumed immediately or within a timeframe by the building is called self-consumption or PV self-consumption.

Self-consumption should not be confused with self-sufficiency ([Luthander et al., 2015](#)). The ratio of self-consumption describes the local use of PV electricity while the self-sufficiency ratio describes how PV production can cover the needs of the building. These concepts are completely different, but both play important roles in the debate on the development of PV systems.

In order to explain the difference between self-consumption and self-sufficiency, PV generation and electricity demand curves of a typical residential user — over a day — are shown in [Figure 2.3](#).

Figure 2.3: Schematic outline of daily net load ($B + C$), net PV generation ($A + C$) and absolute self-consumption (C) in a building with PV system.

The area below the blue line is the PV generation (areas A and C); and, the area below the green line is the building electricity demand (areas B and C). The overlapping part (area C) is the PV power that is utilized directly within the building. This is sometimes referred to as the absolute self-consumption, as in (Widén, 2014), denoted by $A_{sc}(t)$. However, if the absolute self-consumption is relative to the total PV generation, then it is called self-consumption, i.e. $C/(A+C)$. Furthermore, the absolute self-consumption relative to the total electricity demand is also a commonly used metric, so-called self-sufficiency, i.e. $C/(B+C)$.

The term self-sufficiency is also known as ‘autarky rate’ (Grundner *et al.*, 2014; Linssen *et al.*, 2017), and there is no consensus on a common nomenclature. In the following, the term ‘self-sufficiency’ will be used in this thesis as referred to in (Schreiber *et al.*, 2013), which defines the ‘self-sufficiency’ as the absolute self-consumption normalized by the total power demand. This definition clearly expresses the degree to which the PV generation is sufficient to meet the building’s electricity needs.

To define self-consumption and self-sufficiency more formally, the instantaneous building power consumption is denoted by $P_{load}(t)$, and the instantaneous PV generation is denoted by $P_{pv}(t)$. Self-consumption (ϵ_{sc}) and self-sufficiency (ϵ_{ss}) can be expressed as:

$$\varepsilon_{sc} = \int \frac{A_{sc}(t)}{P_{pv}(t)} dt \quad (2.1)$$

$$\varepsilon_{ss} = \int \frac{A_{sc}(t)}{P_{load}(t)} dt \quad (2.2)$$

where

$$A_{sc}(t) = \min\{P_{pv}(t), P_{load}(t)\} \quad (2.3)$$

According to equations 2.1 and 2.2, the self-consumption and self-sufficiency ratio can vary from a few percent to a theoretical maximum of 100%, depending on the PV system size and the local load profile.

2.3. Self-consumption schemes

Several countries have adopted different schemes in order to regulate the PV self-consumption. These schemes allow self-produced PV electricity to reduce the PV system owner's electricity bill, on-site or even between distant sites. Some schemes compensate electricity consumption and the PV electricity production, some compensate real energy flows, while others are compensating financial flows. While details may vary, the bases are similar.

In order to compare existing self-consumption schemes, the (IEA-PVPS, 2016) published a comprehensive guide to analyse and compare self-consumption policies and schemes. This 'Review of PV Self-Consumption Policies' proposes a methodology to understand, analyse and compare schemes that might be fundamentally diverse, sometimes under the same wording. It also proposes an analysis of the most important elements impacting the business models of all target groups, from grid operators to electric utilities.

Before defining the main self-consumption schemes, it is necessary to introduce some basic terms:

- *Retail electricity price (retail)*

The retail price is the electricity price from the utility grid company or from the retail electricity provider. These companies sell and purchase electricity on the wholesale market; it is called wholesale electricity. The price of wholesale electricity is usually lower than the price of retail electricity. This is because to the wholesale price of electricity must be added the purchasing charges, then organizing the

delivery to the customer, adding sales taxes and state charges such as low-income assistance and renewable energy incentives; finally, the retail price of electricity is obtained (Mirza *et al.*, 2012; Costa-Campi *et al.*, 2015; Sekizaki, Nishizaki *et al.*, 2016).

- *Prosumer*

The neologism ‘prosumer’ refers to an electricity consumer producing electricity to support its own consumption (and possibly for injection into the grid). The word is built based on the association of ‘producer’ and ‘consumer’. The term prosumer was coined by Alvin Toffler in 1980 (Kotler, 1986) and it is used widely nowadays (IEA-PVPS, 2016). In this thesis, the term prosumer will be used in parallel with ‘PV system owner’ to qualify the same thing.

- *Bill savings*

This term reflects the difference between the value of an electricity bill without a PV system and the value of an electricity bill with a PV system and any of the self-consumption schemes.

Now, the definition of the main self-consumption schemes used worldwide is provided:

- *Feed-in tariff (FiT)*

Feed-in tariff occurs when electricity produced by the PV system is injected into the grid and it is paid —usually by the utility grid— at a predefined price -at a rate per kWh that may be higher or lower than the retail electricity rates— and guaranteed during a fixed period (Couture *et al.*, 2010). This assumes that a PV system produces electricity for exporting into the grid with or without self-consumption. The most successful examples of FiT systems can be found in China, Japan, Germany and Italy, to mention a few (IEA-PVPS, 2016).

- *Net-metering or Net-energy-metering (NEM)*

If more electricity is produced than consumed, depending on the legislative arrangements in place as well as the arrangements with the electric utility grid, PV owners may receive a benefit for this positive balance, which is credited on the consumer’s account toward the next billing cycle (Poullikkas, 2013). Net-metering is an energy compensation (credit in kWh) when the excess of PV electricity is

valued at the same price as the retail price ([Darghouth et al., 2011](#)). A NEM scheme allows such compensation to occur during a longer period of time, ranging from one month to several years, sometimes with the ability to transfer the surplus of production to the next months. This system exists in several countries and has led to some rapid markets development.

- *Virtual net-metering (VNM)*

Virtual net-metering is a characteristic of a Net-metering scheme that allows the distribution of credits across more than one meter (e.g. in multi-tenant properties). VNM is a bill crediting system for a grid-connected PV community. It works when PV electricity is not used on-site but is instead externally shared among subscribers. In this case, PV owners receive credits on their electricity bills for the excess of PV electricity ([Watts et al., 2015](#)).

- *Net-billing*

This is a monetary compensation (credit in monetary unit). While self-consumption assumes an energy netting (kWh produced are locally consumed and reduce the electricity bill), Net-billing assumes two different flows of energy that might have different associated prices. The prices related to these two flows are netted to calculate the reduction for the consumer's electricity bill. In this business model, the compensation for the excess electricity will be below or equal to the retail price of electricity.

Under a Net-billing scheme, a consumer will see an advantage when an excess of PV electricity is recorded over longer time intervals and when installing a PV system with smaller capacity relative to the household electricity consumption ([Watts et al., 2015](#)).

- *Tendering*

Tendering occurs when PV electricity is exported into the grid and other customers may buy this electricity and pay rates corresponding to the PV production costs. On the supply-side, only the most cost-effective projects are selected by a bidding process. This scheme has been adopted in many countries around the world, with the clear aim of reducing the cost of PV electricity. Since bidders must compete with each other, they tend to reduce the bidding price to the minimum possible and decrease their margins ([Haas, 2003](#); [IEA-PVPS, 2016](#); [SolarPower Europe, 2016](#)).

- *Power Purchase Agreements (PPA)*

A PPA is a financial agreement where an investor arranges for the design, permitting, financing and installation of a PV system on a customer's property at little to no cost. The investor sells the PV electricity generated to the host customer at a fixed price that is typically lower than the local utility's retail price. This lower PV electricity price serves to offset the customer's purchase of electricity from the grid while the investor receives the income from these sales of electricity as well as any tax credits and other incentives generated from the system. PPAs typically range from 10 to 25 years and the investor remains responsible for the operation and maintenance of the system for the duration of the agreement. At the end of the PPA contract term, the customer may be able to extend the PPA, have the investor remove the system or choose to buy the PV system (Davidson *et al.*, 2015; EPA, 2017; SEIA, 2017).

2.4. Regulatory frameworks

Given the diversity of policies allowing for PV self-consumption that are being implemented worldwide, in order to facilitate the comparison between existing all self-consumption schemes, several parameters have been proposed, covering all relevant aspects of the process (IEA-PVPS, 2016). These parameters aim at categorizing all kinds of policies supporting self-consumption and to clarify the wording used in several schemes, especially Net-metering and Net-billing schemes. The table below provides the parameters description used in Tables 2.2 and 2.3.

Table 2.1 shows the meaning of the mentioned parameters, which can be grouped into three main blocks. Parameters 1, 2 and 3 indicate whether self-consumption is permitted and under what financial arrangement. Parameters 4, 5 and 6 are about the excess of PV electricity. Finally, the parameters from 7 to 13 refer to other regulations allowed in each self-consumption scheme.

Table 2.1: Main parameters to define PV self-consumption schemes. Source: IEA-PVPS

Nº	Parameter	Meaning
1	Right to self-consumption	This parameter identifies whether the prosumer has the legal right to connect a PV system to the grid and self-consume a part of its PV-generated electricity.
2	Revenues from PV self-consumption	This parameter is based on the source of revenue from each kWh of PV self-consumed. It comprises not only the billing savings but also possible additional revenues such as a self-consumption bonus or green certificates.
3	Charges to finance grid costs	This parameter indicates whether the PV system owner must pay part of the total grid costs on the PV self-consumed.
4	Revenues from excess PV electricity	This parameter explains which compensation the prosumer will receive when PV electricity is injected into the grid.
5	Maximum timeframe for credit compensation	This parameter refers to schemes that allow credits for all electricity injected. Such credits can, in general, be used during a certain period during which compensation is permitted.
6	Geographical compensation	This parameter indicates whether consumption and PV generation can be compensated in different locations.
7	Regulatory scheme duration	This parameter indicates the duration of the compensation scheme in term of years.
8	Third-party ownership	This parameter indicates whether policies are permitting a third-party to own the PV generation asset when a self-consumption scheme is in place.
9	Grid codes and additional taxes/fees	This parameter describes which additional costs must be borne by prosumer, and which specific grid codes can be asked (e.g. grid code requirements such as phase balancing, frequency-based power reduction, reactive power control, voltage dips, inverter reconnection conditions, output power control, etc.).
10	Other enablers of self-consumption	Are there other additional supports to self-consumption such as a storage system or demand-side management?
11	System Size Limitations	This parameter states which segments are considered by the compensation scheme and if applicable which capacity limit is applied.
12	Electricity System Limitations	This parameter explains whether the regulator has foreseen a maximum penetration of PV above which the self-consumption regulation does not apply anymore. For instance: above 2% of the electricity demand or above 10% of the minimum peak load.
13	Additional features	This last parameter includes all other elements not considered above. For example, rules for aggregation of RES would be described here in case they are required when selling PV electricity on the electricity market.

Based on these parameters, [Table 2.2](#) and [Table 2.3](#) summarize the main characteristics of the PV self-consumption schemes used in countries from Europe, America, Asia and Oceania, in order to show the main characteristics related to the procedures of grid-connected PV systems on buildings.

Table 2.2: Summary of PV self-consumption schemes for some countries of Europe. Source: IEA-PVPS

Parameter Table 2.1	BELGIUM	DENMARK	FINLAND	FRANCE	GERMANY	ITALY	SPAIN	SWEDEN	SWITZERLAND	NETHERLANDS	UK
1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill
3	Capacity based fee	None	None	None	None	Above 20 kW	Yes ('sun tax')	None	None	None	None
4	Retail	Retail	Retail	FiT	FiT	SSP	Type 1: none Type 2: yes	Various offers from utilities + Green certificates	FiT	Retail and NEM	Generation tariff + export tariff
5	1 year	1 Hour	Real-time, hourly	Real-time	Real-time	Payment twice per year	Real-time	1 year	Real-time	1 year	Real-time
6	On-site	On-site	On-site	On-site	On-site	On-site	On-site	On-site	Multi-family Housing	Multi-family Housing	On-site
7	Unlimited	20 years	Unlimited	20 years (FiT)	20 years (FiT)	Unlimited	Unlimited	Subject to annual revision	Unlimited	Unlimited	20 years
8	Yes	Yes	Yes	None	All	Yes	None	Yes	Yes	Yes	Yes
9	Capacity based fee	Yes	Grid codes	Sharing fixed grid costs.	Grid codes	None	Above 10 kW	Grid codes	Grid codes	None	None
10	Time-of-use (ToU) tariffs	ToU	No	ToU	Battery storage incentives	None	None	ToU	None	ToU	None
11	Up to 10 kW	6 kW	Power <100 kVA or energy <800 kWh/y	None	Minimum 10% of self-consumption	None (below 20 MW), SSP up to 500 kW	100 kW but below or equal to capacity contracted	Below 100 A Max or 30 MWh/year	None	15 kW	30 kW
12	None	800 MW	No	None	52 GW of PV installations	None	Distributor's license	None	None	None	None
13	Green certificates	None	No	Projects to increase the fixed part of grid costs.	RES must be paid by the prosumer (above 10kW)	None	Taxes on batteries	None	Direct subsidies up 30 kW and some specific rules.	None	None

Table 2.3: PV self-consumption schemes for some countries of America, Asia and Oceania. Source: IEA-PVPS

Parameter Table 2.1	BRAZIL	CANADA	CHILE	MEXICO	USA	AUSTRALIA	CHINA	ISRAEL	JAPAN
1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill + bonus	Savings on the electricity bill	Savings on the electricity bill
3	None	None	None	None	In specific states	In specific states	None	None	
4	Retail	Ontario: Retail and NEM	Lower value than the Retail	Retail and NEM	Retail and NEM	FiT	Retail + bonus	Retail and NEM	FiT
5	3 years	Depending on the jurisdiction	1 year	1 year	Vary by state	30 minutes	Real-time	2 years	Real-time (30 minutes)
6	VNM	On-site	On-site	VNM	On-Site	On-site	On-site	Credits can be transferred to other consumers	On-site
7	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited	20 years	Unlimited	10 years (FiT)
8	Yes	Yes	Yes	Yes	Yes	Yes	None	Yes	Yes
9	None	Yes	None	None	Vary by state.	Yes	None	Systems costs grid, back-up and balancing costs	None
10	Time-of-use (ToU)	ToU	None	None	ToU	None	None	None	ToU, Storage and DSM
11	1 MW	Vary from jurisdiction	100 kW	500 kW	from 10 kW to 10 MW	None	20 MW - 35 kV	5 MW	Below 10 kW
12	None	None	None	None	In some states	None (except additional grid codes)	7 GW for distributed PV installations	None	None
13	None	In Ontario FiT	None	Additional incentives	Depending on the state	None	None	None	None

Tables 2.2 and 2.3 outline in a general manner what is happening in the world. It is necessary to note that each country could have different schemes. For instance, in the U.S, by 2015, 42 states had laws crediting customers for exported electricity, typically through a ‘net-metering’ scheme. Three states currently have FiT that are accepting new applicants. In most cases, the financing of these measures is done through indirect public funding and/or absorbed by utilities. In 2015, PPAs have emerged as an effective financial mechanism for residential systems and are even beginning to rival third-party ownership in some markets (IEA-PVPS, 2016; Schelly *et al.*, 2017).

Another region that encourages the PV self-consumption is Europa (Dusonchet and Telaretti, 2015). For instance, in Germany, the EEG (the German Renewable Energy law) has introduced the FiT idea and has continued to promote it partially. It introduced a FiT for PV electricity that is rewarded in the consumer electricity bill. In September 2012, Germany abandoned FiT for installations above 10 MW in size and continued to reduce FiT levels in 2013 and 2014. Since August 2014, 30% of the surcharge for renewable electricity will have to be paid by prosumers for the self-consumed electricity for systems above 10 kW. This part will increase up to 40% in 2017 (Braun *et al.*, 2009; Moshövel *et al.*, 2015; Merei *et al.*, 2016).

In other countries, traditional schemes have been modified and new models have been created. In Italy, for instance, in 2009 switched from the net-metering mechanism to the so-called ‘*Scambio Sul Posto*’ (SSP) (Spertino *et al.*, 2013) for systems below 200 kW and 500 kW for PV systems installed starting from 2015. The SSP is a variation of the net-billing scheme, in which electricity fed into the grid is remunerated through an ‘energy quota’ based on electricity market prices. In the SSP, different prices are attributed to consumed and produced electricity, allowing a financial compensation with additional features, guaranteed export price (Dusonchet and Telaretti, 2015; Gaspari and Lorenzoni, 2017).

Spanish context

The Royal Decree (RD) RD 900/2015, adopted on 9th of October 2015, regulates administrative, technical and economic modalities for electricity supply and generation with self-consumption. The regulations of the RD apply to any renewable generation facility that produces electricity for self-consumption and is connected to the national grid. The RD establishes two self-consumption models:

- *Type 1*: Supply with self-consumption. This type of self-consumption model applies to installations no larger than 100 kW. The electricity is only generated for self-consumption. The surplus of the PV electricity can be exported to the grid, but it is not remunerated with economic compensation.
- *Type 2*: Generation with self-consumption. This refers to a consumer in a single facility or supply point which is associated to one or several production facilities connected within the grid, or which share connection infrastructure with it or is connected to it. In this modality, the owner of the PV installation is legally treated as both a consumer and producer. The surplus of the generated electricity can be exported to the grid and is remunerated with the economic compensation, i.e. renewable self-consumption is thus considered to be a form of economic production rather than a form of saving.

The [RD 900/2015](#) also establishes a backup charge billed to all PV producers that are linked to the electricity grid (popularly known as ‘sun tax’). It is divided into two parts: *i*) a fixed charge based on the installed capacity (€/kW/year), and *ii*) a variable charge based on the self-consumed electricity (€/kWh).

The fixed charge is applicable in two cases: when a storage system is used⁶, on the one hand; and, on the other hand, when PV installations more than 100 kW_p (with no storage) are managed in order to reduce the contracted power ([Solartradex, 2016](#)).

The variable charge applies to both types of modality, but there are exemptions for type 1 installations equal or less than 10 kW of installed capacity, and for the installations located in extra-peninsular systems: islands (Balearic and Canary) and autonomous cities (Ceuta and Melilla). Other exemptions are the cogeneration facilities that are registered with ‘Electricity Production Facilities Administrative Register’ with the requirements set by RD 661/2007, those installations are exempted from payment charges until 31st of December 2019.

The original RD has undergone modifications (the last update was published on 1st of July 2017). In a decision dated 25th of May 2017, the Spanish Constitutional Court annulled the prohibition of self-consumption in community facilities, included in the original document. The sentencing also annulled the Articles 19 to 22 of the RD, which regulate the administrative registration of electric self-consumption, whose management has been entrusted to the General Directorate of Energy Policy and Mines of the Ministry of Industry, Energy and Tourism ([UNEF, 2017](#)).

⁶ Only when storage is used to reduce contracted power (peak-shaving function).

2.5. PV Systems and Smart Grids

Smart grids may be defined as ‘electricity networks that can intelligently integrate the behaviour and actions of all users connected to it –generators, consumers and those that do both– in order to efficiently deliver sustainable, economic and secure electricity supplies’ ([European Commission, 2006](#); [Clastres, 2011](#)).

In any electric energy system, the customers’ objective is to minimize their energy cost, whereas utilities are not only concerned about the cost, but also other issues such as load shape, peak load, quality of service, etc. In this respect, the smart grids are attempting to connect large penetrations of PV electricity (susceptible of being deployed in a generalized manner in the built environment) with buildings demand, through communications signals. With these developments, both utilities and prosumers can have access to two-way communication infrastructures, control devices, and visual interfaces that allow them to send, retrieve, visualize, process and/or control their electricity needs ([Bozchalui *et al.*, 2012](#)).

The latest version of the inventory of smart grid projects in Europe ([Covig *et al.*, 2014](#)) included 459 smart grid projects from all 28 European Union countries and others. Through an in-depth analysis of the database, 58 projects with the primary focus on PV integration into the electricity grid were identified.

As for the geographical distribution of investments, PV smart grid projects are not uniformly distributed across Europe, with Italy, France, and Spain accounting for about 60% of the total investments ([Fulli and Gangale, 2016](#)).

Smart grids will, therefore, enable a higher interaction between the main stakeholders —utility grid and prosumers— of the electricity market. Through smart grids (smart meters, smart pricing, smart peak-load curtailment, demand-side management, etc.) the electricity consumption of buildings will be able to adjust its demand to the generation in order to minimize the imported grid electricity. In this way, the profitability of the investment in a PV system for self-consumption will probably increase with a smarter grid.

Due to the dependence of PV generation on a variable energy source — the sun —, for a higher overall efficiency, the correlation between generation and consumption in the built environment is highly desirable. In essence, two methods are used for improved self-consumption, the first one through Demand Side Management (DSM) and the second one using an energy storage system. These techniques can be either used separately or combined, as shown in [Fig. 2.4](#).

Figure 2.4: Scheme of a PV Smart Grid, using DSM and battery energy storage system. Source: (Castillo-Cagigal, Gutiérrez, et al., 2011).

Demand-side management (DSM)

According to [Castillo-Cagigal et al. \(2011\)](#), DSM is defined as actions that influence the way that consumers use electricity in order to achieve savings or higher efficiency in energy use.

There are other definitions of the concept of demand-side management (DSM), where the common denominator is to improve the electrical system on the consumption side ([Palensky and Dietrich, 2011](#)). The term is used for load shifting, which can be used to shift the power demands of the loads in a building —some appliances and machines— from time periods with the highest consumption to periods with PV surplus generation, as shown in [Fig. 2.5](#).

Figure 2.5: PV power and load consumption daily profile for (a) without DSM and (b) with DSM. Source: (Castillo-Cagigal, Gutiérrez, et al., 2011)

Load shifting can be achieved either manually, where persons switch on electric devices when the sun is shining, or automatically, which requires control algorithms and devices, and sometimes also weather forecasts of ambient temperature and solar irradiance. DSM can also be combined with battery storage to further increase the self-consumption (Castillo-Cagigal, Caamaño-Martín, *et al.*, 2011; Castillo-Cagigal, Gutiérrez, *et al.*, 2011).

Energy storage, in particular, has attracted much interest as a cost-effective solution to accommodate a large share of variable generation and increased demand peaks (Fulli and Gangale, 2016). Storage provides flexibility by shifting the time between PV generation and electricity consumption, thus reducing the need for expensive grid reinforcements. The flexible nature of storage can offer a wide range of services at short notice to help with system balancing. Battery energy storage for grid-connected PV systems will be analysed in greater depth in Chapter 3.

2.6. Relevant studies

Finally, to conclude this Section, other important research related to PV self-consumption schemes is summarized below.

The role of grid-connected PV systems in commercial buildings in warm and sunny climates is analysed by [Braun and Rüther \(2010\)](#). In this work, the load consumption of a large urban commercial building located in Brazil is presented. The authors conclude that PV systems can contribute to alleviating the distribution grid, shifting demand peaks when there is a good match between loads and the PV power.

An analysis of Feed-in-Tariff remuneration models was carried out by [Couture and Gagnon \(2010\)](#). This paper presents an overview of seven different ways to structure the remuneration of a FiT policy, divided into two broad categories: *i*) remuneration dependent on the electricity price, and *ii*) remuneration independent from it. This paper examines the advantages and disadvantages of these different FiT models, and concludes with an analysis of these design options, with a focus on their implications for both investors and society. The authors conclude that premium price policies create incentives to encourage electricity generation when it is needed most, which can alleviate peak supply pressures and improve the market integration of renewable energy sources.

The impact of the rate design and net metering on the bill savings from distributed PV for residential customers in California was studied by [Darghouth et al. \(2011\)](#). This paper examines the value of the bill savings that customers receive under Net-metering, and the associated role of the retail rate design, based on a sample of approximately 200 residential customers of California's two largest electric grid utilities. This research concludes that the bill savings per kWh of the PV system vary by more than a factor of four across the customers in the case study.

A comparison of Net-metering and Feed-in-Tariff schemes for residential PV systems was carried out by [Poullikkas \(2013\)](#). The effect of the size of the PV system with respect to the Net-metering supporting scheme is examined by varying the PV capacity and the effect of the electricity retail cost. The comparative results indicate that a Net-metering scheme performs better than a FiT scheme when the household electricity bill is taken into account.

Widén (2014) studied PV Self-consumption with detailed monitoring data from 200 Swedish households. He demonstrated that PV Self-consumption can be improved by appliance scheduling (washing machines, clothes dryers and dishwashers) through load shifting. However, the main conclusion was that there is an overall small contribution to the potential PV self-consumption from optimal scheduling of the studied appliances and that radically different market conditions would be needed to make load scheduling provide to local distribution.

A comparative assessment of Net-metering and Net-billing schemes for Spain was carried out by Dufo-López and Bernal-Agustín (2015). In this paper, a modified definition of some of the modalities that can be applicable to the two drafts (at that time) of the RD 900/2015 was proposed. Also, a mathematical formulation for the assessment of the different modalities of Net-metering and Net-billing used in different countries was shown, taking into account the drafts and the model proposed. The paper concludes that the first Spanish draft would have been a superior regulation for PV Net-metering; however, the second draft impedes the profitability of the PV, so no user will install a grid-connected PV system if this second draft is finally approved.

Watts *et al.* (2015) analysed the potential of grid-connected PV systems in Chile through the comparison of Net-metering and Net-billing schemes. This paper reviews the opportunity to take advantage of these market conditions within the residential sector, modelling PV arrays across ten cities in Chile. A review of how Net-metering and Net-billing affect the value of the PV production is applied and a comparison using LCOE is conducted. Net-metering is found to be a better policy choice to promote PV than Net-billing because electricity exported to the grid is paid at the complete retail rate. Payback periods are found to be low, between 6 years in northern areas with high retail rates and 13 years in other areas with lower radiation and retail rates.

Darghouth *et al.* (2016) analysed the impact of retail rate design on distributed PV systems, through Net-metering and market feedback loops. In this paper, the impacts of these two schemes were examined in the U.S. through to 2050 for both residential and commercial customers. The results indicate that PV deployment trends depend on Net-metering rules and retail rate structures.

Pyrgou *et al.* (2016) studied the past and the future of the Feed-in Tariff scheme in Europe. This work discusses the FiT scheme implementation for PV systems in four case study countries (Denmark, Germany, Cyprus, and Spain). A model describing the conditions under which a FiT scheme is led to collapse is also introduced, and a parametric analysis revealing the sensitivity of the different parameters involved is delivered. The study concludes with significant policy implications that should be considered for future implementation of the scheme.

[Ramírez *et al.* \(2017\)](#) studied the economic aspects and policy implications for European countries which use Feed-in tariff and Net-metering schemes. The authors have developed an economic model to evaluate the profitability of PV projects combining these support schemes. Their results show not only the circumstances under which PV is economically profitable but also the kind of PV systems, locations, minimum levels of tariff prices and specific combinations of support schemes that should be promoted.

[Martín-Chivelet and Montero-Gómez \(2017\)](#) presented a study to optimise PV self-consumption in office buildings. This paper stresses the importance of matching the local PV generation with the building's load on annual terms to reach around 100% self-consumption and to improve the self-sufficiency rate on the building, without either storage or DSM. For that purpose, this paper proposes a methodology that helps BIPV designers to achieve these targets. Its application to a real case shows that the different facades of the building envelope may also play a role in the local PV production if their orientations receive sufficient insolation during the hours of electrical consumption.

The impact of Net-metering restrictions on the cost competitiveness of residential PV systems was studied by [Comello and Reichelstein \(2017\)](#). This paper presents a theoretical and empirical analysis of the effects of Net-metering restrictions in the USA. The authors found that if PV surplus electricity is credited at some rate set at or above the cost of PV electricity, there will be sufficient incentives for investors in residential grid-connected PV systems to continue in the current mode of solar rooftop installations, even though the profitability of these investments might be substantially reduced.

A methodology for analysing the performance of a PV self-consumption facility with different Net-metering schemes was presented by [Ayala-Gilardó *et al.* \(2017\)](#). It was based on the possibility of doing Net-metering for different time intervals. The obtained results show that, depending on the specific Net-metering scheme in the case study presented (3 kW of PV power installed in Málaga-Spain; and, yearly consumption of the building about 3600 kWh) the PV self-consumption ranges from 34% to 71%, while the PV self-sufficiency ranges from 49% to 100%.

Chapter 3

Battery energy storage for PV systems in buildings

3.1. Introduction

Energy Storage Systems (ESSs) can be defined as any installation or method, usually subject to independent control, with the help of which it is possible to store energy generated in a power generation system, keep it stored, and use it when necessary ([Hall and Bain, 2008](#); [Huggins, 2010](#); [Petricca *et al.*, 2013](#); [Zobaa, 2013](#)).

ESSs available for largely medium and small-scale applications can be divided into five main groups: mechanical, electrochemical, electrical, thermal, and chemical ([Huggins, 2010](#); [Zobaa, 2013](#); [Kousksou *et al.*, 2014](#)). According to the International Renewable Energy Agency ([IRENA, 2017](#)), within these groups, mechanical storage accounts for 99% of the global electricity storage capacity of 148 GW of discharge power. Electrochemical storage is a distant second at 0.9% and finally, supercapacitors account for a tiny percentage (0.1%). [Fig. 3.1](#) shows a general classification of ESSs with subcategories.

Figure 3.1: Classification of main ESSs technologies available. Source: Compiled by the author based on the data of IRENA (2017).

All these storage systems have shown to provide a reliable supply of buildings at places with or without a grid connection (Nair and Garimella, 2010; Camargo and Dörner, 2016). However, ESSs technologies discussed in this thesis only relate to small-scale storage systems (typically below 1MW/1MWh) coupled with distributed generation, or also called Distributed Energy Storage (DES), which refer to stationary electric energy storage systems located at or near the end use that they serve, typically at residential, commercial or industrial building (Zogg *et al.*, 2007; Ibrahim *et al.*, 2008; Aneke and Wang, 2016; Gallo *et al.*, 2016).

Technologies such as compressed air and pumped hydroelectric energy storage are not suited for DES due to the sheer size of the installations and the associated costs. Superconducting magnetic energy storage (SMES) and super capacitors are high-power devices that have very high efficiencies and can withstand several cycles without appreciable loss of energy storage capacity; however, they are not discussed in this thesis due to their high implementation costs and the relative infancy of the technologies (Hall and Bain, 2008; Zheng *et al.*, 2015). The flywheel technology is best suited to short-duration, high-power discharges and is hence well established in the critical load and backup market (Baker, 2008). Even though flywheels have a high cycling capacity, they tend to have high friction losses and their installation and maintenance incur high costs (Ibrahim *et al.*, 2008).

Table 3.1: Brief description of the main types of energy storage technologies. Source: IRENA (2017) based on IEA (2017).

ESS	Description
Pumped Storage hydropower	Uses excess energy generated to pump water from a lower to higher reservoir: stored energy then generates hydropower during high-demand periods.
Compressed air energy storage	Compressed air uses energy during low demand periods to compress air. Then it injects the air into a depleted natural gas reservoir. Next, the compressed air is used to power a generator during times when energy demand is highest.
Flywheel	Flywheel operates by storing kinetic energy in a rotating cylinder which is supported by magnetic bearings and operates in a vacuum to eliminate frictional loss.
Batteries	Batteries consisting of one or more cells, in which chemical energy is converted into electricity and used as a source of power.
Thermal	Includes a number of different technologies that accommodate a wide range of needs. Allows for excess electricity to be converted to thermal energy and stored (short-term or seasonal) for later use. Generally, not converted back to electricity, except in the case of concentrating solar (thermal) power technologies.
Supercapacitors	Stores electricity as electrostatic energy; often combined with batteries.
Superconducting magnetic	Uses superconducting technology to store electricity. It enables storing electricity in a magnetic field created by the circulation of a direct current in a superconducting ring which is cooled to a temperature below the critical superconductivity temperature.
Fuel cells	A fuel cell is an electrochemical cell that converts the chemical energy from a fuel into electricity through an electrochemical reaction of the hydrogen-containing fuel with oxygen or another oxidizing agent.
Hydrogen	Power-to-Gas is the process of converting surplus renewable energy into hydrogen gas by rapid response electrolysis and its subsequent injection into the gas distribution grid. Power-to-Gas allows for the storage of significant amounts of energy and the provision of CO ₂ neutral fuels in the form of the resulting renewable energy gas mix of hydrogen and methane.

The DES technology most commonly used is electrochemical energy storage (Glaize and Geniès, 2013; Zakeri and Syri, 2015). This technology possesses a number of desirable features, including pollution-free operation, high round-trip efficiency, and flexible power and energy characteristics to achieve different grid functions, long cycle life, and low maintenance (Yang *et al.*, 2011; Glaize and Geniès, 2013; Badwal *et al.*, 2014). Although the high cost of electrochemical storage technologies has not prevented their deployment (especially in off-grid and grid-support applications), a fall in the costs is expected in the coming years due to their modularity, scalability and use of new raw material (World Energy Council, 2016).

In electrochemical storage, on one hand, flow batteries or so-called ‘redox flow batteries’ have both poor power density and low energy density compared to other technologies, making them unsuitable for unconditioned-spaces buildings (Piergiorgio, Massimo, and Federico, 2014).

On the other hand, batteries or ‘accumulators’, have been widely used together with renewable energy systems around the world on both large scale (power generation plants) and small scale (in buildings) due to the ease of installation, scalability, relatively low cost, high energy density, ease of management, and good

control among other advantages possessed by the batteries compared to other technologies previously analysed. It is for this reason that the term ‘energy storage’ is used in this thesis to make specific reference to battery systems.

A primary battery is discarded after providing electrical power until its chemical energy is exhausted (Glaize and Geniès, 2013). A secondary battery, also called a ‘rechargeable battery’, can have its spent chemical energy restored by the application of a charging current in a direction opposite to that of the discharge current (Doeff, 2013). The types of batteries discussed in this thesis are secondary batteries.

The battery system is only one part of a major system that contains other subsystems such as monitoring and control systems and a power conversion system. So, the term ‘**Battery Energy Storage System**’ (BESS) is introduced to indicate more formally the set of subsystems that work together in order to provide electrical storage.

3.2. Elements of a BESS

BESSs together with PV systems will be referred to hereinafter as ‘PV-battery systems’, and the PV-battery systems which are also connected to the electrical grid will be referred to as ‘grid-connected PV-battery systems’ or ‘PV hybrid systems’, as shown in Fig. 3.2.

Figure 3.2: Elements of a BESS and its integration with PV systems, the electrical grid, and loads.

Below is a brief description of each of the BESS elements.

Battery bank

A battery element comprises two electrodes immersed in an electrolyte. Usually, the electrodes are in the solid state and the electrolyte is in the liquid or gelled state. The two electrodes are respectively qualified as ‘positive’ and ‘negative’. The terms ‘anode’ and ‘cathode’ will not be used because each electrode changes its role depending on whether the secondary battery is being charged or discharged.

A 'battery bank' is the serial and/or parallel connection of several battery elements in the same container in order to increase its capacity and voltage. In this thesis, the term 'battery' is used to refer to a 'battery bank', which may contain one or more 'battery elements'.

Battery Management System (BMS)

A BMS is an electronic system that manages a battery (single element or battery bank), protecting the battery from operating outside its safe limits, monitoring its state, calculating secondary data, reporting that data, and controlling its environment, authenticating it and/or balancing it. Their functions are mainly the integration of software and tools to make it possible to control date information about the state of charge of the batteries, PV generation, and expected load consumption.

Power Electronics

In addition, the BESS may need to incorporate power electronics to interact with the utility grid and adhere to local interconnection requirements. For instance, while most conventional electric systems run on alternating current (AC), batteries deliver electricity as direct current (DC). This means that a power conversion system that contains bi-directional inverters is required. The power conversion system, in this case, converts DC power from the battery to AC power for grid use or site demand. With the use of a rectifier, AC flows — from PV or even the grid — back to the battery for charging after conversion to DC power.

3.3. PV-battery systems configuration

BESS and DC power sources like PV generators can be coupled via power electronics on a DC bus or via separate power electronics equipment on an AC bus.

DC-coupled PV-battery systems

In DC-coupled systems, the PV generator and the BESS are connected to the DC bus via a charge controller or DC/DC converter, as shown in Fig. 3.3. On this DC bus bar, one DC/AC converter is integrated to provide AC power. An advantage of this configuration, widely used in small- and medium-sized off-grid applications, is the cost-reduction potential of the system components as only one full inverter and one or two DC-DC converters are needed. On the other hand, the available power of the battery is limited by this inverter, which is previously dimensioned. Furthermore, existing PV systems cannot be easily upgraded with storage without replacing the power electronics (Vetter and Rohr, 2014).

Figure 3.3: DC-coupled configuration of PV-battery systems.

AC-coupled PV-battery systems

In AC-coupled system configurations (as shown in Fig. 3.4), the PV generator and the BESS are connected to the AC grid via two separate inverters. The conventional PV system, consisting of PV generators and PV inverters, is in principle not affected by the integration of a BESS. Therefore, installed PV systems can easily be complemented by storage at a later point in time without any adaptation. Due to the modular concept, the sizing of the BESS is almost independent of the size of PV system components (Vetter and Rohr, 2014).

Figure 3.4: AC-coupled configuration of grid-connected PV-battery systems.

It is important to note that, in the context of residential PV-storage systems, there is a growing number of manufacturers selling hybrid inverters (Fronius, Ingeteam, SMA). A hybrid inverter (sometimes referred to as a multi-mode inverter) is an inverter which can simultaneously manage inputs from both PV panels and a battery bank, charging batteries with either PV or the electricity grid. Their capabilities may go beyond this; however, some devices also handle inputs from wind turbines, generators and other power sources.

3.4. Applications of grid-connected BESS

Normally, BESSs have been widely designed for stand-alone PV systems in order to store the PV surplus and to provide energy during other periods of time when there is no PV generation (IEA, 2017). However, in PV hybrid systems, the approaches above belong to a set of goals that involve reducing energy dependence on the utility grid and providing energy and economic benefits for the prosumer (Gitizadeh and Fakharzadegan, 2014).

In the United States, until 2017, most of residential BESS were both grid-independent back-up and off-grid applications. However, according to GTMResearch (2017), installations of grid-connected residential BESS will surpass off-grid and grid-independent back-up ones (Uninterruptable Power Supply UPS equipment) for the first time. The report predicts 57% of 2017's deployments will be grid-connected, with the percentage increasing to 99% by 2022 (see Fig. 3.5).

Figure 3.5: Share of U.S. residential Battery Energy Storage Systems installations by primary application. Source: (GTMResearch, 2017).

According to a review of the literature (Caamaño-Martín *et al.*, 2008; Toledo *et al.*, 2010; McKenna *et al.*, 2013; Mulder *et al.*, 2013; Purvins *et al.*, 2013; Hoppmann *et al.*, 2014; Weniger *et al.*, 2014; Moshövel *et al.*, 2015; Timpert, 2017), PV prosumers could mainly use BESSs for the purposes described below.

Back-up power

This is the classic application of BESS. Back-up protects sensitive equipment from power quality fluctuations/outages, ensuring operability during grid outages. A UPS is the most common type of equipment used to keep critical loads powered during blackouts and brownouts.

When battery backup is coupled with PV systems, during normal circumstances, the electricity grid and PV electricity supply the loads. If the grid fails, a transfer switch opens, and the PV inverter is still sending electricity to the loads. The loads inside the building are still receiving power (either from PV input or from the batteries' stored energy). When the utility grid is cut off, the power outage is not even noticed until the battery is drained.

Time-of-use (TOU) bill management

In TOU pricing, the electricity prices are set for a fixed period. The utility grid uses TOU pricing to drive down demand at peak periods by using high prices to influence customers' consumption rather than more invasive controls such as dynamic or passive demand response mechanisms, or even power cuts. Typically, TOU tariff is likely to have two or three price levels (e.g., 'off-peak', 'mid-peak', and 'on-peak') where the price is determined by the time of day. Customers can be expected to vary their usage in response to this price information and manage their electricity costs by shifting their usage to a lower cost period. In this sense, BESSs play an important role in building environment with a dynamic pricing control, by storing both PV and grid electricity during low off-peak price periods and using the stored energy when the price is high, consumers can avoid paying high bill rates.

Optimizing PV self-consumption

In this application, PV power charges the battery when PV generation exceeds demand and discharges it when demand exceeds PV production and would otherwise be satisfied by the grid connection. In this way, PV could theoretically provide the entire annual consumption of a prosumer in terms of electricity. An adequate dimensioned BESS can significantly increase daily, monthly and annual use of local PV generation.

Peak-shaving

Peak-shaving is the process of reducing the amount of power imported from the utility grid during peak demand periods. Utilities typically have variable pricing based on demand, and the pricing during the peak demand periods is typically the highest. The goal of using storage in the peak-shaving application is to discharge the BESS in order to supply the highest loads when needed and charge the BESS with PV generation. Some benefits include that, on one hand, prosumers save on their electricity bills by reducing peak demand, and, on the other hand, utilities reduce the operational cost of generating power during peak periods (reducing the need for peaking units).

Figure 3.6: Applications of BESS in grid-connected PV-battery systems.

BESS can offer important benefits not only to a PV prosumer but also to the utility grid by solving issues arising from the injection of electricity into the distribution grid ([IEA-PVPS, 2016](#)). For example, utility grid operators can use BESS for the following purposes.

Deferral of distribution grid upgrade investments

When electrical demand grows faster than the grid capacity, a temporary excess of demand may overload the electrical infrastructure. Instead of upgrading it immediately, a BESS combined with PV can be used to cover the excess demand and defer upgrade investments.

Frequency and voltage regulation

Power fed into the public grid has traditionally been generated by synchronous generators. This enables the grid frequency and voltage to remain constant. However, when PV systems are used, the PV inverters they can cause an imbalance between generation and demand by pushing a variable supply onto the grid, causing additional frequency and voltage deviations. A BESS can be deployed to mitigate these variations, providing frequency regulation, voltage support, electric supply reserve capacity, and so on, improving the efficiency of centralized generation, and allowing a smoother integration of variable PV generation ([ESMAP-IFC, 2017](#); [Timpert, 2017](#)).

Despite the multiple benefits of storage for PV prosumers, a breakthrough is only possible when their installation becomes economically sound. The financial benefits of PV-battery systems are mostly achieved through the abovementioned applications. However, these benefits are highly dependent on the regulatory framework of each country ([Gitizadeh and Fakharzadegan, 2014](#)).

On the one hand, in countries where self-consumption is permitted (see [Chapter 2](#)) but there is no support mechanism to compensate prosumers for the excess PV electricity injected into the grid, prosumers should analyse whether they are better off investing in electrical storage to store excess PV generation than losing that electricity or modifying their load curve by shifting consumption (deferrable⁷ loads) according to PV production times. On the other hand, in countries where regulations permit self-consumption, prosumers should assess whether it is more economical to store their excess PV generation using a battery than to sell their PV electricity and receive the Feed-in-Tariff (FiT). Ultimately, the impact of BESSs on the electricity market will be determined by the regulatory frameworks and economics of storage solutions. In fact, the use of batteries to store PV excess will become a reality if the decision to invest in batteries is more profitable for the PV prosumer than not doing so ([IEA-PVPS, 2016](#)).

⁷ These loads can be displaced in time. For example, the use of some home appliances as dishwashers, washing machines or dryers has certain time flexibility.

3.5. Terminology used in battery energy storage systems

This section defines the terms most commonly used to express the characteristics of BESSs. These terms will be employed very frequently in this thesis.

Nominal voltage

A battery element provides a nominal voltage (V_n) of between 1 V and a few volts, for example, 2 V for a lead-acid cell and around 3.2 or 3.8 V for a lithium-ion cell, depending on chemistry.

The voltage of a cell is denoted as V_{pc} (per cell) or V/element. The V_n is a value that indicates the operational voltage, usually in a discharge current with medium amplitude, which discharges the battery in the space of a few hours (Glaize and Geniès, 2013). The V_n for battery banks will depend on the number of battery elements, resulting in the sum of V_{pc} connected in series.

Battery capacity

The term capacity — denoted by C — refers to the amount of electricity that can be released by a battery. According to the International System of Units (SI), the unit for measuring the electrical charge is the ‘coulomb’. However, normally, the product of an electrical current — in amperes [A] — for a duration of a certain number of hours will be used. So, the unit ‘ampere-hour’ [Ah] will be used to express the battery capacity.

A battery’s effective capacity depends on certain conditions, which include the discharge current, the temperature, the history of the battery’s operation (ageing), the charge/discharge conditions — usually a threshold level of voltage — and so on.

When current is drawn from a battery, the voltage will decrease gradually from slightly higher than the nominal voltage to a fully discharged voltage. When the discharge voltage is reached, the battery capacity is exhausted and the cell voltage plummets quickly. Similarly, in the charging process, the voltage increases above the nominal voltage until the battery is fully charged and then the charging current is interrupted (or decreased gradually). For a lead-acid cell with a nominal 2 V, the voltage range is typically between 2.6 V during charge until 1.75 V at full discharge. This applies also to lithium batteries, where the voltage ranges - depending on technology- between 4.4 V at full charge until 2.8 V at full discharge.

In order to prolong the batteries lifetime, the cells should not be overcharged/discharged out of their voltage range.

Thus, for the same battery and depending on the usage conditions, a number of different capacity values can be defined.

The charge/discharge current for a battery is often written in reference to its ‘nominal capacity’, or C_n , where n denotes the number of hours taken to charge or discharge the battery. For instance, if a battery is denoted by $C_5 = 20$ Ah, this means it will be discharged by a current of 4 A in 5 hours. A battery whose capacity is $C_{10} = 20$ Ah can be discharged by a current of 2 A in 10 hours.

This variation of capacity in dependence on current is known as C_{rate} . A C_{rate} is a measure of the rate at which a battery is discharged or charged relative to its nominal capacity. When discharging, a battery is able to provide different capacities; a higher C_{rate} will produce a lower capacity and vice versa. C_{rate} depends on the manufacturer’s specifications. For example, for *Sonnenschein A625* battery capacities (Table 3.2), the values of C_{rate} are as follows:

Table 3.2: C_{rate} when charging and discharging a lead-acid *Sonnenschein A625* battery.

	C_1	C_3	C_5	C_{10}	C_{24}	C_{48}	C_{72}	C_{100}	C_{120}
C [Ah]	275	369	410	455	523	565	604	606	623
C_{rate} [A]	275	123	82	45.5	21.8	11.8	8.4	6.1	5.2

Sometimes, the battery capacity is also referred to in terms of delivered energy (E) or practical stored energy. It is equal to the product of nominal voltage for the battery capacity, $E = V_n C$. Although the SI unit of energy is the Joule [J], the units ‘watt-hour’ [Wh] and ‘kilowatt-hour’ [kWh] are widely used because they express the number of watts or kilowatts generated over the duration of discharge, which is usually expressed in hours. It is, of course, necessary to specify the value of current at which the battery is discharged.

Gravimetric energy density

The gravimetric energy density is the ratio of the energy deliverable with a given current to the mass of the battery. The gravimetric energy density is expressed in ‘watt-hours per kilogram’ [Wh/kg].

Volumetric energy density

The volumetric energy density is the ratio of the energy deliverable with a given current to the volume of the secondary battery. The volumetric energy density is expressed in ‘watt-hours per cubic metre’ [Wh/m³].

State of charge and Deep of discharge

The ‘state of charge’ (*SoC*) is an indication of the amount of capacity still available in the battery in relation to its nominal capacity:

$$SoC = \frac{Capacity - \int i_{discharge}(t)dt}{Capacity} \quad (3.1)$$

SoC is a dimensionless parameter, usually expressed as a percentage. For example, *SoC* = 60% indicates that the battery retains 60% of its nominal capacity, as the theoretical maximum is 100%. It also indicates that 40% of capacity – the so-called ‘Depth of Discharge’ (*DoD*) – is not available. *DoD* is an indication of the amount of electricity already extracted from a battery in relation to its nominal capacity. It is also a dimensionless parameter, which is usually expressed as a percentage:

$$DoD = 1 - SoC \quad (3.2)$$

Round-trip efficiency

The round-trip efficiency (η) of a BESS is the ratio of total energy delivered to the loads (discharge) divided by total energy received (charge) from the electrical source power (grid, PV, etc.) (Reddy, 2010; Petricca *et al.*, 2013; Pawel, 2014).

Self-discharge

Self-discharge involves a progressive, time-dependent loss of charge, where the *SoC* diminishes continuously with time without loads, usually at a progressively diminishing rate due to age, cycling and elevated temperature (Niu *et al.*, 2004; Knap *et al.*, 2016). The unit most commonly used is ‘percentage per month’ [%/month].

Cycle life and battery lifetime

The ‘cycle life’ of a battery indicates the number of charge and discharge cycles that a battery can complete before losing considerable performance. The cycle life is strongly dependent on the *DoD*, temperature, discharge current and specific application. A common end-of-life criterion found in the literature review — but certainly not the only one in use — is when the battery has a remaining capacity of 80% of its nominal capacity (Bindner *et al.*, 2005; Schiffer *et al.*, 2007; Jenkins *et al.*, 2008; Sauer and Wenzl, 2008; Dufo-López *et al.*, 2014). Lead-acid batteries, for instance, are not capable of handling more than a few hundred deep discharge cycles before they begin to fail. Some high-cost chemistries, like some types of Li-ion batteries, have the capability to endure more than 10,000 deep discharge cycles (Nishijima *et al.*, 2014; Vetter and Rohr, 2014; Jaffe and De Leon, 2016).

The ‘battery lifetime’ is the number of years for which the battery can operate before ending its cycle life (Dufo-López *et al.*, 2014; IRENA, 2015). The battery lifetime plays an important role in the economic analysis of PV-battery systems. If a BESS has reached its cycle life and must be uninstalled, the residual value of the battery should be considered as part of the total cost (Aichhorn *et al.*, 2012; Jaffe and De Leon, 2016).

3.6. Battery technologies for PV systems

There are different battery technologies available on the market that are suitable for BESS in combination with PV systems, of which the most important are lead-acid, lithium-ion (Li-ion), and nickel-based batteries (Nair and Garimella, 2010; Dunn *et al.*, 2011; Poullikkas, 2013; World Energy Council, 2016).

Nevertheless, at the present time, for grid-connected PV-battery systems, manufacturers are focusing on lead- and lithium-based technologies, which are the most commonly used (Toledo *et al.*, 2010; Albright *et al.*, 2012; Leadbetter and Swan, 2012; Krieger *et al.*, 2013; Ciez and Whitacre, 2016; IEA-PVPS, 2016).

Lead-acid batteries have been – and still are – widely used in both off-grid and grid-connected PV systems (Hoppmann *et al.*, 2014; World Energy Council, 2016). Lead-acid batteries are reliable and globally manufactured and are therefore a well-understood technology. Furthermore, they have lower prices compared to Li-ion batteries (Mulder *et al.*, 2013; World Energy Council, 2016). Li-ion batteries are also a mature technology, especially in consumer electronics, and in recent years their use is being mass-fed and focused on electric vehicles (EVs) and residential PV systems, also called solar home systems (Divya and Østergaard, 2009; Albright *et al.*, 2012; Vetter and Rohr, 2014; IRENA, 2015).

For the reasons described above, this Chapter analyses only lead-acid batteries (used in the experimental stage of this thesis, [Chapter 5](#)) and Li-ion batteries, in order to simulate the behaviour of grid-connected PV-battery systems in several case studies ([Chapter 8](#)).

Figure 3.7: Classification of rechargeable batteries used in PV systems.

Lead-acid batteries

Lead-acid batteries are the oldest type of rechargeable battery and are based on chemical reactions involving lead dioxide, which forms an electrode; lead, which forms the other electrode; and sulfuric acid, which acts as the electrolyte⁸.

The nominal voltage of a lead-acid cell is 2 V and the typical gravimetric energy density is around 30 Wh/kg (Zobaa, 2013). Lead-acid batteries have high energy efficiencies —between 85 and 90%— as well as being easy to install and require a relatively low level of maintenance and low investment cost. The self-discharge rate for this type of battery is between about 2 and 5% per month (at 25 °C), which makes them ideal for long-term storage applications. However, the limiting factors for these batteries are the relatively low cycle life and battery lifetime. Typical lifetimes of lead-acid batteries are between 500 and 3000 charge/discharge cycles or 5–15 years of operation. With regard to temperature levels, although high temperatures — up to 45 °C, which is the upper limit for battery operation — may improve battery performance in terms of higher capacity, they can also reduce the total battery lifetime as well as the battery energy efficiency (Hadjipaschalis *et al.*, 2009).

Lead-acid batteries can be divided into two distinct categories: flooded and valve regulated lead-acid (VRLA). The two types are identical in their internal chemistry, the most significant differences between them are the system level design considerations. On the one hand, flooded lead-acid batteries require: *i*) upright orientation to prevent electrolyte leakage; *ii*) a ventilated environment to allow the diffusion of gases created during cycling; and, *iii*) routine maintenance of the electrolyte. On the other hand, VRLA batteries (or also called sealed lead-acid) are maintenance free and no periodic water refilling is not required. Each cell in VRLA battery will have a valve (automatically operating) to allow the gas to escape if developed by the overcharging the cells and to hinder the entrance of oxygen from the air into the cell. Due to these differences, the lower cost of flooded lead-acid batteries must be balanced against the added complexity and maintenance expenses. VRLA batteries are divided into two categories: absorbed glass mat (AGM) and gel. The different names reflect the different methods of containing the electrolyte. In the gel batteries, a thickening agent is added to turn the electrolyte from liquid to gel. In AGM cells, a glass matrix is used to contain the liquid electrolyte (Misra *et al.*, 2003; Albright *et al.*, 2012). Apart from that, their behaviour is almost identical.

⁸ The electrolyte is any chemical compound that ionizes when molten or in solution, allowing it to conduct electricity.

The above-mentioned features make the lead-acid batteries attractive as power sources for the use in stationary applications, for example, in cars as a starter battery; and non-stationary applications, for instance, backup systems in buildings, high-availability settings like communications towers, off-grid renewable systems, grid-connected electrical storage, etc.

Lithium-based batteries

Lithium-based batteries are rechargeable batteries, in which lithium ions move from the negative electrode to the positive electrode during discharge and back when charging. The electrolyte (liquid electrolytes in lithium-ion batteries consist of lithium salts; and, the lithium-polymer cells uses a polymer electrolyte instead of a liquid one), which allows for ionic movement, and the two electrodes are the constituent components of a lithium-based battery cell (Väyrynen and Salminen, 2012; Manthiram *et al.*, 2017).

Lithium-based batteries consist of two main types: lithium-ion (Li-ion) and lithium-polymer cells. Their advantages over the lead-acid batteries are their higher energy density and energy efficiency, lower self-discharge rate, and extremely low maintenance requirement (Huggins, 2010; Krieger *et al.*, 2013).

Li-ion cells, with a nominal voltage of around 3.7 V, have gravimetric energy densities ranging from 70 to 150 Wh/kg while those of lithium-polymer cells range from 100 to 150 Wh/kg. Energy efficiencies range from 90 to 99% for both of these technologies. For Li-ion batteries, the self-discharge rate is very low at a maximum of 1% per month and the cycle life can reach more than 20000 cycles. However, the lifetime of a Li-ion battery is temperature dependent, with faster ageing at high temperatures. In addition, Li-ion batteries require a battery management system in order to maintain safe operation by limiting the charge and discharge currents and monitoring cell temperature. These precautions are necessary in order to eliminate the possibility of metallic lithium plating occurring due to overcharge. The lifetime of lithium-polymer batteries can only reach about 1000 cycles. Their self-discharge is very dependent on temperature but has been reported to be around 5% per month or less (Hadjipaschalis *et al.*, 2009; Kim and Qiao, 2011; Beltran *et al.*, 2012; Glaize and Geniès, 2013).

Currently, research into lithium-based batteries is mainly concerned with cost reduction through the use of cheaper materials and increased lifetime. The cost is currently estimated to be between 250 and 1000 €/kWh (Aneke and Wang, 2016; Gallo *et al.*, 2016; Battery University, 2017; Guney and Tepe, 2017).

Li-ion batteries can generally be separated into two groups: lithium iron phosphate (LiFePO₄ or LFP) and metal oxides, which include lithium cobalt oxide (LiCoO₂ or LCO), lithium nickel manganese cobalt oxide (LiNiMnCoO₂ or NMC), lithium nickel cobalt aluminium oxide (LiNiCoAlO₂ or NCA), lithium titanate oxide (Li₄Ti₅O₁₂ or LTO), and lithium manganese oxide (LiMn₂O₄ or LMO).

Lithium-based batteries have permitted greater applications development, dominated by the household appliances and electronic devices, on the one hand, and, on the other hand, in the growing of both transport sector (electric vehicles) and the renewable energy penetration (solar home systems and renewable mini-grids).

Table 3.3 outlines the differences between the distinct chemistry technologies on a cell level. The values in the table reflect average values as there is variation in each class.

Table 3.3: Battery subcategory characteristics.

	Battery type	Voltage [V/cell]	Energy density [Wh/kg]	DoD [%]	Efficiency [%]	Self-discharge [%/month]	Cycle life [cycles]	Lifetime* [years]	Price** [USD/kWh]
Lead-acid	Flooded	2	35 - 50	50 - 60	70 - 90	2 - 5	500 - 1500	5 - 10	150 - 250
	VRLA- AGM	2	40 - 60	50 - 60	80 - 90	2 - 5	1000 - 3000	5 - 15	200 - 300
	VRLA- Gel	2	40 - 60	50 - 60	80 - 90	2 - 5	1000 - 3000	5 - 15	200 - 300
Li-ion	LFP*	3,3	90 - 120	70 - 90	90 - 99	<1	1000 - 2000	7 - 20	450 - 750
	LCO	3,6	140 - 200	70 - 90	90 - 99	<1	500 - 1000	7 - 20	250 - 400
	NMC	3,7	150 - 220	70 - 90	90 - 99	<1	800 - 2000	7 - 20	400 - 660
	NCA	3,6	200 - 260	70 - 90	90 - 99	<1	500 - 5000	7 - 20	250 - 400
	LTO	2,4	70 - 80	70 - 90	90 - 99	<1	2000 - 25000	7 - 20	800 - 1000
	LMO	3,8	100 - 150	70 - 90	90 - 99	<1	800 - 2000	7 - 20	350 - 500

* Battery lifetime will depend on specific application, DoD, operation temperature, etc.

** The values are approximate between years 2016 and 2017. 48 - 61% of potential reduction is expected in 2030 (IRENA, 2017).

3.7. Battery lifetime prediction models

The lifetime of batteries is an important design factor of PV-battery systems: batteries not only impact on the performance of the whole system but are also a significant expenditure when considering the lifespan of a PV hybrid system and costs. Therefore, poor prediction of battery lifetime can lead to uncertainty about the viability of PV hybrid systems in the long term.

According to Bindner *et al.* (2005), Schiffer *et al.* and (2007), Dufo-López *et al.* (2014), certain features of the battery operating conditions have a strong impact on the damage mechanisms. These features are the discharge current, minimum and maximum *SoC*, cycling, and temperature.

There are many different models for calculating the battery lifetime. They will usually involve the abovementioned factors either directly or indirectly. In either case, they can be used in various combinations in order to include several phenomena. Thus, this thesis analyses the battery lifetime models proposed by Dufo-López *et al.* (2014), which are: *i*) cycle counting, *ii*) the Ah-throughput method; and, *iii*) the kinetic battery model. These models are widely used by the scientific community (Bindner *et al.*, 2005; Schiffer *et al.*, 2007; Jenkins *et al.*, 2008; Sauer and Wenzl, 2008; Reddy, 2010).

Cycle counting

The method of cycle counting is based on counting the charge/discharge cycles Z_i corresponding to each range of *DoD* (split into m intervals) for a year. The relation between the cycles and the *DoD* is not linear, as shown by the example in Fig. 3.8. In other words, the number of cycles to failure⁹ of a battery goes up exponentially as the *DoD* becomes shallower. This holds for most batteries' chemistries.

For each set of intervals m , the number of Cycles to Failure (CF_i) is provided by most manufacturers. The battery lifetime, in years, can be calculated as follows:

$$Lifetime = \frac{1}{\sum_{i=1}^m \frac{Z_i}{CF_i}} \quad (3.3)$$

⁹ The number of cycles to failure for a rechargeable battery indicates how many times it can undergo the process of complete charging/discharging until failure or it starting to lose capacity.

Figure 3.8: CF_i vs. DoD of the *Sonnenschein* A625 battery. Source: Handbook for Stationary Gel-VRLA Batteries¹⁰.

This method is based on Downing's algorithm (Downing and Socie, 1982), and it is known as *rainflow* algorithm.

Ah-throughput

The Ah-throughput model simply counts the amount of charge through the battery either in charge or discharge operation mode. Ah-throughput models can be extended to include weighting factors on the current depending on a number of factors such as the *SoC*.

A simple Ah-throughput model defines the end of the battery lifetime when a specified number of full charge/discharge cycles (Z_{IEC}) are reached, which are defined by the International Electrotechnical Commissions (IEC, 2002, 2017). The estimation of the lifetime consists of adding the charge or Ah-throughput cycled by the battery and calculating the number of full cycles (Z_N) as follows:

$$Z_N(t + \Delta t) = Z_N(t) + \frac{|I_d(t)|}{C_N} \Delta t \quad (3.4)$$

where $|I_d(t)|$ is the absolute value of the discharge current. When $Z_N(t) = Z_{IEC}$, the end of the lifetime of the battery is reached.

¹⁰ <http://www.sonnenschein.org/PDF%20files/GelHandbookPart2.pdf>

Kinetic battery model

In real batteries, lifetime is generally expressed as the loss of the battery's ability to provide a specific amount of its original nominal capacity (Bindner *et al.*, 2005; Schiffer *et al.*, 2007; Dufo-López *et al.*, 2014). One of the important distinctions of this modelling method is that it generally combines other models by changing the parameters until the battery can no longer meet the initial requirement. For instance, Schiffer presents a model based on the concept of 'weighted Ah throughput' (Schiffer *et al.*, 2007), where corrosion and degradation effects are calculated based on *SoC* and temperature. A simplified flow diagram of this model is given in Figure 3.9.

Figure 3.9: Simplified flow diagram of Schiffer model.

During one simulation step, the *SoC*, corrosion, and degradation parameters are determined and then used to change the battery parameters and to determine the remaining capacity of the battery (80% of the nominal capacity) which is the main output of the model.

The Schiffer model calculates the capacity loss by corrosion and the capacity loss by degradation C_{deg} . The lifetime number of IEC cycles (Z_{IEC}) given in the battery datasheet is related to the stage at which the battery reaches 80% of its nominal capacity. However, as ageing is a combination of cycling and corrosion, the effective weighted number of cycles without corrosion would be higher: approximately $1.6 Z_{IEC}$. So, the battery lifetime is reached when the weighted number of cycles without corrosion Z_w is equal to $1.6 Z_{IEC}$. Then, the capacity loss by degradation (cycling) is calculated as:

$$C_{deg}(t) = C_{degLimit} e^{-c_z \left(1 - \frac{Z_w(t)}{1.6 Z_{IEC}}\right)} \quad (3.5)$$

where $C_{degLimit}$ is the degradation limit. To calculate the capacity loss due to degradation, the Ah throughput is weighted with the impact of the *SoC*, discharge current and the temperature. Due to the large number of variables and parameters derived from the Eq. 3.5, readers can refer to the scientific paper by Schiffer *et al.* (2007), where the model is explained in detail.

The battery lifetime prediction models generally used by simulation tools are cycle counting and Ah-throughput models. According to Dufo-López (2014), these models do not correctly predict the ageing of the batteries, because the battery lifetime results are higher than the results obtained in real batteries. On the other hand, with the Schiffer model, the results simulated are very similar to data obtained in experimental measurements, suggesting that, the implementation of this model in simulation tools, can be most helpful for an adequate economic evaluation of PV-battery systems.

3.8. Relevant studies

Finally, to conclude this Chapter, relevant research related to grid-connected PV-battery systems is mentioned below.

Braun *et al.* (2009) presented an analysis of PV self-consumption in Germany using Li-ion storage. The authors use a tool developed by the Fraunhofer Institute to analyse the energy flows in residential PV-battery systems, called Sol-ion. The results indicate that PV-battery systems would become economically interesting with specific battery costs below 350 €/kWh.

Leadbetter and Swan (2012) presented the modelling, simulation, and sizing results of BESS (Li-ion and lead-acid batteries) for residential electricity peak shaving. The model simulated and provided performance results of a range of battery and inverter sizes specific to a variety of residential houses. The results suggested that typical battery capacity sizes ranged from 5 kWh/2.6 kW (for low electricity intensity homes) to 22 kWh/5.2 kW (for electricity intense buildings with electric space heating). Based on the battery cycling profile, the battery life was estimated to be in the range of 10–20 years for a specific case study presented.

Alam *et al.* (2013) carried out a research related to PV-battery systems in Australia. This paper investigated the solar PV impacts and developed a mitigation strategy through an effective use of distributed BESS (lead-acid batteries) integrated with solar PV units. The storage was used to consume surplus solar PV power locally during the PV generation peak, and the stored energy was utilized

in the evening for the grid peak-load support. A charging/discharging control strategy was developed, taking into account the current *SoC* of the battery and the intended length of the charge/discharge period, to effectively utilize the available capacity of the storage. The proposed strategy could also mitigate the impact of sudden changes in PV output due to unstable weather conditions by putting the storage into a short-term discharge mode. The proposed PV impact mitigation strategy was tested on a practical distribution grid and validated through simulations.

Mulder *et al.* (2013) carried out research on the dimensioning of PV-battery systems depending on the incentive and selling price conditions. The analysis was based on BESS available on the market (lead-acid and Li-ion batteries) and on real household measurement data. The article also showed the battery throughput cost with a direct comparison to the electricity cost. The results indicated that batteries could not be recommended to investors today. However, if the electricity price increased by 4% then batteries would quickly become attractive and would not need subsidies.

McKenna *et al.* (2013) studied the economic and environmental impacts of lead-acid batteries in grid-connected PV systems under current feed-in tariff arrangements in the UK. A new lead-acid battery model was used to simulate hypothetical power flows using measured data on domestic PV systems. The simulation results indicated that the net benefit of the battery was negative, even when considering an idealized lossless battery. The environmental impact of the use and production of the lead-acid battery was also described and also found to be negative, and the authors concluded that the use of lead-acid batteries in domestic grid-connected PV systems is not recommended.

The potential of using BESS in the public low-voltage distribution grid in order to defer upgrades needed to increase the penetration of PV was presented by Tant *et al.* (2013). A multi-objective optimization method was proposed in order to visualize the trade-offs between three objective functions: voltage regulation, peak power reduction, and annual electricity cost. The results provided insight into the dimensioning and required specifications of the battery and the inverter. Furthermore, a comparison between Li-ion and lead-acid battery technologies was presented.

The effect of grid feed-in curtailment of a PV system with heat storage or Li-ion battery was simulated by Riesen *et al.* (2013). The case studied was based on a Swiss household with an annual electrical energy consumption of about 5000 kWh. The effect of electricity generation forecast imprecision on cost balance optimization was also evaluated. The simulations showed that even relatively small electrical storage capacities are sufficient to considerably reduce the peak power imported from the utility grid.

Hoppmann *et al.* (2014) developed a model that investigated the economic viability of BESS (lead-acid and Li-ion batteries) for residential PV in Germany under eight different electricity price scenarios from 2013 to 2022. Additionally, they ran the model with a large number of different PV and storage capacities to determine the economically optimal configuration. They concluded that additional policy incentives to foster investments in battery storage for residential PV in Germany would only be necessary for the short run. At the same time, the impending profitability of integrated PV-battery systems was likely to further spur the ongoing trend toward distributed electricity generation with major implications for the electricity sector.

Battery control strategies for PV systems were developed by Li and Danzer (2014). They presented two strategies, one to reduce the grid power, especially at peak times, and the second to increase PV self-consumption. In this paper, the control strategies for various optimization goals were developed on the basis of the predicted household load consumption and PV generation. The authors concluded that the efficiency of the model proposed depended on the accuracy of the irradiance, local load, and human behaviour. Furthermore, the study considered the Li-ion battery lifetime and economic factors.

Yang *et al.* (2014) proposed a sizing strategy for grid-connected BESS (Li-ion batteries) in the distribution grid under a high PV penetration level. The main objective was to optimize the size of the distributed BESS and to derive the cost-benefit analysis when the distributed BESS was applied for voltage regulation and peak-load shaving. Based on the proposed method, the cost-benefit sizing of a PV-battery system could be determined.

An analysis of PV-battery systems was carried out by Bortolini *et al.* (2014). In this paper, the authors present a technical and economic model for the design of a grid-connected PV-battery system, in which the electricity demand is satisfied through the PV and lead-acid batteries with the utility grid as the backup source. The case study analysed showed that a 25.5% reduction of the electricity cost with respect to the grid electricity price benchmark could be achieved.

A Li-ion battery cost analysis in PV household applications was carried out by Naumann *et al.* (2015). In this study, the authors used a multi-parameter economic model which allowed profitability estimation for BESS with sensitivity to both technical and economic parameters, such as the battery lifetime criterion, battery ageing behaviour, electricity prices, and storage investment costs. Using this model, they derived a clear picture of the system profitability with dependence on all major influencing parameters. They demonstrated that applying the battery ageing model (rainflow cycle counting algorithm) and given the German market price trends, PV-battery system profitability was expected to be reached in the next years.

An analysis of the maximal possible grid relief from PV-peak-power impacts by using BESS was presented by [Moshövel *et al.* \(2015\)](#). A MATLAB-based model of a Li-ion storage system was presented. The model is applicable for a wide range of PV generator sizes, different battery capacities, and diverse control strategies. The results showed that BESS strategies based on forecasts (solar radiation and household load demand) had significantly higher potential to relieve the grid than a system that only maximized self-consumption. Besides, the battery control strategy used was able to reduce the utility grid power by up to 70%.

A feed-in tariff scheme was discussed by [Brusco *et al.* \(2016\)](#). The results showed that a reduction of the electricity bill equal to 45% could be achieved when the PV-battery system was adopted, whereas it was equal to 34% when only the PV system was adopted. This article ends with an assessment of the impact of the integrated PV-battery system on the load profile from the grid perspective and the satisfactory degree of self-sufficiency achieved by the prosumer.

[Quoilin *et al.* \(2016\)](#) presented a statistical analysis and economic assessment in order to quantify the self-consumption rate of a residential PV-battery system. The authors simulated PV self-consumption in various European countries, for various household profiles, with or without batteries. The following conclusions could be drawn from the results: *i)* Self-consumption is a non-linear, almost asymptotic function of PV and battery size. Achieving 100% self-consumption is not realistic for the studied countries without excessively oversizing the PV system and/or the battery. *ii)* The cost of Li-ion batteries is most likely still too high for large-scale market uptake in Europe. 3) Home battery profitability and future uptake depend mainly on the indirect subsidies for self-consumption provided by the structure of retail prices. 4) The self-sufficiency rate varies considerably between households. For a given household, the volume of self-consumption cannot be predicted in a deterministic way. This study also provides a simulation tool for the prediction of self-consumption and a method for the optimal sizing of such systems.

[Merei *et al.* \(2016\)](#) presented a techno-economic analysis of PV-battery systems in commercial applications. This paper presents optimization results with respect to self-consumption and the degree of self-sufficiency for a supermarket in Aachen, Germany. The optimisation is achieved using real measurement data of load profile and solar radiation. Besides, techno-economic analyses and sensitivity analyses were carried out to demonstrate the influence of different PV system sizes, PV system costs, and interest rates. Moreover, to raise self-consumption, different battery sizes with different Li-ion batteries costs were investigated and analysed for 2015 and 2025 scenarios as well. The results showed that the installation of a PV system can reduce the electricity costs through PV self-consumption. Also, adding a BESS could reduce the electricity costs, even more, assuming that the battery costs can be reduced to 200 €/kW h in the future.

[Khalilpour and Vassallo \(2016\)](#) presented a novel methodology for investment decision making, optimal sizing, and operation scheduling of grid-connected PV-battery systems. The methodology uses periodical weather data, electricity price, PV-battery system cost, PV-battery specifications, desired reliability, and other critical design and operational parameters. The analysis includes grid-to-load, PV-to-load, battery-to-load, battery-to-grid, grid-to-battery, PV-to-battery, and PV-to-grid power flows as well as the battery's state of charge. This decision support method enables the prosumer (ranging from a small house to large-scale industrial plants) to implement the most efficient electricity-management strategy while achieving the goal of minimizing the electricity bill.

[Truong *et al.* \(2016\)](#) conducted an economic analysis of residential PV-battery systems in Germany using a Li-ion battery. They demonstrated that using rooftop PV systems with BESS could increase households' electricity self-consumption and thus reduce the electricity bill. They reveal the conditions under which a positive return on investment can be achieved and outline that the battery could be a worthwhile investment in many, but not all, of the investigated scenarios.

A study of lead-acid batteries coupled with PV systems for increased self-sufficiency in households in Belgium is presented by de [Oliveira e Silva \(2016\)](#). This paper analyses the use of residential lead-acid battery storage coupled with PV and its possible interaction with the grid for different limits of feed-in power without any support policies. The results show that it is possible to reach self-sufficiency values of up to 40%, without BESS and PV generation. Beyond 40%, energy storage must be used, strongly raising the cost of the electricity consumed and therefore the need for supportive policies for widespread adoption. This research also presents an optimisation tool for studies of distributed PV systems with BESS.

[Cucchiella *et al.* \(2016\)](#) presented an economic analysis of PV-battery systems for residential consumers in Italy. They evaluated the profitability of PV systems without subsidies and also assessed the profitability of BESSs (lead-acid batteries) in a mature market. Furthermore, the authors conducted a sensitivity analysis of the critical variables and proposed a mathematical model to define the break-even point of the increase in self-consumption at which residential PV-battery systems become economically viable. They conclude that BESSs are useful only when the relationship between PV generation and load profile allows them to induce a significant increase of self-consumption (10 – 24% points with BESSs of 0.5 – 1 kWh per installed kW of PV power).

[Parra and Patel \(2016\)](#) presented a study of the effects of tariffs and economic benefits of PV-battery systems in Switzerland. The economic benefits of the BESS were analysed for three diverse types of tariffs. Furthermore, the reduction of battery capacity and annual discharge throughout the battery lifetime were simulated for lead-acid and Li-ion batteries. The authors demonstrated that the

economic benefits are strongly dependent on the regulatory context. The results show that simple retail tariffs (tariffs in which the electricity price is constant throughout the day) are the best option for prosumers in comparison with other types of tariffs.

An Australian case study of PV-battery systems was carried out by [Akter *et al.* \(2017\)](#). The authors presented a comprehensive framework for conducting an economic analysis of a residential house along with the integration of PV systems and BESS. The proposed framework was developed by considering different tariff structures of the existing energy market as well as the investment costs for the PV-battery systems. The economic evaluations were carried out based on different economic measures such as replacement cost, electricity bill, simple payback analysis, net present value, and discounted payback analysis. The results from the analysis demonstrated that the profitability of the PV-battery systems is feasible under present market Australian scenarios.

A techno-economic analysis of PV-battery systems (included lead-acid and Li-ion based battery systems) in Germany is presented by [Linssen *et al.* \(2017\)](#). They carried out simulations, taking into consideration the temporal high-resolution consumer load and PV production profiles, the technical and economical PV and battery system parameters, and the regulatory framework in Germany. The results also include the cost-optimal system configuration under the given framework, the share of self-consumption, the degree of autarky, grid feed-in, and supply as well as various battery system parameters. The conclusions indicate that the break-even battery system price compared to PV systems without BESS is calculated to be approximately 900 €/kWh (without a BESS support scheme) to 1200 €/kWh, with the German BESS support scheme. In Germany, the installation of a PV-battery system is funded by a public support program including a reduced interest rate and an investment grant, this support scheme was considered by the authors in the calculations, which led to an additional price reduction of approx. 30% of the initial battery system price.

To conclude, the analyses of PV-battery and PV-hybrid systems carried out so far have shown that in some regulatory frameworks, where incentives for the installation of BESS exist, the storage is economically profitable. Likewise, from the technical point of view, the BESS increase the initial self-sufficiency of the PV system from a few percentage points (depending on the capacity of the battery, the electrical building demand, and the control strategies) to theoretically reach the 100 %. Despite the BESS costs are still high, a reduction of more than 50% is expected in the next ten years. This fact, along with the cost-reduction of PV technology, the installation of grid-connected PV-battery systems would become more attractive from the prosumers point of view.

Chapter 4

HVAC systems and buildings climate control

4.1. Introduction

Heating, ventilation, and air conditioning (HVAC) systems provide the people working/living inside buildings with ‘conditioned air’ so that they will have a comfortable and safe environment. The term ‘conditioned air’ means that the air should be clean, and the temperature, humidity, and movement of the air should be within certain acceptable comfort ranges. The American Society of Heating, Refrigerating and Air Conditioning Engineers ([ASHRAE, 2016](#)) has established standards which outline indoor comfort conditions that are thermally acceptable to 80% or more of the building’s occupants. Generally, these comfort conditions, sometimes called the ‘comfort zone’, are between 20 and 24 °C in winter and between 23 and 26 °C in summer ([Halawa and Van Hoof, 2012](#); [ETH, 2013](#); [Holopainen *et al.*, 2014](#)).

Climate control of buildings has drawn a lot of attention in recent years in both academia and industry. In fact, in the building sector — as mentioned previously in the introduction to this thesis — HVAC systems represent between 40 and 60% of energy consumption in Europe and more than 50% in the United States ([Fong *et al.*, 2010](#); [Perez-Lombard *et al.*, 2011](#); [Chua *et al.*, 2013](#)).

Savings related to HVAC systems are therefore a natural objective of many research groups that are working to achieve economically competitive solutions able to reduce the external energy demand required to ensure comfortable conditions.

The percentages mentioned above depend largely on many variables, such as the climatic zone (solar irradiance and temperature), the type of building, the building design and the quality of the envelope, the profiles in terms of electricity consumption, and the efficiency of the HVAC equipment. Some technologies used in HVAC systems are shown in Table 4.1, which distinguishes whether these technologies can deliver heat, cold, ventilation, or a combination of all three.

Table 4.1: Different types of HVAC equipment.

Commercial products used to condition air	Heating	Ventilation	Cooling
Boilers	✓		
Furnaces	✓		
Heating Coils	✓		
Direct Heaters (gas, electricity or fireplace)	✓		
Air Conditioners		✓	✓
Chilled Water			✓
Refrigeration			✓
Cooling Coils			✓
Fans		✓	
Heat Pumps	✓	✓	✓

Energy consumption for climate control purposes is expected to face an increase in demand within the next 30 years (IEA-SHC, 2016). This is, for instance, clearly demonstrated by the fact that in recent years, a tremendous increase in the market for air-conditioning and heat pumps has been observed worldwide, especially in developing countries (EHPA, 2016; IEA-SHC, 2016). This increase can be explained considering the changes that have taken place in the public perception regarding climate and comfort requirements; space cooling, for instance, is moving quickly from luxury to necessity, leading to a fast-growing market. Regarding energy use for space heating, even if it has not seen such a significant increase in the last years, according to the Buildings Performance Institute Europe, it still represents the most energy-intensive use in European buildings (BPIE, 2011).

Besides, through the building directive 2010/31/EU (EU, 2010), Europe has recently sent an important signal regarding the reduction of energy demand in buildings: by 2020, all new and refurbished buildings should be near to zero energy. If, on the one hand, external energy demand for heating and cooling will have to

decrease, as the current normative framework establishes, and, on the other, climate and comfort requirements make the HVAC market grow, as shown by market factors, substantial use of renewable energy sources will have to be made to supply the climate control equipment. In order to implement efficient solutions that could provide energy savings, reductions in emissions of greenhouse gases, and improvements in the electricity grid manageability, the development of efficient renewable-energy-driven HVAC systems is a research topic of increasing interest.

Renewable energy sources for HVAC

The International Energy Agency ([IEA, 2007](#)) defines renewable energy as energy derived from natural processes that are replenished constantly. This definition applies to a wide range of energy sources derived directly or indirectly from the Sun including solar, hydro, wind, wave, biomass, and also includes non-solar sources such as geothermal, tidal, and ocean currents.

Renewable Energy Sources for Heating and Cooling (RES-HC) technologies can replace fossil fuels in the residential and tertiary sectors as well as in several industrial processes. Thus, RES-HC can not only reduce energy imports but also improve the efficiency of the energy system contributing to the reduction of greenhouse gas emissions ([REN21, 2016](#)).

Solar thermal, geothermal, and biomass are the main types of RESs that can be used as direct sources of heat. Furthermore, thermal energy can also be extracted indirectly from the air, the water or from the ground by means of aerothermal, hydrothermal and geothermal electricity-driven heat pumps respectively. Theoretically, any form of renewable-based electricity technology can be used to power these appliances. However, the use of solar energy as a primary source seems to be one of the most promising possibilities, mainly due to the facility of incorporating the solar photovoltaic technology into the urban fabric and more precisely in building envelops as it will be discussed in this thesis.

Figure 4.1: Renewable energy sources for heating and cooling production.

4.2. Heat pump technology

Heat pumps are a type of equipment that is able to force heat flow in the opposite direction to the spontaneous direction by absorbing heat from a lower temperature source (such as air, ground, or water) and releasing it to a warmer one (such as buildings or industrial applications). In order to transfer heat from heat sources in the surroundings to a building, external energy is required. In the case of vapour compression heat pumps, which represent the vast majority of those used today, the external energy consists of electricity, whereas in the case of absorption heat pumps an external heat source is used. Reversible heat pumps can also be used for cooling. In this case, heat is transferred in the opposite direction, from the building that is cooled, to surroundings at a higher temperature, just like in a common air conditioning unit.

As mentioned above, depending on the heat source used, we can distinguish between three main types of heat pumps: air-source, water-source, and ground-source (also called geothermal) heat pumps. An ideal heat source for heat pumps in buildings has a high and stable temperature during the heating season. In fact, this implies that the temperature differential from the heat source to the heat sink (the interior of the building) is lower, leading to higher efficiency. Commonly used heat sources are: ambient and exhaust air, soil, and groundwater (usually used for small- and medium-sized heat-pump installations), while sea/lake/river water, rock (geothermal) and wastewater are usually used for large heat-pump systems since greater initial investment is required. Today's heat pump can reduce the electricity

use for heating by approximately 50% compared to electric resistance heating such as furnaces and baseboard heaters (Brandoni et al., 2014; Ghafoor and Fracastoro, 2015).

According to the European Heat Pump Association (EHPA, 2016), in its Market and Statistics Report 2016, air is the most widely used heat source in Europe and will remain so in the next years, as shown in Fig. 4.2. Nowadays, in fact, about 85% of heat pumps installed in Europe use air as their energy source. In particular, the most common type of heat pump is the air-to-air heat pump, which extracts heat from outside air and transfers it to the inside of the building.

Figure 4.2: Development by category of heat pump sales in Europe 2006–2015.

Source: EHPA (2016).

The dominant role of air as a heat source can be explained simply by taking into account that air-source heat pumps require the lowest initial investment if compared with other technological possibilities, such as water-source or geothermal heat pumps. For this reason, even if air-to-air heat pumps achieve a lower seasonal performance factor than heat pumps using sources with higher and more stable temperature (mainly due to the rapid fall in capacity and performance with decreasing outdoor temperature and evaporator defrosting cycles), it is estimated that in the next years this solution will remain the most widely used.

4.2.1. Air-to-air reversible heat pumps

An air-to-air reversible heat pump is a system which transfers heat from outside to inside a building, or vice versa (Trask, 1987). Under the principles of vapour compression refrigeration cycle (see Fig. 4.3), this kind of heat-pumps use a refrigerant system involving a compressor and a condenser to absorb heat at one place and release it at another.

Figure 4.3: a) Pressure-enthalpy diagram, showing vapour compression cycle. b) Simple vapour compression cycle. Source: (Hundy, Trott and Welch, 2008).

This process can be explained with the pressure-enthalpy diagram (Fig. 4.3a). This diagram describes the liquid (refrigerant) and gas phase of a substance. The saturation curve defines the boundary of pure liquid and pure gas, or vapour. In the region marked vapour, the fluid is superheated vapour. In the region marked liquid, it is subcooled liquid. At pressures above the top of the curve, there is no distinction between liquid and vapour. Above this pressure, the gas cannot be liquefied (critical pressure). In the region beneath the curve, there is a mixture of liquid and vapour. The simple vapour compression cycle (Fig. 4.3b) is superimposed on the diagram in Fig. 4.3a. The evaporation process or vaporization of refrigerant is a constant pressure process and therefore it is represented by a horizontal line. In the compression process, the energy used to compress the vapour turns into heat and increases its temperature and enthalpy, so that at the end of compression the vapour state is in the superheated part of the diagram and outside the saturation curve (Hundy *et al.*, 2008).

The direction of refrigerant flow between the indoor and outdoor coils is established in a first line through the compressor by an electrically operated reversing valve, and alternatively through second and third lines, depending upon whether the system is operating in the heating or cooling mode, by series-connected check and float valves in each of such lines. When heating mode operation is resumed following a defrost cycle, the float valve has delivered all liquid-refrigerant to the indoor coil. Since there is no liquid refrigerant in the outdoor coil to be drawn into the compressor under these conditions, the usual trap type accumulator is not required and is therefore eliminated in the present system (Trask, 1987).

A reversing valve allows the heat pump to work automatically in either heating or cooling mode. The process used for heating (Fig. 4.4), is as follows:

1. The compressor (in the outside unit) pressurizes the refrigerant, which is piped inside.
2. The hot gas enters the inner condensing coil. Room air passes over the coil and is heated.
3. The refrigerant cools and condenses.
4. The refrigerant, now a pressurized liquid, flows outside to a throttling valve, where it expands to become a cool, low-pressure liquid.
5. The outdoor evaporator coil uses outside air to boil the cold, liquid refrigerant into a gas.

If the outdoor air is so cold that the heat pump cannot adequately heat the home, electric resistance strip heaters usually provide supplemental heating.

Figure 4.4: Heat pump cycle in the heating process. Source: Fehr (2009)

Typical capacities range from 1–20 kW for single-family buildings up to 100 kW for multi-dwelling residential applications. For commercial applications, the capacity is even bigger, and for industrial and district heating installations, the capacity can reach the range of several megawatts.

Air-to-air heat pumps come in several variants, with the most typical ones being: *i*) compact (monobloc) units, in which all of the heat pump components are combined inside one case; and *ii*) split systems, in which the external and internal heat exchangers are installed in two cases, with one installed on the outside of the building and the other inside. Both are connected via a refrigerant line.

Electrical reversible air-to-air heat pumps are experiencing a significant market penetration due to two main characteristics: the first one is that by using the same installation, both heating and cooling requirements can be met, simply inverting the operating cycle with a reversing valve, that is, making that internal and external heat exchangers work as condensers and evaporators, respectively, in the heating phase or as evaporators and condensers in the cooling period. The second relevant advantage of these systems in comparison with other HVAC solutions is that both processes are developed with high efficiencies, which contribute to improving the overall energy efficiency of the building.

4.2.2. Heat-pump performance

The steady-state performance of an electric vapour-compression reversible heat pump in a given set of temperature conditions, that is, the ratio of useful output to energy input, is referred to as the Coefficient of Performance (COP) in heating operation mode and the Energy Efficiency Ratio (EER) in cooling operation mode.

The COP and EER of a system vary significantly during system operation mainly due to the close relationship that exists between the temperatures of the heat source and the heat distribution system. In fact, the ideal COP of a heat pump is determined solely by the condensation temperature and the temperature lift, that is, the difference between condensation and evaporation temperature, as [Eq. 4.1](#) shows:

$$COP = \frac{T_C}{T_C - T_E} \quad (4.1)$$

where T_C and T_E are the condensation and evaporation temperatures in absolute units, respectively. The ideal COP equation shows that for a fixed evaporation temperature, depending on the outdoor air ambient condition, the lower the condensation temperature, the higher the COP. For this reason, heat-pump systems perform particularly well when coupled with low-temperature heat

exchangers inside the building, such as underfloor heating systems or a thermally activated building structure (TABS). Furthermore, Eq. 4.1 shows that heat pumps can perform with high COP when operating at low temperature differentials; that is, for a fixed condensation temperature (depending on the type of heat exchangers installed in the building), the higher the external heat source temperature, the higher the COP. These aspects are shown in Fig. 4.5, in which the COP is plotted as a function of outside air temperature and flow temperature¹¹.

Figure 4.5: Effect of temperature range on heat pump performance. Source: Energy efficiency in buildings, CIBSE Guide F, second edition, January 2004.

It should be mentioned that the COP of air-to-air heat pumps is about 200%-400% compares to 100% for a resistance heater and 70-95% for a fuel-powered boiler. Additionally, air-to-air heat pumps consume approximately a third to one-quarter of the electricity of a standard electrical heating for the same amount of heating (Wu, 2009).

Another important advantage of air-to-air heat pumps, as an electric system, is that no flammable or potentially asphyxiating fuel is used at the point of heating, reducing the potential danger to users, and removing the need to obtain gas or fuel supplies except for electricity.

Furthermore, from the point of view of demand-side management (DSM), using such systems characterized by high thermal inertia presents the advantage of allowing decoupling of the times at which heat generation and heat demand occur, enabling the possibility of an efficient management of the system. Such a configuration would, for instance, make it possible to pre-heat a room during the early morning hours (when electricity prices are typically lowest), limiting the peak

¹¹ Water (refrigerant) flow temperature through the radiator.

electricity demand during hours when the retail electricity price is higher, as was demonstrated by the Automatic Control Laboratory in ETH Zurich (ETH, 2013). As regards the efficiency of an ideal heat pump operating in cooling mode, the EER depends on the evaporation temperature and the temperature difference between evaporator and condenser only, as shown by Eq. 4.2:

$$EER = \frac{T_E}{T_C - T_E} \quad (4.2)$$

where T_E and T_C are the evaporation and condensation temperatures in absolute units, respectively. In this case, for a fixed evaporation temperature (basically depending on the building thermal load and required indoor temperature), the lower the external air temperature, the higher the EER. In this way, for a fixed condensation temperature (depending on the external air temperature), higher EER values can be reached by increasing the supply temperature.

A further aspect that must be addressed is that not only the COP and the EER but also the thermal capacity of the system is closely related to the outdoor temperature. Since the outside air temperature fluctuates widely throughout the year, this means that properly choosing the set point design is a critical task. In fact, as the outdoor temperature decreases, the heating capacity (as well as the COP) of an air-source heat pump decreases rapidly. For this reason, supplemental heating sources (sometimes integrated into the same heat pump) are generally required in colder climate regions. In cooling mode, as the outdoor air temperature increases, the capacity (as well as the ERR) decreases. Considering the close relationship between the heat pump's operating conditions and its efficiency and capacity, the operating performance of an electric heat pump over the season is assessed by the seasonal performance factor (SPF). This parameter — which takes into account the variable heating and/or cooling demands, the variable heat source and sinks temperatures over the year, and the energy demand for defrosting — is defined as the ratio of the heat delivered to the total energy supplied over the season.

The report presented by the 'Institute for Diversification and Energy Saving of Spain' (IDAE, 2014) attempts to estimate the SPF for different electrically driven heat pumps. The SPF results from multiplying the nominal COP by a weighting factor (WF) and a correction factor (CF):

$$SPF = COP \cdot WF \cdot CF \quad (4.3)$$

The WF takes into account the different climatic zones of Spain indicated by the Technical Building Code (CTE - *Código Técnico de la Edificación*) and has been calculated using an exclusively technical test. The CF takes into account the difference between the temperature of distribution and the temperature for which the COP was obtained in the test (IDAE, 2014).

Regarding the levels of efficiency of electric heat pumps, Directive 2013/114/EU (EU, 2013) has established the minimum performance requirements for heat pumps for them to be considered renewable. This normative establishes that 2.5 is the minimum average SPF for an electrically driven heat pump to be considered renewable. For example, if the SPF is 2.5, and the primary energy factor in Peninsular Spain is 2.403 (IDAE, 2016), i.e. 41%, then to obtain a thermal energy unit using a heat pump powered by the electricity grid, 0.96 units of primary energy are needed $1/(0.41 \times 2.5)$, which justifies it is renewable.

In addition, according to the factors of CO₂ emissions in Spain (IDAE, 2016) (0.357 for conventional electricity and 0.252 for natural gas), it is possible to calculate the CO₂ emissions to generate a kilowatt-hour (thermal) produced by a heat pump compared with a condensing boiler. The results indicate that 143 grams of CO₂ are emitted with a heat pump; in contrast, 229 grams of CO₂ are emitted with a condensing boiler, for the same value.

4.3. Thermal comfort in buildings

Thermal comfort is considered as an aspect of a sustainable building in almost all sustainable building evaluation methods and tools (Halawa and Van Hoof, 2012; Gauthier, 2013). Several metrics for assessing indoor thermal comfort in buildings have been proposed in the scientific literature over the last decades and have been used in order to describe the human thermal perception of the thermal environment to which an individual or a group of people is exposed.

The most commonly used indicator for evaluating comfort is the indoor thermal condition ISO 21929-1. This indicator has been adopted in building regulations and indoor environment classification methodologies and is divided into sub-indicators such as air temperature, humidity, and air velocity.

In this Chapter, two thermal comfort methods described in Holopainen et al. (2014) have been analysed: the Predicted Mean Vote (PMV), or the so-called Fanger method, and the Adaptive Comfort Method.

On one hand, PMV is a heat balance model that views the human being as a passive recipient of thermal stimuli. The resulting PMV is calculated with Fanger's equation (Fanger, 1970) and widely used with international standards ISO 7730 (ISO, 2005). Thus, variables such as clothing, physical activity, CO₂ concentration, relative humidity, and outdoor and indoor temperatures, among others, are involved in this method. On the other hand, the Adaptive Comfort Model assumes that humans consciously or unconsciously modify their behaviour to adapt to thermal conditions. Therefore, the thermal balance equations cannot be strictly applied because the thermal adaptation is, by nature, a dynamic process (De Dear and Brager, 2002). The adaptive comfort formula does not directly take into account the classical comfort factors described above but simply establishes the indoor comfort temperature as a function of outdoor temperature (Nicol and Humphreys, 1973; Olesen, 2012; ASHRAE, 2013; Gauthier, 2013).

4.3.1. Fanger's method

PMV combines four physical variables (air temperature, air velocity, mean radiant temperature, and relative humidity) and two personal variables (clothing insulation and activity level) into an index that can be used to predict the average thermal sensation of a large group of people in a space. The PMV index is calculated with the following equation (Fanger, 1970).

$$PMV = (0.303e^{-0.036M} + 0.028) \cdot [(M - W) - E_s - E_b - C_b - H] \quad (4.4)$$

where the different terms are defined as follows:

- M is the metabolic heat generation rate in watts per square metre [W/m²];
- W is the external work (normally zero) in watts per square metre [W/m²];
- E_s is the heat exchange by evaporation on the skin;
- E_b is the evaporative heat exchange during breathing;
- C_b is the heat exchange by convection during breathing;
- H is the sensitive heat losses from the skin by radiation and convection.

In Eq. 4.4, the terms E_s , E_b , C_b , and H correspond to the heat exchange between the body and the surrounding environment and are calculated by the following equations:

$$E_s = -3.05 \cdot 10^{-3} \cdot [5773 - 6.99 \cdot (M - W) - p_a] - 0.42 \cdot [(M - W) - 58.15] \quad (4.5)$$

$$E_b = 1.7 \cdot 10^{-5} M(5867 - p_a) \quad (4.6)$$

$$C_b = 0.0014 \cdot M(34 - t_a) \quad (4.7)$$

$$H = 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} h_c (t_{cl} - t_a) \quad (4.8)$$

where

- p_a is the partial water vapour pressure in Pascals [Pa];
- f_{cl} is the clothing area factor (ratio of clothed/nude surface area);
- t_a is the ambient air temperature in degrees Celsius [°C];
- t_r is the mean radiant temperature in degrees Celsius [°C];
- t_{cl} is the surface temperature of clothing in degrees Celsius [°C];
- h_c is the convective heat transfer coefficient.

The clothing area factor is calculated as follows:

$$f_{cl} = \begin{cases} 1.00 + 1.290 I_{cl} & \text{for } I_{cl} \leq 0.078 \text{ m}^2\text{°C/W} \\ 1.00 + 0.645 I_{cl} & \text{for } I_{cl} > 0.078 \text{ m}^2\text{°C/W} \end{cases} \quad (4.9)$$

where

I_{cl} is the thermal resistance of clothing, in square metres Kelvin per watt (m²K/W).

The convective heat transfer coefficient h_c is:

$$h_c = \begin{cases} 2.38(t_{cl} - t_a)^{0.25} & \text{for } 2.38(t_{cl} - t_a)^{0.25} > 12.1\sqrt{v_{ar}} \\ 12.1\sqrt{v_{ar}} & \text{for } 2.38(t_{cl} - t_a)^{0.25} \leq 12.1\sqrt{v_{ar}} \end{cases} \quad (4.10)$$

where

v_{ar} is the relative air velocity (relative to the human body).

The surface temperature of clothing, t_{cl} , is calculated as follows:

$$t_{cl} = t_s - I_{cl} \{ 3.96 \cdot 10^{-8} f_{cl} \cdot [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} h_c (t_{cl} - t_a) \} \quad (4.11)$$

The main problem in implementing the calculation method results from the fact that the term corresponding to t_{cl} is unknown a priori. This term must be determined by an iterative process. The first guessed value for t_{cl} is taken by averaging the air temperature (t_a) with the skin external temperature (t_s), which is calculated from:

$$t_s = 35.7 - 0.028(M - W) \quad (4.12)$$

Finally, the other index proposed in Fanger, (1970) and in the ISO Standard 7730, is the PPD (Predicted Percentage of Dissatisfied), which quantifies the expected percentage of people who will be dissatisfied in a given thermal environment. PPD and PMV are related as follows:

$$PPD = 100 - 95 e^{-(0.03353 PMV^4 + 0.2179 PMV^2)} \quad (4.13)$$

Figure 4.6: Evolution of PPD on the basis of PMV.

Thermal comfort zones (categories A, B, and C) are defined by the ranges of PMV values from -0.2 to 0.2 , -0.5 to 0.5 , and -0.7 to 0.7 , which correspond respectively to PPD values below 6, 10, and 15%. On analysing Fig. 4.6, it can be concluded that due to individual differences between people, even for the situation that is, on average, considered by the population as thermal neutrality ($PMV = 0$), 5% of people would feel a thermal discomfort situation ($PPD = 5\%$).

4.3.2. Adaptive comfort method

According to [Nicol and Humphreys \(1973\)](#), the adaptive method expresses indoor comfort temperature (T_{comf}) as a function of outdoor temperature ($T_{outdoor}$):

$$T_{comf} = aT_{outdoor} + b \quad (4.14)$$

Thus, the adaptive comfort formula does not directly take into account the classical comfort factors indicated in the PMV method. These comfort factors are instead indirectly taken into account by the constants a and b , which vary between sources. For instance, [Auliciems and de Dear \(1986\)](#) proposed the following equation:

$$T_{comf} = 0.31T_{outdoor} + 17.6 \quad (4.15)$$

where the values 0.31 and 17.6 were defined by empirical field studies. Other values of a and b are intended for naturally ventilated buildings, and these models are part of ASHRAE 55 and EN15251.

In the ANSI/ASHRAE Standard 55-2013 ([ASHRAE, 2013](#)) and its subsequent modification ([ASHRAE, 2014](#)), this relationship is stated as:

$$T_{comf} = 0.31T_{outdoor} + 17.8 \quad (4.16)$$

For the assessment of buildings, the limits of the comfort zones are given by the following two categories:

Category I, 90% acceptability¹²: $T_{comf} \pm 2.5$

Category II, 80% acceptability: $T_{comf} \pm 3.5$

In Europe, the *Comité Européen de Normalisation* (CEN) published the Standard EN 15251:2007 for the design and assessment of the energy performance of buildings. Based on this standard, [Nicol and Wilson \(2011\)](#) presented the indices a and b — for non-mechanically cooled buildings (NCBs) in free-running mode — using the formula:

$$T_{comf} = 0.33T_{outdoor} + 18.8 \quad (4.17)$$

¹² The values of ‘acceptability’ indicates the percentage of occupants that would be satisfied with the comfort temperature. Occupants also have the opportunity to adapt by adjusting their clothing, opening/closing.

The limits of the comfort zones are given by the following three categories:

Category I, 90% acceptability: $T_{comf} \pm 2$

Category II, 80% acceptability: $T_{comf} \pm 3$

Category III, 65% acceptability: $T_{comf} \pm 4$

Figure 4.7: Temperature limits for NCBs in free-running mode (EN 15251). Source: Nicol and Wilson (2011).

Figures 4.6 and 4.7 are used as models to present the results of both Fanger's method and Adaptive method presented in the case study of Section 8.1.

4.4. Relevant studies

Solar heating and cooling

The thermal energy required for environmental conditioning of buildings can be supplied using different technologies that use solar irradiance as the primary energy source. Solar-assisted HVAC systems may be operated by (1) photovoltaic systems combined with vapour compression heat pumps or (2) solar thermal collectors connected to thermally driven heat pumps.

Several studies have been conducted to determine which of these two solutions is technically and economically more beneficial. [Eicker *et al.* \(2014\)](#), for instance, compared the performance of the previously mentioned solar-assisted HVAC systems in different cities. The results indicated that by using the electrical approach, savings of up to 50% in terms of primary energy can be achieved, while the maximum savings provided by the thermal approach are about 37%.

[Hartmann *et al.* \(2011\)](#) compared solar thermal and solar electric cooling systems for a typical small office building in two different European climates (Freiburg and Madrid). They found that the solar electric system outperforms the solar thermal one in terms of primary energy savings as well as in economic terms in both climates.

[Ghafoor and Fracastoro \(2015\)](#) compared a multi-purpose thermally driven sorption chiller (for space heating, cooling, and domestic hot water) supplied by solar collectors with a multi-purpose reversible heat pump operated by PV-supplied electricity. The systems, applied to a small reference office building supposed to be located in four different cities (three in Italy and one in Pakistan), were simulated in order to analyse the economic profitability of the solutions. They found that the current installation prices of PV systems (supposed to be of the order of 2€/WP) always made multi-purpose PV-based heat pump systems more cost-effective than thermally driven ones.

[Poulet and Outbib \(2015\)](#) established that the production of thermal energy using a configuration based on a heat pump associated with PV modules allows higher annual efficiencies in comparison to the approach based on the use of thermal panels.

The electrically driven systems, stimulated by a very significant decrease in the price of PV modules in the last years, seem to be closest to mass market application, in particular in the case of small- to medium-size units. PV-driven reversible heat pumps are the most promising and close to a market solar solution today but are still in their technical infancy. In fact, although all the components necessary to implement this technical approach have long been on the market and are deeply known, with innumerable PV systems and compression heat pumps having been installed all over the world, the operation of the combined system is not well known yet and needs international R&D work to better understand the optimal configurations under several criteria.

As a demonstration of this lack of knowledge about PV driven heat pumps, the IEA has recently promoted a new specific project ([IEA-SHC, 2016](#)) called ‘New Generation Solar Cooling & Heating Systems (PV or solar thermally driven systems)’ to investigate the implementation possibilities of new solar-driven cooling and heating systems. One of the main objectives of the task is to develop the best-suited climate control system technology focusing on reliability, adaptability, and

quality in order to assist the market development of these applications. In this context, the price decrease of PV modules, which was around 85% between 2009 and 2016 according to [IEA PVPS \(2016\)](#), coupled with increased electricity prices has substantially modified the profitability of this technology, opening up the possibility of its use in applications that were little considered until now, such as the thermal conditioning of buildings. However, a research review in the area of control of electric conditioning equipment (including reversible heat pumps) leads to the conclusion that specific strategies for combining these systems with locally generated PV electricity have not been proposed yet. In this sense, and in order to identify effective and close to the market solutions to minimize the energy demand of buildings according to Directive 2010/31/EU, the combination of heat pumps powered by onsite PV systems has great potential applicability.

Advanced control of building climate

The reduction of energy consumption of heating and cooling systems has attracted great interest in the last years. Novel approaches are proposed for the efficient use of solar energy in these systems. One direction deals with more energy-efficient components and better architectural design. Another direction is aimed at improving the efficiency of existing or slightly retrofitted systems in combination with solar energy through better configurations and new control algorithms. The latter approach can be rapidly implemented and aims to reduce energy usage and costs while guaranteeing comfort for occupants ([Zhang *et al.*, 2013](#)).

Unfortunately, the building dynamics are slow, and the buildings are subject to intermittent disturbances (e.g. the weather, behaviour of consumption and occupants, luminance, and air quality). This gives rise to a constrained control problem in which predictions are used in order to make use of the storage capacity of a building appropriately ([Oldewurtel *et al.*, 2012](#)).

Given those restrictions, it is not efficient to apply standard control techniques (e.g. regulators, compensators, PIDs). On the contrary, it is feasible to predict the change in the dependent variables of the modelled system that will be caused by changes in the independent variables. The current practice in the building control industry is to use (non-predictive) Rule-Based Controllers (RBCs) that perform control actions based on typically uncoordinated conditional rules ([ETH, 2013](#)). However, recent works using Model Predictive Control (MPC) have shown that significant energy savings are possible if weather and occupancy predictions are incorporated into the controller ([Oldewurtel *et al.*, 2010](#); [Afram and Janabi-Sharifi, 2014](#); [Záčeková *et al.*, 2014](#)).

In this context, MPC is an advanced method of process control that has been in use since the 1980s. MPC refers to a range of control methods that use a model to obtain the control signal by minimizing an objective function (Camacho and Bordons, 2013). Typical MPC structures consist of a dynamic model of the system process, a history of past control actions, and an objective function over the receding prediction horizon to calculate optimal control strategies (Camacho and Bordons, 2013).

MPC uses the current plant measurements, the current dynamic state of the process, the MPC models, and the process variable targets and limits to calculate future changes in the dependent variables. These changes are calculated to hold the dependent variables close to target while honouring constraints on both independent and dependent variables. The main advantage of MPC is the fact that it allows the current timeslot to be optimized while taking future timeslots in account. This is achieved by optimizing a finite time horizon but only implementing the current timeslot. Therefore, MPC has the ability to anticipate future events and can take control actions accordingly.

In particular, during each sampling interval, a finite-horizon optimal control problem is formulated and solved over a finite prediction horizon. The result is a trajectory of inputs and states into the future that satisfies the dynamics while optimizing some given criteria. When applied in building climate control, this means that at the current point in time, a plan for heating, cooling, and ventilation is formulated for the next several hours to days based on predictions of the upcoming conditions. Predictions of any disturbances (e.g. occupancy) and time-dependencies of the control costs (e.g. dynamic electricity prices) or of the constraints (e.g. thermal comfort range) can be easily included in the optimization (Zhang *et al.*, 2013).

MPC works on linear processes, and although many real processes are not linear, they can often be considered to be approximately linear over a small operating range. Linear MPC approaches are used in the majority of applications with the feedback mechanism of the MPC compensating for prediction errors due to the structural mismatch between the model and the process. When linear models are not sufficiently accurate to represent the real process nonlinearities, several approaches can be used. In some cases, the process variables can be transformed before and/or after the linear MPC model to reduce the nonlinearity. The process can be controlled with nonlinear MPC, which uses a nonlinear model directly in the control application. The nonlinear model may be in the form of an empirical data fit (e.g. artificial neural networks) or a high-fidelity dynamic model based on fundamental mass and energy balances. The nonlinear model may be linearized to derive a Kalman filter or specify a model for linear MPC (ETH, 2013).

Besides its ability to handle constrained control problems, one frequently given reason why MPC can lead to energy savings in building climate control is the ability to easily incorporate weather forecasts and make use of the building for thermal storage. The use of weather forecasts in building climate control is, however, not straightforward, since the weather forecasts are subject to errors, which introduces uncertainty to the resulting control problem. In order to achieve a good control performance, it is crucial to properly account for these uncertainties in the controller. The same consideration should be included for occupancy, generation (if existing), or consumption predictions.

Occupancy, generation, and consumption, in terms of both the heat gains that are introduced to the building and the constraints due to the need to meet the occupants' comfort requirements, could be inserted in the MPC system. Today, occupancy information is used only in the form of schedules in building climate control, often in addition to instantaneous adjustments of lighting and sometimes in addition to instantaneous adjustment of both lighting and ventilation based on occupancy sensor measurements. However, it appears to be desirable to take into account information about occupancy in order to achieve an energy-efficient building climate control ([Maasoumy and Sangiovanni-Vincentelli, 2014](#)).

In the work of [Zhang *et al.* \(2013\)](#), the potential benefit of long-term vacancy information is investigated and an advanced control strategy using occupancy predictions is compared with simple control strategies that are based on current measurements. They state that MPC can also be beneficial in the area of electricity grids and dynamic electricity tariffs. From an electricity network perspective, it is important to reduce the peak electricity demands, since the peaks determine the necessary capacity of the network. Price signals are used as an economic incentive for consumers to shift their electricity demand in time according to the price signal and hence behave in a grid-friendly manner. When using MPC, this price signal can be directly incorporated in the formulation of the optimization problem.

Another important line of research in control of building consumption has been developed around DSM techniques. DSM is defined as actions that influence the way in which consumers use electricity in order to achieve savings or higher efficiency in energy use ([Strbac, 2008](#); [Palensky and Dietrich, 2011](#)). DSM techniques are focused on the modification of the aggregated consumption shape. In general, these techniques aim to smooth this shape with the final goal of flattening it. The DSM mechanisms may be varied in nature; for instance, they include changing the regulatory framework, encouraging consumer awareness, pursuing a reduction in the consumption of electrical appliances, making the active participation of consumers in electricity markets possible, and so on.

Although there are several practical experiences of DSM and part of its technology requirements have already been developed, its implementation is slow. However, the combination of DSM with an automatic control of demand and local generation leads to a new concept called active demand-side management (ADSM) (Castillo-Cagigal *et al.*, 2011; Matallanas *et al.*, 2012). These techniques have been previously implemented in the residential sector from both the individual and the collective perspective. From the results, it can be concluded that ADSM could be beneficial for building climate control.

HVAC and PV systems

Many studies simulating PV systems coupled with HVAC equipment have been published, demonstrating the interest in using PV electricity to condition the indoor climate in buildings, as is indicated below:

A comparative study of different solar cooling systems for buildings in a subtropical city (Hong Kong) was developed by Fong *et al.* (2010). In this paper, five types of solar cooling systems were considered in a comparative study, which is commonly featured in a region that features a long hot and humid summer. The solar cooling systems included solar PV electric compression refrigeration, solar mechanical compression refrigeration, solar absorption refrigeration, solar adsorption refrigeration, and solar solid desiccant cooling. Component-based simulation models of these systems were developed, and their performances were evaluated during a year. Through this comparative study, it was found that solar PV electric compression refrigeration and solar absorption refrigeration had the highest energy saving potential of 48 and 43% respectively.

A study concerning modelling and simulation of a grid-connected PV system for supplying heat pumps with thermal energy storage was developed by De Coninck *et al.* (2010). The model described an energy concept consisting of a dwelling with a grid-connected PV system, a compression heat pump, a hot-water storage tank, and a control strategy. The multi-disciplinary model was developed in *Modelica*. The results of a simulation study show the benefits of adding thermal storage capacity with regard to the overall seasonal performance factor and the impact on the electrical grid. Likewise, two control strategies were analysed: one focusing on operation during daytime and another focusing on limiting net power exchange peaks. Both alternative control strategies are able to substantially reduce the number of net power exchange peaks, even with relatively small storage tanks.

A study of DSM with heat pumps, thermal storage, and battery storage in order to increase local self-consumption of grid-connected PV systems was carried out by Williams *et al.* (2012). Self-consumption levels of 55 to 65% from a PV installation of 5.5 kW_p can be reached in the case of a four-person household with a medium to low standard of thermal insulation. Additional electrical storage in the form of a 5-kWh Li-ion battery bank is added. Finally, storage control algorithms are proposed and simulated that allow a reduction of the peak injection into the grid to as low as 55% of the nominal peak-output power of the PV system. The original contributions include a quantitative analysis and values for the increase in self-consumption and household autonomy as a function of building standard, the additional impact of battery storage as a function of battery size, and the reduction of peak injection by applying smart algorithms for storage control.

Daut *et al.* (2013) carried out an assessment of an air-conditioning system powered by PV electricity. This research focused on the design and construction of a direct current (DC) air-conditioning system integrated with a PV system consisting of PV panels, solar charger, DC/DC converter, and batteries. The air-conditioning system can be operated on solar and can be used in non-electrified areas. This paper concluded that the system design needs to consider both air-conditioner and PV system in order to achieve space cooling. With regard to air conditioning, the cooling capacity must be determined first as it will give a rough idea of how to design and construct a system with enough electrical energy supplied to it. The size of the PV-battery system should be determined under consideration of these factors in order to supply the electricity needs.

A performance analysis of different solar cooling systems was carried out by (Naranjo-Mendoza *et al.*, 2014), in Guayaquil, Ecuador. In this study, three different solar cooling systems were analysed. The first one includes 175 kW of a single-effect absorption chiller powered by evacuated tubes solar thermal collectors. This system was compared with two 140 kW compression chiller systems (air-cooled and water-cooled) powered by a grid-connected PV system. The three systems were designed to satisfy a cooling demand of the top floor in one governmental building (app. 1296 m²) which was selected as the case study. The results indicated that the primary energy consumption of the absorption systems is higher than the consumption of compression systems due to the high natural gas demand for the auxiliary heater. The electricity consumption of the absorption systems was also high and cannot be neglected. The cooling tower fan and pump consume more than 60% of the entire absorption system electricity consumption. On the other side, the systems powered by the PV system reduced noticeably the primary energy consumption achieving energy savings up to 67%. Authors concluded that the solar-powered single-effect absorption systems could not generate primary energy savings in the case of Guayaquil. In contrast, PV powered

compression systems seems to be by far better alternative to conventional systems considering the primary energy savings obtained through the high electricity generation.

Aguilar *et al.* (2014) presented a study based on experimental results that analyse the possibility of using PV panels to produce electricity to power the compressor of an inverter air-conditioning unit without the use of batteries. The aim of the research was to study a reversible heat pump with a nominal cooling capacity of 3.52 kW and a nominal heating capacity of 3.81 kW. Three PV panels of 235 W_p were connected directly to the heat pump. The heat pump takes the electricity from the grid and solar panels simultaneously through the inverter. The experimental results show that during the summer months, the PV electricity contribution of PV panels is about 65%. When the heat pump works in heating mode, the results show that the average solar contribution is about 50%.

Thygesen and Karlsson (2014) performed a simulation and an analysis of a solar-assisted heat pump system with two different storage types: one system had 48 kWh of battery capacity and the other had a hot water storage tank where the electricity was stored as heat. The system with batteries had a self-consumption of 89% of the annual PV generation and the system with a hot water storage tank had a self-consumption of 88%. However, the LCOE of the system with batteries was twice as high as that of the system with the hot water storage tank.

Beccali *et al.* (2014) carried out a life cycle assessment and comparison of small solar thermal cooling systems and a conventional compression chiller assisted by PV. The results indicate that the systems with the grid-connected PV systems performed best compared with the use of absorption cooling coupled with a solar thermal system. In addition, two more configurations were investigated to further define the PV-assisted systems, which minimize their interaction with the grid through the use of battery storage.

A paper presented by Brandoni *et al.* (2014) focused on assessing the effect of introducing renewable energy production including PV, taking as a reference case a small-size sustainable community located in central Italy that aims to reach a CO₂ emission reduction of at least 30% by 2025. DSM strategies related to the introduction of heat pump systems powered by the excess derived from renewables have been studied to reduce the impact on the power grid. In particular, the analysis performed was aimed at finding the optimal configurations necessary to achieve thermal comfort in buildings where heat pumps were introduced when DSM strategies were in action. The use of heat pumps provides an interesting reduction in the electricity excess, helping to avoid grid stability problems when a large share of renewable sources is introduced. Moreover, the study of the obtained DSM strategy at dwelling level confirms its feasibility in maintaining internal comfort when proper thermal energy storage was included in the heating system.

[Li et al. \(2015\)](#) presented an experimental study of solar PV for heating and cooling in a hot summer and cold winter zone (Shanghai, China). Four working modes were investigated: cooling in summer and heating in winter for both daytime and night-time. This work demonstrated that consistent and reliable heating and cooling systems can be achieved by the solar PV system in winter as well as in summer and therefore it can be used as a good solution to reduce the peak load of the electrical grid in the hot summer and cold winter zone or in areas with similar weather conditions around the world. In the experimental study, an inverter with an efficiency of around 70 – 80 % was used, which means there is higher energy loss in energy conversion, motivating the development of HVAC systems using direct current.

To sum up, despite the importance of thermal systems in the energy balance of buildings, the researchers above indicate that specific strategies for combining local PV generation with electricity-powered air-conditioning equipment, especially reversible heat pumps, are still under examination. In addition, the implementation of the battery systems into the PV systems to supply HVAC, along with control strategies, is quite interesting because these systems have not been analysed in detail in order to determine whether or not they are competitive with the electricity grid, from both the technical and economical point of view.

The state of the art of this Thesis finalizes with this Chapter, where three important fields were studied: PV systems, battery energy storage systems and HVAC systems. In Part III, the methodology will be addressed, which includes the experimental stage, the modelling of the grid-connected PV-battery systems, and the economic evaluation of PV-battery systems.

Part III

Methodology and validation

Chapter 5

Experimental stage

5.1. General approach

In the previous chapters, the state of the art developments in the research about PV systems, battery energy storage systems, heating ventilation and air conditioning systems, and the economic viability of PV-battery systems have been presented. This Chapter presents the experimental stage of this doctoral thesis. The results of the testing measures shall contribute to the definition of a grid-connected PV-battery system modelling presented in [Chapter 6](#).

This research was conducted in Spain at the premises of the *Instituto de Energía Solar - Universidad Politécnica de Madrid* (IES-UPM), where a prototype of a nearly zero-energy residential building called ‘Magic Box’ has been installed since 2006 ([Fig. 5.1](#)). Magic Box was the first European entry in the Solar Decathlon international competition and has been recognised internationally as an outstanding urban-scale PV system integration project ([Calvo-Fernandez *et al.*, 2005](#); [PVdatabase, 2007](#)). Several research initiatives have been carried out with the prototype ([Castillo-Cagigal, Caamaño-Martín *et al.*, 2011](#); [Castillo-Cagigal, Gutiérrez *et al.*, 2011](#); [Masa-Bote *et al.*, 2014](#)), such as the project ‘Residential electricity demand side management with PV technology 2008–2010’. In this project, the first theoretical and experimental evidence of the possibilities of performing an Active Demand Side Management (ADSM) of domestic electricity consumption was demonstrated worldwide.

Figure 5.1: Upper and frontal (South) views of Magic Box prototype

Relevant parameters

According to the connection characteristics, both electrical and communication, the relevant parameters have been divided into five groups: *i*) grid-connected PV-battery system parameters, *ii*) HVAC electricity consumption, *iii*) thermal comfort sensors, *iv*) battery inverter monitoring, and *v*) meteorological data. Table 5.1 describes main features of the relevant parameters considered in the experimental stage.

Table 5.1: Measured parameters in the experimental stage.

Parameter	Unit	Meaning	Equipment
P_{load}	W	Total electrical consumption	Household appliances
P_{pv}	W	PV generation	Six independent PV arrays
P_{grid}	W	Exported/imported grid power	-
P_{bat}	W	Charge/discharge battery power	Lead-acid battery bank of 22 kWh
P_{hvac}	W	HVAC consumption	Two heat pumps from <i>Daikin</i>
T_{indoor}	°C	Indoor temperature	STR100 thermistors
RH	%	Relative humidity	SCR110 sensor
CO_2	ppm	Concentration of CO_2	SCR110 sensor
SoC	%	Battery state of charge	SMA Sunny Backup 5000
$T_{outdoor}$	°C	Outdoor temperature	Platinum thermoresistance
G_{hrz}	W/m ²	Global horizontal irradiance	Eppey pyranometer

5.2. Grid-connected PV-battery system

PV system

The PV system of Magic Box consists of six independent monocrystalline silicon PV arrays (*Isofotón* I-110 and *Isofotón* I-55 PV modules), with 7 kW_p of total nominal power. This system was designed to exploit the different Sun's apparent heights along the year. To achieve this goal, the PV system is distributed in different south-oriented surfaces with different tilts (see Fig. 5.2), which allows one or more PV arrays to maximise the solar gain depending on the season. Each PV array has an associated string-type inverter, and, therefore, the PV AC power is supplied to a common AC bus. In Table 5.2, the main features of each PV array are shown.

Figure 5.2: Distributions of PV arrays at the Magic Box

Table 5.2: Characteristics of PV arrays

Arrays		1	2	3	4	5	6
Tilt		12°	12°	25°	25°	38°	90°
PV inverters	Model	SWR 1700E	SWR 1700E	SB 1200	SB2000HF- 30	SWR 1100E ¹³	SB 700
	Serial Number	1453601475	1404313569	2001925620	2120014064	654006746	2000210990
	V _{DC max} [V]	400	400	400	700	400	250
	V _{DC MPP} [V]	139 – 400	139 - 400	100 - 320	175 - 560	139 – 400	119 – 250
	I _{DC max} [A]	12.6	12.6	12.6	12	10	7
	V _{AC nom} [V]	230	230	230	230	230	230
	I _{AC nom} [A]	6.5	6.5	5.2	8.7	4.3	3
	P _{AC nom} [kW]	1.55	1.55	1.20	2.00	1.00	0.07
PV generators	P _{DC nom} [kW]	1.45	1.44	1.34	1.34	0.80	0.61
	I _{sc} [A]	6.4	6.4	6.4	6.5	3.2	4.4
	V _{oc} [V]	324.1	323.1	302.2	307.5	349.2	208.4
	E _{pv} [kWh/year]	1745	1683	1774	1774	1026	572

¹³ The inverter is currently not operated due to technical failures.

Both the PV system and the battery energy storage system (BESS) are connected to the distribution grid through the SMA *Automatic SwitchBox*. In addition, three electricity meters have been connected in order to register the exchange of electric power between the grid, the PV generation and the loads, as Fig. 5.3 below shows.

Figure 5.3: Connection diagram of the grid-connected PV-battery system

The *Automatic Switch Box* is a component of the BESS. In default operation conditions, if the grid fails, the *Automatic Switch Box* will disconnect the PV system and the loads from the public grid and connect them to the battery inverter. The battery inverter evaluates the data collected by the Automatic Switch Box and coordinates all switching operations (see Fig. 5.4).

Figure 5.4: Internal connection diagram of the *Automatic Switch Box*.

Battery energy storage system

The house is equipped with a stationary lead-acid battery bank (*Sonnenschein* A602/625) with *dryfit* gel VRLA (valve-regulated lead-acid battery) technology. Lead-acid batteries are still widely used in both off-grid and grid-connected PV systems (Hoppmann *et al.*, 2014; World Energy Council, 2016). Lead-acid batteries are reliable, globally manufactured and, therefore, are a widely understood technology. Furthermore, it has lower prices compared to other storage technologies for PV systems (Mulder *et al.*, 2013; World Energy Council, 2016), such as Lithium batteries as discussed in Chapter 3. The VRLA technology also provides some

advantages compared to other types of lead-acid batteries, such as no maintenance, high current capability, deep-discharge conditions, good power density, and wide operating temperature (Misra *et al.*, 2003; Doeff, 2013).

The battery bank is divided into 24 cells, with each cell having a capacity (C_{10}) of 455 Ah and a nominal voltage of 2V. Therefore, the total battery bank voltage is 48V, with a capacity of around 22 kWh. The storage system has a bidirectional battery inverter, SMA Sunny Backup 5000 (SBU5000), for switching between battery voltage at DC and all power exchanges produced through the AC bus. The battery inverter does not only implement the current conversion but also allows for the controlling and monitoring of the power flows from and to the battery.

The installation of PV inverters, battery inverter and battery bank are illustrated in Fig. 5.5. Tables 5.3 and 5.4 show the technical data of both the SBU5000 and the batteries, respectively.

Figure 5.5: Detail of the technical room with inverters and battery storage system.

Table 5.3: Technical data of the battery inverter

Technical data	SMA Sunny Backup 5000
Serial Number	1260002490
Output (loads)	
Nominal power/current during grid operation	7.4 kW / 32 A at 35 °C
Max. power/current during grid operation for 30 min	8.9 kW / 38 A at 35 °C
Maximum fuse size	40 A
Backup power (nominal / 30 min / 1 min)	5 kW / 6.5 kW / 8.4 kW
Voltage (range)	230 V (187.0 – 253.0 V)
Frequency (range)	50 Hz (45 – 55 Hz)
Permitted grid structure	TN / TT
Typical interruption time in the event of power outage	20 ms
Input PV system	
Nominal AC PV power / current	5.7 kW / 25 A at 35 °C
Maximum fuse size	32 A
Compatible PV inverters	All SMA
Input battery	
Nominal voltage	48 V
Battery type	VRLA / FLA / NiCd
Efficiency/internal consumption	
Max. efficiency backup operation	94 %
Internal consumption day / night (Silent Mode)	48 W / 32 W

Table 5.4: Technical data of the batteries

Technical data	<i>Sonnenschein</i> A602/625 Battery
Nominal Voltage	2 V
Nominal capacity C10	455 Ah
Discharge current I10	45.5 A
Length	147 mm
Width	208 mm
Height	515 mm
Weight	35 kg
Technology	<i>dryfit</i> gel – VRLA
cycling performance	3000 cycles at 60 % Depth of Discharge C10 at 20 °C
Float charge voltage	2.25 V
Max. charge voltage	2.45 V
Boost charge voltage	2.40 V
Internal Resistance	1.2 Ω at 20°C and at 60% DoD

Electricity metering equipment

The grid-connected PV-battery system is equipped with three bi-directional electricity meters connected to the data acquisition system through an RS-485 bus. Each electricity meter consists of a transformer (*Circutor* TM45 50 / 5A) and an electricity monitoring device (*Janitza* UMG 604¹⁴) as shown in Fig. 5.6.

This electricity meters record P_{grid} , P_{pv} , and P_{load} , providing the power and energy measurements with a sampling period of one minute.

Figure 5.6: Connection diagram of the electricity meters.

¹⁴ Accuracy Class 1 according to IEC Standard 62053-21.

Figure 5.7: Photograph showing the electricity meters.

Due to data loss when using the *Janitza* power analyser (around 10% of the total daily data), installation of another set of electricity meters was carried out, without uninstalling the first one. Fig. 5.8 shows the second connection diagram with transformers (HOBUT CT151 25/5) along with the electricity monitoring device (*rbz* METER 3PH). It should be noted that the substantial difference between both electricity meters schemes is that in the second one is unidirectional. The latter causes the P_{grid} variable to only have a record of the electricity imported from the grid. Both P_{pv} and P_{load} parameters are not affected, being by definition unidirectional.

In both schemes, there is no electricity meter directly connected to the BESS. Consequently, the battery power (charge/discharge) is estimated by power balance, as follows:

$$P_{bat} = P_{load} - P_{pv} - P_{grid} \quad (5.1)$$

Figure 5.8: Connection diagram of the second set of electricity meters.

Figure 5.9: Photograph showing the second set of electricity meters.

5.3. HVAC electricity consumption

To determine the HVAC electricity consumption (P_{hvac}), two air-to-air electrical reversible heat pumps from *Daikin* (model FTX25KV1B, Fig. 5.10) are used. As highlighted in Chapter 4, this kind of heat pumps is experiencing a significant market penetration due to the capability to cover both heating and cooling loads by using the same installation, the high operating efficiencies compared to other HVAC solutions and the low costs of equipment, installation and maintenance.

Fig. 5.10 shows the main components of the *Daikin* heat pumps installed in the house, both the indoor unit and outdoor unit. Also, Table 5.5 shows the technical data.

Figure 5.10: Heat pump from *Daikin*, model FTX25KV1B. (a) Indoor unit and (b) outdoor unit. Source: *Daikin* operation manual.

Table 5.5: Heat pumps technical data

Cooling capacity	Min.	1.3 kW
	Nom.	2.5 kW
	Max.	3.0 kW
Heating capacity	Min.	1.3 kW
	Nom.	3.0 kW
	Max.	4.0 kW
Nominal efficiency ¹⁵	EER	3.78
	COP	4.36
	SPF ¹⁶	2.79
Annual energy consumption		331 kWh
Energy Labelling Directive		A
Consumption (Thermostat off)		21 W

Figure 5.11: Photograph showing the indoor unit of the heat pumps.

In order to measure the electricity consumption of the heat pumps, an electricity meter (iEM3155¹⁷ from *Schneider Electric*) has been installed (see the connection diagram in [Fig. 5.12](#)).

¹⁵ Nominal efficiency: cooling at 35°/27° nominal load, heating at 7°/20° nominal load

¹⁶ Obtained according to Eq. 4.3, WF = 0.64 and CF = 1.

¹⁷ Accuracy Class 1 according to IEC Standard 62053-21.

Figure 5.12: Connection diagram of the heat pumps and electricity meter.

Figure 5.13: Photograph showing the electricity meter iEM3155.

The electricity meter iEM3155 measures one-minute accumulated energy in watts-hour (E_{hvac}), so the power of the heat pumps (in watts) in the n minute, must be calculated through the Eq. 5.2, as follows:

$$P_{hvac}[n] = 60 \cdot (E_{hvac}[n] - E_{hvac}[n-1]) \quad (5.2)$$

5.4. Thermal comfort sensors

In order to monitor the comfort conditions inside the house, STR100 thermistors from *Schneider Electric* with an accuracy of $\pm 0.35^\circ\text{C}$ are used to measure the T_{indoor} . Likewise, RH (0-100%) and concentration of CO_2 (0-2000 ppm) are measured by the SCR110 sensor from *Schneider Electric with an accuracy of $\pm 2\%$. The positions of these devices and sensors are shown in [Fig. 5.14](#).*

Figure 5.14: Location scheme of heat pumps and indoor sensors

Due to the fact that only one temperature sensor is available for each point and the vertical thermal gradient is not possible to be measured, each sensor has been placed at a height representative of the user's thermal sensation, that is, at a height of 1.75 m from the ground. In any case, heat pumps constitute a forced ventilation HVAC system, therefore, the mixing of the air produced by the fans ensures that there is no significant temperature stratification, whereby each point is representative of all the heights. Likewise, in order to obtain measurements in a better volumetric distribution of the house, six temperature sensors have been installed in the house.

The data from sensors (S) are collected through meters (*rbz* SDIN RTD1, *rbz* SDIN RTD2 and *rbz* SDIN ANALOG) and connected to the serial communication bus, as Fig. 5.15 shows.

Figure 5.15: Connection diagram of the thermal comfort sensors and corresponding meters.

Figure 5.16: Photographs showing two thermal comfort sensors (left) and *rbz* SDIN meters (right).

5.5. Data concentration system

The data concentration system (*rbz TJ mon*) receives information of all metering equipment previously explained through the serial communication bus RS485 (see Fig. 5.17). Data coming from the metering equipment, are subsequently classified and stored in servers. This task was carried out thanks to the ROBOLABO¹⁸ team of the ETSIT-UPM, which allowed the author of this thesis, accessing and monitoring relevant parameters, which were the basis for the present investigation.

Figure 5.17: Connection diagram of the data concentration system.

¹⁸ <http://www.robolabo.etsit.upm.es/>

Figure 5.18: Photograph showing the electricity meter iEM3155.

The data are stored in files that are updated every minute. These files are classified into folders according to the corresponding metering device, as shown in Table 5.6. Access to these files is done through SSH¹⁹ protocol. In case of using Windows operating system, the WinSCP software must be used and then enter the server name: monitoring.robolabo.etsit.upm.es. The user credentials and password must be authorized by the ROBOLABO team.

Table 5.6: Files used from data concentration system

Meter	Folder	Output file	Parameters
JANITZAUMG 604	janitzas	janitza01-YYYY-MM-DD	$P_{grid}, P_{pv}, P_{load}$
SDIN meter 3PH	meter_3phase	meter_3phase-YYYY-MM-DD	$P_{grid}, P_{pv}, P_{load}$
iEM3155	meters	HVAC-YYYY-MM-DD	P_{grid}
SDIN RTD1	rtds	rtd1-YYYY-MM-DD	T_{indoor}
SDIN RTD2	rtds	rtd2-YYYY-MM-DD	T_{indoor}
SDIN ANALOG	analog	analog1-YYYY-MM-DD	RH and CO_2

¹⁹ The SSH protocol (also referred to as Secure Shell) is a method for secure remote login from one computer to another.

All the folders generate daily files with the following structure:

<Timestamp> <Date> <Time> <errorBit> <DATOS>

The column called <DATOS> is different in each file, as follows:

- janitza01-YYYY-MM-DD: <col11 ... col30>

In this file, there are 30 columns (col). In the col08, col09 and col10 columns, the measured powers in watts of P_{grid} , P_{pv} and P_{load} are registered, respectively. Likewise, in the col16, col17 and col18 columns the energy values are recorded in watts-hour.

- meter_3phase-YYYY-MM-DD: <col11 ... col20>

In the col08, col09 and col10 columns, the measured powers in watts of P_{grid} , P_{pv} and P_{load} are registered, respectively.

- HVAC-YYYY-MM-DD: <col11 col12 col13 col14 col15>

In the col03 and col04 columns, the energy values of both LHP1 (line of heat pump 1) and LHP2 (line of heat pump 2) are recorded in watts-hour, respectively.

- rtd1-YYYY-MM-DD: <S1 S2 S3 S4>
- rtd2-YYYY-MM-DD: <S5 S6>

In these two files, the indoor temperature (T_{indoor}) is recorded in tenths of a degree centigrade.

- analog1-YYYY-MM-DD: <S7CO2 S7HR>

In this file, the measurements correspond to a 12-bit AD converter. Therefore, to obtain the values of CO_2 [ppm], and RH [%], the following equations must be used:

$$CO_2 = 2000 \cdot (S7_{CO2} - 819) / (4095 - 819) \quad (5.3)$$

$$RH = 100 \cdot (S7_{RH} - 819) / (4095 - 819) \quad (5.4)$$

5.6. Battery inverter monitoring

Data from SMA inverters can be monitored in real time by the communication hub, called *Sunny WebBox*. The *WebBox* is a multi-functional data logger which offers a wealth of options for displaying, archiving and processing data. The *WebBox* connects the SMA devices (PV inverters and battery inverter) collecting and documenting all data of the devices, thus permitting interruption-free monitoring of the PV-battery system. The *WebBox* diagnostics and provides recorded data via local computer or through an internet connection as shown below.

Figure 5.19: Connection diagram of the SMA inverters along with the *WebBox*.

Figure 5.20: Photograph showing the *WebBox* mounting.

A screenshot of the *WebBox* user interface is shown in Fig. 5.21. Although the *WebBox* records information about all SMA inverters, only three variables obtained from the SBU5000 are used for monitoring and controlling the battery inverter, according to Table 5.7 details.

Table 5.7: Variables used from Sunny Backup inverter

Variable name	Unit	Description	variable type
BatSoc	%	Battery state of charge	read-only
GdCurNom	A	Nominal grid current	programmable
InvChrgCurMax	A	AC charging current	programmable

Nº	Denominación	Valor mín.	Valor máx.	Valor	Unidad
1	AfraEna			Disable ▾	
2	AptTmBoost	1	600	120	min
3	AptTmEqu	1	48	10	h
4	AptTmFul	1	20	5	h
5	AuthCode	0	4294967296	0	
6	AutoEquChrgEna			Enable ▾	
7	AutoStr	0	10	0	
8	BatChrgCurMax	10	1200	277.55	A
9	BatChrgVtgMan	41	63	54	V
10	BatCpyNom			455	Ah
11	BatFanTmpStr	20	50	40	degC
12	BatProISoc	0	90	40	%
65	GdCsmPEgyMtr			0	kWh
66	GdCurNom	0	1000	0	A
67	GdFeedEgyMtr			0	kWh
122	GnTmStr	0	1522491	0	hhmmss
123	GnVtgMax	202	264,5	249.984	V
124	GnVtgMin	172,5	252,996	172.5	V
125	GnWarmTm	5	900	60	sec
126	InvChrgCurMax	0	50	21.7	A
127	InvFrqNom	40	70	50	Hz
128	InvRs			---	

Figure 5.21: Screenshot showing the *WebBox* user interface. The two programmable variables are highlighted.

Once the state of charge has been obtained, the current limiters of the battery inverter can be controlled through the parameters GdCurNom and InvChrgCurMax. As shown in Fig. 5.22 below:

Figure 5.22: Diagram of the task performed in order to control the battery inverter.

These tasks are programmed in a PC connected directly to the local network of the house. The PC is equipped with Ubuntu-Linux operating system. Thanks to the operating system along with the C++ programming language, multiple high-level controllers have been developed in a previous study (Castillo-Cagigal, Caamaño-Martín, *et al.*, 2011). These controllers can manage the stream limiters in order to implement battery control strategies.

As shown in the previous figure, the tasks are divided into two subsystems:

- i) Battery monitoring: read and store the battery state of charge.
- ii) Battery inverter controlling: manage the operation of the battery through charge and discharge commands. Its operation is conditioned by the evolution of the real PV generation and load profiles.

In the Appendices 1 and 2 at the end of this Thesis, the programming codes of these two subsystems are shown. As a result of the programmed tasks, two daily files are generated and stored in the local PC of the house:

- /home/magicbox/data/SBU/SBU_datas-YYYY-MM-DD
- /home/magicbox/data/batController/batController- YYYY-MM-DD

The weather station stores the data in daily text files (dataYYY_MM_DD.txt). These files are stored in the directory '*D:\datos*' of the Helios CPU, shared to the local network of the IES. That is, to access these files, it is enough to be connected to any computer to the local network of the IES. Data stored in the file has the following format:

<Timestamp> <Date> <DATA>

The <DATA> section has 20 columns, where *Ghrz* is registered in col01 and *T_{outdoor}* [°C] in col07.

Both the *Ghrz* and *T_{outdoor}* are used as input variables to calculate comfort conditions within the house, according to the comfort methods analyzed in the case study of the [Section 8.1](#).

To finish this Chapter, it should be mentioned that the experimental stage was divided into two parts:

- i*) HVAC electrical consumption, indoor temperature, CO2 and RH were measured through a series of tests in controlled conditions, performing a considerable number of tests in 112 days from February 2016 to June 2017 (analysed in [Chapter 8, Section 8.1](#)).
- ii*) Grid-connected PV-battery system parameters (P_{pv} , P_{grid} , P_{load} , P_{bat} , and SoC) were analyzed in 44-day experimental measurements between January and June 2017. This result has interesting practical implications in the design and modelling of PV-battery systems analysed in the next chapter.

Chapter 6

Grid-connected PV-battery systems modelling

This Chapter describes the battery control strategies used in this thesis, along with the formulation of the mathematical model. The general aim of implementing control strategies is to profit from the use of local PV production to provide an efficient supply to local demand (HVAC or total). Thus, two battery control strategies are proposed: optimising self-consumption and peak-shaving. These control strategies have been verified experimentally with the data obtained from the experimental stage presented in [Chapter 5](#). Finally, a simulation tool called *PVbat* is presented, which implements the control strategies proposed in this Chapter. With this tool, three cases studies have been analysed, which are presented in [Chapter 8](#).

6.1. Battery control strategies

Control strategy 1: Optimising self-consumption

The purpose of this strategy is to import energy from the grid as little as possible. In this strategy —according to the parameters presented in [Table 5.1](#)— the PV generation (P_{pv}) supplies the local demand (P_{load}) directly; the excess of P_{pv} charges the battery (P_{bat}), and if the battery is full, the PV surplus is exported to the grid (P_{grid}). Likewise, from a demand-side point of view, P_{load} is supplied first by P_{pv} .

If more power is required, it is obtained from the battery, and finally, it is imported from the grid. It is to be noted that a direct power exchange between the grid and the battery is not allowed in any circumstance. Although in a PV hybrid system it is technically feasible to charge the battery from the grid, for example, at times of low electricity prices, such possibility has not been considered in this thesis. The reason is that the battery charge regime would strongly depend on local electricity prices and might not be coherent with the objective of efficient supply of HVAC load by PV electricity.

Control strategy 2: Peak-shaving

The purpose of this strategy is to reduce the demand for electricity during the peak usage times. In this strategy, as in strategy 1, the P_{pv} supplies the P_{load} , the excess of PV charges the battery, and if the battery is full, the PV surplus is exported to the grid. From a demand-side point of view, strategy 2 is similar to strategy 1; the difference is that the battery is discharged only to supply power peaks. In fact, P_{load} is supplied first by PV and then by the grid, however, in this case, the power supplied from the grid is limited to an established value (P_{max}^{20}). If the demand exceeds this limit, the battery is discharged so that the grid demand is curtailed. Also, in this case, power exchanges between the grid and battery are not allowed.

The different operations of the control strategies are shown in the Fig.6.1. Fig. 6.1a shows the operation of strategy 1, and Fig. 6.1b shows the operation of strategy 2 with an illustrative value of $P_{max} = 805$ W. Both strategies are showed for the same day, where P_{bat} , P_{grid} , and SoC are simulated based on specific P_{pv} and P_{load} .

Figure 6.1: Example of how battery control strategies work for the strategy 1 (a) and strategy 2(b). P_{pv} : PV power; P_{load} : electricity consumption; P_{bat} : battery power; P_{grid} : grid power; SoC : Battery state of charge.

²⁰ In some countries, customers can choose the power contracted with the utilities.

As shown in Fig. 6.1a, the battery supplies (positive P_{bat}) the local demand until it reaches the minimum state of charge allowed (in this case $SoC_{min} = 40\%$). Then, the required power is imported from the grid (positive P_{grid}). PV generation is first used to supply the local demand; the surplus of PV charges the battery (negative P_{bat}) up to 100%, and the PV excess is exported to the grid (negative P_{grid}).

In strategy 2 (Fig. 6.1b), the battery reduces the grid power demand over P_{max} , which represents a reduction of the assumed initial contracted power required to supply the P_{load} . However, in terms of grid electricity savings arisen from the battery, the outcome is minimal. In this example, the SoC evolution is almost not affected, decreasing from 80% to 73%, and then, the battery is fully charged within two hours. The potential benefit of peak-shaving control strategy can be explained by considering the impact that the contracted peak power has on the electricity bill, which strongly depends on the regulatory framework and/or billing contract conditions. In Spain, for instance, the power term has an impact on the electricity bill, increasing by nearly 100% since 2007 to the present day (RD 1634/2006; Orden ETU/1282/2017). Therefore, a BESS control strategy focused on reducing power peaks supplied by the grid is worthy of study.

Different studies of PV hybrid systems have proposed battery control strategies related to strategy 1 (Widén, 2014; Moshövel *et al.*, 2015; Quoilin *et al.*, 2016; Linssen *et al.*, 2017) or strategy 2 (Palensky and Dietrich, 2011; Leadbetter and Swan, 2012; Purvins, Papaioannou and Debarberis, 2013; Yang *et al.*, 2014) separately. This thesis proposes a unique model for both approaches, as shown in Sections 6.2 and 6.3, to perform annual simulations combining both control strategies for different approaches, such as seasonal periods, hourly electricity price, days of maximum solar irradiance, among others.

6.2. Battery control algorithm

On the one hand, the actual BESS is controlled by tasks programmed in a PC connected directly to the local network of the house, whereby the battery inverter is used to provide actual information about the battery bank, specifically the state of charge (SoC). Similarly, the tasks programmed have real-time access to the data concentration system, where the actual values of P_{grid} , P_{bat} , P_{pv} and P_{load} are recorded and stored as showed in the Section 5.5. On other hand, in the algorithm proposed in the present Chapter, the actual values of P_{pv} and P_{load} are used in order to simulate the P_{grid} , P_{bat} and SoC . These simulated values are subsequently compared with the actual values collected from the experimental stage. The general scheme of the battery control strategies algorithm for both strategies is presented

in Fig.6.2 and will be explained in the next section by means of its mathematical formulation.

Figure 6.2: Battery control algorithm diagram.

6.3. Mathematical modelling

The general formulation of the mathematical model presented here was designed to complement an existing control algorithm (Castillo-Cagigal *et al.*, 2011). The improved model enables the choice between the two control strategies proposed in this thesis.

Battery charge

When $P_{pv}[n] > P_{load}[n]$, the battery inverter works in self-consumption mode, and the battery bank is charged only with $P_{surplus}$. Then, a first approximation of the battery power $P_{bat,0}[n]$ is calculated for each discrete time step n :

$$P_{bat,0}[n] = \begin{cases} coef[n] \times P_{surplus}[n], & P_{required}[n] \geq P_{surplus}[n] \\ coef[n] \times P_{required}[n], & P_{required}[n] < P_{surplus}[n] \end{cases} \quad (6.1)$$

where the PV surplus power, $P_{surplus}$ is as follows:

$$P_{surplus}[n] = |P_{load}[n] - P_{pv}[n]| \quad (6.2)$$

The power required to complete battery's charge ($P_{required}$) is as follows:

$$P_{required}[n] = \begin{cases} \frac{V_{dc} C |SoC[n] - SoC_{up}|}{\Delta t}, & SoC[n] < SoC_{up} \\ \frac{V_{dc} C |SoC[n] - SoC_{max}|}{\Delta t}, & SoC_{up} \leq SoC[n] < SoC_{max} \\ 0, & SoC[n] \geq SoC_{max} \end{cases} \quad (6.3)$$

where the state of charge SoC must be among $0 \leq SoC[n] \leq 1$.

The charge coefficient, $coef$, represents the gradual reduction of $P_{bat,0}$ to avoid over-charging. In this model, the $P_{bat,0}$ in charge has a negative value; thus the $coef$ is between -1 and 0.

$$coef[n] = \begin{cases} 0.5 \left(\frac{SoC[n] - SoC_{up}}{SoC_{max} - SoC_{up}} - 1 \right), & SoC_{up} \leq SoC[n] \leq SoC_{max} \\ -1, & SoC[n] < SoC_{up} \end{cases} \quad (6.4)$$

The battery is charged up to SoC_{up} (upper limit of the state of charge), and it will continue charging from that point until the maximum state of charge SoC_{max} but with less power to avoid over-charging the battery: $SoC_{up} \leq SoC_{max}$

Typical values of SoC_{up} and SoC_{max} are 95% and 100% respectively (values obtained from the battery inverter SMA Sunny Backup 5000), which means that the battery is charged with all the available power up to $SoC = 95\%$, then it continues being charged, but with less and less power until it reaches $SoC = 100\%$.

Δt is the time interval in which the data are analysed, expressed in hours and it is between $0 < \Delta t \leq 1$. For example, if n is recorded every minute, then Δt will be $1/60$.

V_{dc} (V) is the nominal voltage of the battery bank, and C (Ah) is the nominal capacity. For each step n , the capacity C will be the result of the following condition:

$$\frac{P_{bat,0}[n]}{V_{dc}} \approx C_{-rate} \quad (6.5)$$

where C_{-rate} (A) is a measure of the rate at which the battery is charged/discharged relative to its nominal capacity (see [Section 3.5](#) in [Chapter 3](#)). If detail of C_{-rate} is not available, the value of the nominal capacity at C_{10} could be used.

Battery discharge

The battery is discharged when $P_{load}[n] > P_{pv}[n]$. Then, the battery power $P_{bat,0}$ is as follows:

$$P_{bat,0}[n] = \begin{cases} P_{surplus}[n], & P_{remaining}[n] \geq P_{surplus}[n] - P_{max} \\ P_{remaining}[n], & P_{remaining}[n] < P_{surplus}[n] - P_{max} \end{cases} \quad (6.6)$$

where, $P_{remaining}$ is the power that can be extracted from the battery, as follows:

$$P_{remaining}[n] = \frac{V_{dc} C |SoC[n] - SoC_{min}|}{\Delta t} \quad (6.7)$$

The maximum power, P_{max} , or curtailed power is a specific variable of strategy 2, ($P_{max} > 0$), which determines the maximum power imported from the grid.

Besides, the battery will never be discharged, $P_{bat,0}[n] = 0$, if at least one of the following conditions is met:

$$P_{max} > P_{surplus}[n], \text{ or } [(SoC_{min} \leq SoC[n] \leq SoC_{low}) \& \Delta SoC \geq 0], \text{ or } SoC[n] < SoC_{min}$$

The battery will be allowed to discharge until the minimum state of charge SoC_{min} , and only when SoC overcomes the SoC_{low} level, it will be possible to discharge the battery again. In this way, a process of hysteresis is implemented to avoid undesirable switches of the controller at low SoC levels ($0 \leq SoC_{min} \leq SoC_{low}$)

Finally, ΔSoC is the difference between the present state of charge $SoC[n]$ and the previous $SoC[n - 1]$.

$$\Delta SoC = SoC[n] - SoC[n - 1] \quad (6.8)$$

Losses in the battery inverter

Generally, the efficiency of an inverter indicates how much input power (P_{input}) is converted to output power (P_{output}). The conversion efficiency of an inverter is a function of the operating power. The model proposed by Schmidt (1994) is used to calculate the efficiency of the battery inverter (η) as a function of the normalized output power (ρ_o). This model is based on experimental measures, and proposes the following equation to describe the conversion efficiency:

$$\eta(\rho_o) = \frac{P_{output}}{P_{input}} = \frac{P_{output}}{P_{input} + losses} = \frac{\rho_o}{\rho_o + (k_0 + k_1 \cdot \rho_o + k_2 \cdot \rho_o^2)} \quad (6.9)$$

were

$$\rho_o = \frac{P_{output}}{\max(P_{output})} \quad (6.10)$$

The parameters k_0 , k_1 and k_2 have the following interpretation: k_0 represents the inverter self-consumption losses. An efficient inverter is characterized by self-consumption losses lower than 0.5%. k_1 represents the losses linearly dependent on

the operating power; and, k_2 represents the losses that depend quadratically on the operating power. The characteristic parameters k_0 , k_1 and k_2 can be adjusted to a set of values, derived from the experimental measurement, and as far as possible distributed throughout the power range. Specifically, the following equations can be used:

$$k_0 = \frac{1}{9} \cdot \frac{1}{\eta_1} - \frac{1}{4} \cdot \frac{1}{\eta_{0.5}} + \frac{5}{36} \cdot \frac{1}{\eta_{0.1}} \quad (6.11)$$

$$k_1 = -\frac{4}{3} \cdot \frac{1}{\eta_1} + \frac{33}{12} \cdot \frac{1}{\eta_{0.5}} - \frac{5}{12} \cdot \frac{1}{\eta_{0.1}} - 1 \quad (6.12)$$

$$k_2 = \frac{20}{9} \cdot \frac{1}{\eta_1} - \frac{5}{2} \cdot \frac{1}{\eta_{0.5}} + \frac{5}{18} \cdot \frac{1}{\eta_{0.1}} \quad (6.13)$$

where $\eta_{0.1}$, $\eta_{0.5}$ and η_1 are the instantaneous efficiency values corresponding to $\rho_o = 0.1$, 0.5 and 1 , respectively. If experimental measurements are not possible, the values of η can be deduced from the inverter efficiency curve, as shown in [Fig. 6.3](#).

Figure 6.3: Battery inverter efficiency curve in discharge.

Based on these concepts, and considering the losses caused by the inverter, a new P_{bat} is calculated by the following polynomial expression according to the characteristic efficiency coefficients of the inverter, in both charge (k_{c0} , k_{c1} , k_{c2}) and discharge (k_{d0} , k_{d1} , k_{d2}).

$$P_{bat}[n] = -P_{inverter,cha} \left(\frac{-(1 + k_{c1}) + \sqrt{(1 + k_{c1})^2 - 4k_{c2} \left(k_{c0} - \frac{|P_{bat,0}[n]|}{P_{inverter}} \right)}}{2k_{c2}} \right), \forall \frac{|P_{bat,0}[n]|}{P_{inverter}} > k_{c0} \quad (6.14)$$

$$P_{bat}[n] = P_{inverter,dis} \left(\frac{-(1 + k_{d1}) + \sqrt{(1 + k_{d1})^2 - 4k_{d2} \left(k_{d0} - \frac{|P_{bat,0}[n]|}{P_{inverter}} \right)}}{2k_{d2}} \right), \forall \frac{|P_{bat,0}[n]|}{P_{inverter}} > k_{d0} \quad (6.15)$$

The losses in L the battery inverter, for both charge and discharge, are calculated as follows:

$$L_{charge} = \sum_{n=1}^m \frac{P_{bat,0}[n] - P_{bat}[n]}{P_{bat,0}[n]}, \quad \forall P_{bat,0}[n] < 0 \quad (6.16)$$

$$L_{discharge} = \sum_{n=1}^m \frac{P_{bat,0}[n] - P_{bat}[n]}{P_{bat,0}[n]}, \quad \forall P_{bat,0}[n] > 0 \quad (6.17)$$

where m is the total number of data available. For example, for a value per minute ($\Delta t = 1/60$) over a period of 24 hours, $m = 24/\Delta t = 1440$.

Next State of Charge

The next state of charge, $SoC[n + 1]$, is calculated as follows:

$$SoC[n + 1] = \frac{V_{dc} C}{V_{dc} C} \frac{SoC[n] - \Delta t P_{bat}[n]}{V_{dc} C} \quad (6.18)$$

Imported and exported grid power

The grid power, P_{grid} , is calculated by the following expression:

$$P_{grid}[n] = P_{load}[n] - P_{pv}[n] - P_{bat}[n] \quad (6.19)$$

P_{grid} will automatically have a positive value when it is imported from the grid and will be negative when it is exported to the grid.

Finally, the integrated values of P_{pv} , P_{load} , P_{bat} , and P_{grid} are the corresponding energies expressed in kilowatt-hours through the following equations:

$$E_{pv} = 10^{-3} \times \Delta t \sum_{n=1}^m P_{pv}[n] \quad (6.20)$$

$$E_{load} = 10^{-3} \times \Delta t \sum_{n=1}^m P_{load}[n] \quad (6.21)$$

$$E_{charge} = 10^{-3} \times \Delta t \sum_{n=1}^m P_{bat}[n], \quad \forall P_{bat}[n] < 0 \quad (6.22)$$

$$E_{discharge} = 10^{-3} \times \Delta t \sum_{n=1}^m P_{bat}[n], \quad \forall P_{bat}[n] > 0 \quad (6.23)$$

$$E_{exported} = 10^{-3} \times \Delta t \sum_{n=1}^m P_{grid}[n], \quad \forall P_{grid}[n] < 0 \quad (6.24)$$

$$E_{imported} = 10^{-3} \times \Delta t \sum_{n=1}^m P_{grid}[n], \quad \forall P_{grid}[n] > 0 \quad (6.25)$$

Self-sufficiency and Self-consumption

In the particular case of PV-battery systems, the P_{load} can be supplied from two sources: PV system (directly or indirectly through the battery) and the grid. The percentage of P_{load} supplied from the PV system is the self-sufficiency (ε_{ss}) of the system. Likewise, the P_{pv} can have three destinations: P_{load} , the battery, and the grid. The percentage of P_{pv} directly towards both the battery and P_{load} is the self-consumption (ε_{sc}) of the system. Therefore, in this thesis, the expressions to calculate self-sufficiency and self-consumption in PV-battery systems are as follows:

$$\varepsilon_{ss}(\%) = 100 \times \frac{E_{load} - E_{imported}}{E_{load}} \quad (6.26)$$

$$\varepsilon_{sc}(\%) = 100 \times \frac{E_{pv} - E_{exported}}{E_{pv}} \quad (6.27)$$

Loss-of load

In the case of using strategy 2 ($P_{max} > 0$), the method to quantify the loss-of load (*LoL*) indicates the percentage of E_{load} that will not be supplied either by E_{pv} or $E_{discharged}$ or $E_{imported}$. This occurs when $P_{pv} = 0$, $SoC \leq SoC_{min}$ and principally due to the imported power restriction in which P_{grid} should not be higher than P_{max} .

$$LoL(\%) = 100 \times \frac{E_{LoL}}{E_{load}} \quad (6.28)$$

where,

$$E_{LoL} = 10^{-3} \times \Delta t \sum_{n=1}^m P_{LoL}[n] \quad (6.29)$$

$$P_{LoL}[n] = P_{grid}[n] - \min\{P_{grid}[n], P_{max}\}, \quad \forall P_{grid}[n] > 0 \quad (6.30)$$

Load factor

Load factor (*LF*) is the ratio of the total imported electricity from the grid in a given period (annual in present cases analysed) divided by the total possible electricity that could have been imported in the same period, at the peak kilowatt level established by the customer during the billing period. In general, a low load factor means highly variable load. Load factor is calculated using two simple values: *i*) actual kilowatt-hours used during the billing period ($E_{imported}$), in kWh/year; and, *ii*) the peak demand, in kW, as follows:

$$LF(\%) = 100 \times \frac{E_{imported}}{365 \times 24 \times \max(P_{grid})} \quad (6.31)$$

6.4. Experimental validation

The proposed model has been implemented in MATLAB® and validated with the experimental data obtained from the measuring and control equipment.

As an example of the experimental validation, the results of a typical winter day (January 25, 2017) are shown in Fig. 6.4. In this figure, the actual P_{pv} and P_{load} measured are shown (Fig. 6.4a), based on these values, the SoC was simulated and compared with the actual SoC obtained from the battery inverter (Fig. 6.4b). Likewise, the simulated P_{bat} is compared with the P_{bat} obtained from the experimental measurements (Fig. 6.4c), and finally the simulated P_{grid} is compared with the measured P_{grid} (Fig. 6.4d). As can be seen, the simulated values are in accordance with the measured values. In any case, a detailed quantitative analysis of the errors is presented in Section 6.5.

Figure 6.4: Experimental measures of January 25, 2017. (a) P_{pv} and P_{load} measured; (b) SoC measured vs. SoC simulated; (c) P_{bat} measured vs. P_{bat} simulated; (d) P_{grid} measured vs. P_{grid} simulated. The system has been configured with the following parameters: Strategy 1; $SoC[1] = 0.78$; $SoC_{max} = 1$; $SoC_{low} = 0.45$; $SoC_{min} = 0.40$.

To validate strategy 2, the results obtained on February 15, 2017, with a limiting $P_{max} = 805$ W, are shown in Fig. 6.5. In the same way as the previous figure, the simulated values of SoC , P_{bat} and P_{grid} are in accordance with the measured values.

Figure 6.5: Experimental measures of February 15, 2017. (a) P_{pv} and P_{load} measured; (b) SoC measured vs. SoC simulated; (c) P_{bat} measured vs. P_{bat} simulated; (d) P_{grid} measured vs. P_{grid} simulated. The system has been configured with the following parameters: Strategy 2; $SoC[1] = 0.92$; $SoC_{max} = 1$; $SoC_{low} = 0.45$; $SoC_{min} = 0.40$. $P_{max} = 805$ W.

In addition to the specific days presented in Fig. 6.4 and Fig. 6.5, 44-day experimental measurements (63360 one-minute samples) between January and

June 2017 have been carried out. In Fig. 6.6, the determination coefficients²¹ (R^2) that show the quality of the model to replicate the SoC , P_{grid} and P_{bat} , are shown.

Figure 6.6: Measured data versus simulated data during the 44-day experimental campaign. 63360 one-minute samples for (a) SoC , (b) P_{grid} and (c) P_{bat} .

As can be seen in Fig. 6.6, the determination coefficients are higher than 0.94 in all the variables, which is an indication that the model has a good fit to reproduce the real operating conditions of the grid-connected PV-battery system. In Fig. 6.6a a small outside mainstream data (within the dotted line) is observed, these data correspond to the measurements of few hours in a single day, in which, the battery state of charge measured abruptly changed (when the battery was in discharge, the SoC changed from 60% to 83%), which caused that the following simulated values have a difference about 20% with the measured values.

²¹ R^2 is a statistic that provides information about the fit of a model. In regression, R^2 is a measure of how well the regression line approximates the real data points. An R^2 of 1 indicates that the regression line perfectly fits the data.

6.5. Accuracy of the model

Below, the parameters used to measure the accuracy (and therefore the error) of the proposed model are presented. Each parameter has advantages and disadvantages (see Table 6.1). In this regard, several authors have proposed different statistical parameters to quantify the error (Armstrong and Collopy, 1992; Wallström and Segerstedt, 2010; Prestwich *et al.*, 2014). In this thesis because no individual statistical parameter is fully satisfactory, four statistical formulations have been chosen as follows:

i) Mean Absolute Percent Error (MAPE) is the most common measure of forecast error. MAPE is the average absolute percent error for each time simulated data minus actuals divided by actuals (see Eq. 6.32). With zero or near-zero values, MAPE can give a distorted picture of the error. The error on a near-zero item can be infinitely high, distorting the overall error rate when it is averaged in. For forecasts of items that are near or at zero volume, Symmetric Mean Absolute Percent Error (SMAPE) is a better measure.

$$MAPE(\%) = 100 \times \frac{1}{j} \sum_{t=1}^j \left| \frac{e_t}{z_t} \right| \quad (6.32)$$

where,

$e_t = z_t - \hat{z}_t$ is the residual series, that is, the difference between the values measured experimentally (z_t) and the values predicted by the model ($\hat{z}_t$). j is the total number of analysed values.

ii) SMAPE is an alternative to MAPE when there is zero or near-zero demand for data. SMAPE self-limits to an error rate of 200%. However, a percentage error between 0% and 100% is much easier to compare with other statistical parameters. That is the reason why the Eq. 6.33 is used in this thesis. Thus, SMAPE can be defined as the simulated values minus actuals divided by the sum of simulated values and actuals.

$$SMAPE(\%) = 100 \times \frac{1}{j} \sum_{t=1}^j \left| \frac{e_t}{z_t + \hat{z}_t} \right| \quad (6.33)$$

iii) Root Mean Square Error (RMSE) is the standard deviation of the residuals (prediction errors), so it is expressed in the same measurement unit. Residuals are a measure of how far from the simulated data points are. In other words, it

describes how concentrated the data is around the line of best fit. RMSE is commonly used in forecasting and regression analysis to verify experimental results.

$$RMSE = \sqrt{\frac{1}{j} \sum_{t=1}^j e_t^2} \quad (6.34)$$

iv) Standard deviation is a measure of the dispersion of a set of data from its mean and is also expressed in the same measurements unit. It is calculated as the square root of variance by determining the variation between each data point relative to the mean. If the data points are further from the mean, there is a higher deviation from the data set.

$$\sigma_e = \sqrt{\frac{1}{j} \sum_{t=1}^j (e_t - \frac{1}{j} \sum_{t=1}^j e_t)^2} \quad (6.35)$$

Table 6.1: Comparison of four accuracy measure methods.

Accuracy measure	Advantages	Disadvantages
MAPE	It keeps the positive and negative errors from cancelling out each other. This measure compares accuracy between differently scaled time-series data.	The error on a near-zero item can be infinitely high, distorting the overall error rate when it is averaged in.
SMAPE	For forecasts of items that are near or at zero volume, SMAPE is a better measure compared with MAPE.	SMAPE is not symmetric since over and under forecasts are not treated equally.
RMSE	It is more useful when large errors are particularly undesirable.	RMSE has different results when compared to different sized test samples.
Standard deviation	Shows how much data is clustered around a mean value, and it gives a more accurate idea of how the data is distributed.	It is affected very much by the extreme values of a series in as much as the squares of deviations of high values proportionately bigger than the squares of the lower values.

The results of errors calculated for the variables SoC , P_{grid} , and P_{bat} , calculated during 44-day experimental measurements, are shown in [Table 6.2](#). In addition, the results of errors of a typical day (January 25, 2017, from [Fig. 6.4](#)) are also shown in [Table 6.3](#).

Table 6.2: Error calculation (on a per-minute basis) of 44-day experimental measurements.

Variable	MAPE	SMAPE	RMSE	σ_e
SoC	1.29 %	0.67 %	2.72 %	2.86 %
P_{grid}	70.29 %	40.56 %	75.97 W	77.07 W
P_{bat}	179.53 %	40.08 %	57.80 W	77.03 W

Table 6.3: Error calculation (on a per-minute basis) of a typical day (from Fig. 6.4).

Variable	MAPE	SMAPE	RMSE	σ_e
SoC	1.92 %	0.95%	1.74 %	2.09 %
P_{grid}	54.13 %	33.37 %	79.36 W	88.81 W
P_{bat}	34.94 %	26.94 %	116.07 W	128.68 W

On the one hand, the simulated SoC has errors between 0.5 and 3%, which indicates that the model can predict with $> 97\%$ accuracy the behaviour of the SoC ; this is very useful when calculating the cycling, aging, and battery lifetime. On the other hand, although the Fig. 6.6 shows the determination coefficients high > 0.9 in all variables, the errors for P_{grid} and P_{bat} are unreasonably high. It is because these parameters have many zeros or near-zero values. For this reason, four different power-ranges have been selected in order to expose better how the errors are, as shown in Table 6.4.

Table 6.4: Error calculation for different power ranges.

Variable	Power in absolute values [W]	MAPE [%]	SMAPE [%]	RMSE [W]	σ_e [W]	errors (%)
P_{grid}	[0,100]	148.20	84.14	39.02	36.41	>60
P_{bat}		381.20	78.03	34.74	55.30	
P_{grid}	(100,500]	22.52	16.65	69.45	65.57	40
P_{bat}		16.78	11.10	54.41	74.02	
P_{grid}	(500,1000]	6.00	3.15	72.61	72.77	20
P_{bat}		6.52	3.39	71.39	82.96	
P_{grid}	> 1000	3.93	1.99	125.33	138.43	10
P_{bat}		6.63	3.43	146.83	196.63	

As Table 6.4 shows, when P_{grid} and P_{bat} have high values (>500 W), the percentage error is lower, indicating that the model has MAPE and SMAPE errors < 7 %. For low power values (< 100 W), the high percentage errors are mainly affected by the low-magnitude values and the measurements uncertainty. This can be verified on the values of RMSE and standard deviation, which show that the

residuals are < 60 W, which is an acceptable value considering that only the load of battery inverter in silent mode is about 32 W, and that the P_{grid} and P_{bat} absolute ranges are between 2000 and 6000 W.

In order to explain the aforementioned, Fig. 6.7 shows how the errors—in a specific period of time— vary depending on the power magnitude.

Figure 6.7: Specific errors for different power values. Comparison between experimental and simulated P_{grid} of February 15, 2017.

In the same way, MAPE, SMAPE and e_t errors were calculated for all the data analysed (63360 samples), as shown in Fig. 6.8. Here, error distribution is plotted depending on the magnitude of the power.

Figure 6.8: Error distribution of MAPE, SMAPE and residuals for all the data analysed of P_{grid} and P_{bat} .

Fig. 6.8 shows the errors calculated for all the data measured versus simulated data of P_{grid} and P_{bat} . Not unexpectedly, for high absolute values of power, the MAPE and SMAPE errors are low (below 10%). On the other hand, the near-zero values present higher values of MAPE and SMAPE errors, even when the residuals are distributed in an equitable manner.

Another way to analyse the accuracy of the model is with the accumulated electricity in four time-intervals selected: *i*) 15-minute (programmed integration time in the most of smart meters), *ii*) 1-hour (balancing period in certain self-consumption schemes), *iii*) 1-day (measurements were recorded on whole days); and, *iv*) 44-day (total number of days analysed). The errors are calculated for the electricity imported from the grid ($E_{imported}$), the electricity exported to the grid ($E_{exported}$), the electricity discharged from the battery ($E_{discharged}$), and the electricity charged into the battery ($E_{charged}$), as shown in Table 6.5.

Table 6.5: Error calculation for the accumulated electricity.

Time interval		MAPE [%]	SMAPE [%]	RMSE [kWh]	$ e_t $ [kWh]
15-minute	$E_{imported}$	38.14	24.87	7.1×10^{-3}	5.2×10^{-3}
	$E_{exported}$	55.21	29.98	19×10^{-3}	20×10^{-3}
	$E_{discharged}$	40.45	19.77	4.7×10^{-3}	7.1×10^{-3}
	$E_{charged}$	66.52	62.47	14×10^{-3}	19×10^{-3}
1-hour	$E_{imported}$	37.57	25.32	25×10^{-3}	18×10^{-3}
	$E_{exported}$	69.67	40.77	59×10^{-3}	63×10^{-3}
	$E_{discharged}$	41.39	22.77	16×10^{-3}	24×10^{-3}
	$E_{charged}$	66.59	62.61	48×10^{-3}	65×10^{-3}
1-day	$E_{imported}$	30.43	20.52	0.402	0.227
	$E_{exported}$	7.13	5.84	0.320	0.306
	$E_{discharged}$	20.13	10.92	0.222	0.362
	$E_{charged}$	21.60	15.49	0.439	0.704
44-day	$E_{imported}$	9.97	5.24	14.61	-
	$E_{exported}$	1.09	0.54	6.38	-
	$E_{discharged}$	4.50	2.20	6.04	-
	$E_{charged}$	9.16	4.80	13.90	-

Table 6.5 shows that in the short periods of time (15-minutes and 1-hour) the MAPE and SMAPE errors are between 20% and 70%, although in terms of accumulated electricity, the RMSE and e_t errors are lower than 0.06 kWh. As the integration period increases to 44 days, the MAPE and SMAPE errors fall below 10% and with absolute differences below 15 kWh, which is equivalent to an average difference of 14.20 W in each measurement (of total 63360), which is a negligible value.

Another important aspect to be considered in a realistic situation is the quality of data. The input data can be obtained from simulations from software tools (typically hourly values) or measured data. Time resolution is a very important factor in the accuracy of the model (as indicated in Wright and Firth, 2007; Cao and Sirén, 2014), where the results will be more realistic with sub-hourly data,

especially to capture the high-peak powers. The latter is precisely required by self-consumption schemes, demand-side management solutions; and by smart grids, which are based on sub-hourly measures (sensors, communication protocols, smart meters, etc.). Once P_{pv} and P_{load} are entered, the model works to obtain P_{bat} , P_{grid} , and SoC in each time-step, depending on the control strategy used.

With all these considerations, the model presented in this Chapter is considered valid, and it was used to develop a software simulation tool presented in the following section. With this tool, three case studies were performed, which are presented in [Chapter 8](#).

6.6. Technical and economical grid-connected PV-battery systems simulator

In this Thesis, a simulation tool called *PVbat* is presented, which implements the control strategies proposed in this Chapter along with an economic assessment of the PV hybrid systems, which will be presented in [Chapter 7](#).

The first motivation to design and develop this software was born as a result of implementing the model and control strategies exposed in this thesis, as well as the formulations of the economic analysis. All this to analyse in an agile way different PV-battery sizes and settings in several case studies. Throughout the doctoral studies, I had used other software (both payment and free access) for the analysis and design of renewable energy systems, which for a first approximation worked well, however, for a more exhaustive analysis (sub-hourly data, different control strategies for storage, battery lifetime, specific PV self-consumption schemes and multi-variable analysis) were no longer reliable. In addition, the simulations performed with these tools were not consistent with the measures of the experimental stage. Finally, the support to new research related to the PV-battery systems field was the main motivation to develop this simulator.

PVbat is a software tool (developed in MATLAB®) designed to simulate the power flows between the PV system, the loads inside the building, the battery (charging and discharging), and the grid (imported and exported). Besides, *PVbat* uses ageing battery modelling in order to calculate the battery lifetime. After the technical analysis is performed, an economic analysis is made taking into account three electrical market scenarios²², namely Spain, Ecuador and Portugal.

The development of this tool is for me a source of personal pride. In addition to the time devoted to the programming, it has supported some research: two end-of-

²² The proposed markets reflect those included in the cases studies of this thesis.

career projects, two master's degree projects and a doctoral thesis. I hope that more and better features can be added to future research.

Fig. 6.9 shows the variables of the simulator, both input and output. Technical and economical parameters are distinguished through different block diagrams, as shown below:

Figure 6.9: Scheme of input and output variables in the *PVbat* simulator.

PVbat uses sequential data (annual series) from P_{load} and P_{pv} as main data entry. The simulator also uses another input parameters of the PV system and the battery system in order to calculate (through the battery control strategies) the destination of P_{pv} (to P_{load} , to P_{bat} in charge, and/or P_{grid} exported) and the source from where P_{load} is supplied (from the P_{pv} , P_{bat} in discharge, and/or P_{grid} imported). Data are handled from an excel file in specific time intervals from 1 minute to 1 hour for a full year. *PVbat* also calculates the battery state of charge, the percentages of self-consumption and self-sufficiency of the PV-battery system as well as the battery lifetime.

The economic analysis takes into account the costs associated with PV-battery system equipment (PV system cost, BESS cost, O&M, and lifespan of the PV system) as well as the electricity prices and the financial variables (discount rate and inflation). As a result, the annual billing saving, the levelized cost of electricity (LCOE) and the payback-time parameters are obtained.

The simulator also allows analysing other features, which are explained through the screenshots of the tool, as shown in Figures 6.10 and 6.11. In the same manner, Table 6.6 shows a brief description of each function.

Figure 6.10: Main screen of the *PVbat* simulator.

Figure 6.11: Economic analysis screen (Spanish scenario).

Table 6.6: Meaning of the principal features of the *PVbat* simulator.

Feature	Name	Meaning
1	OPEN	Opens the selected file with input data.
2	SIMULATE	Runs the program after all the information is entered.
3	PLOT	Plots the results on a MATLAB environment.
4	EXPORT	Exports results in an Excel file.
5	OPTIMISE	Optimises battery size according to the control strategy selected.
6	PK-SHAVING	Calculates the minimum power to be contracted with the grid when the peak-shaving strategy is used.
7	LIFE BATTERY	Calculates battery lifetime.
8	ECONOMIC	Opens a new window to calculate economic parameters.
9	SETTINGS	Allows choosing battery control strategy and time of operation.
10	ANALYSE	Performs an overview report of economic analysis after all information is entered.
11	PLOT	Performs a sensitivity analysis, varying prices of both PV and battery systems.
12	SENSITIVITY	Performs a sensitivity analysis, varying sizes of both PV and battery systems.

For detailed operation, the explanation of each function is described below:

1) OPEN: The data entry process is carried out via an Excel file, where the annual values of P_{pv} , P_{load} and T_{indoor} are stored. The accepted time intervals are: 1-minute, 2-minutes, 5-minutes, 10-minutes, 15-minutes, 20-minutes, 30-minutes or 1-hour. The simulator can be configured to supply total electricity consumption of a building or a specific load (for example HVAC electrical consumption). An example of the data entry is shown in Fig. 6.12.

	A	B	C	D
1	Ppv [W]	Specific load [W]	Other loads [W]	
2	0,00	640,46	60,00	
3	0,00	640,42	60,00	
4	0,00	642,98	100,00	
5	0,00	652,24	120,00	
6	0,00	665,81	120,00	
7	0,00	683,64	120,00	
8	0,00	722,47	60,00	
9	0,00	740,94	60,00	
10	15,19	719,77	300,00	
11	52,78	701,23	360,00	
12	101,72	673,20	400,00	
13	153,81	622,41	420,00	
14	287,09	552,49	500,00	
15	383,86	491,62	450,00	
16	334,21	450,29	600,00	
17	291,74	418,48	1100,00	

Figure 6.12: Example of Excel file data.

2) SIMULATE: After correctly input the information (PV system and BESS parameters), *PVbat* simulates and presents the results on the same main screen, as can be seen in Fig. 6.10. Here, an annual overview report is presented, showing the self-consumption rate, the self-sufficiency rate, the destination of the electricity PV (loads, battery and/or grid), as well as the origin of the electricity that supplies the demand (PV, battery and/or grid).

3) PLOT: In this function, three figures are plotted. Fig. 6.13: annual power interaction between P_{pv} , P_{load} , P_{grid} and P_{bat} , as well as the *SoC*. Fig. 6.14: A pie chart to represent percentages of the results shown in point (2). Fig. 6.15: Three load duration curves are plotted (grid demand without PV system, grid demand with PV system and grid demand with PV-battery system). A load duration curve illustrates the variation of the load in a downward form such that the greatest load is plotted in the left and the smallest one in the right. On the time axis, the time duration for which the load continues during the year is given.

Figure 6.13: Example of results of an annual power interaction between P_{pv} , P_{load} , P_{grid} and P_{bat} (upper). Corresponding annual SoC cycling (bottom).

Figure 6.14: Pie charts of the electricity percentages. PV generation (left), and electricity demand (right).

Figure 6.15: Example of load duration curves results.

4) EXPORT: After simulation, results are exported to an Excel file. The data series has the same time interval as the data entered. In this file, the parameters P_{grid} (imported/exported), P_{bat} (discharged/charged) and the SoC are exported.

5) OPTIMIZE: This functionality calculates through iterations, what is the minimum battery capacity in order to achieve one of two objectives (specific self-sufficiency rate or specific peak-shaving limit power). As shown in Fig. 6.16:

Figure 6.16: Screenshot of the ‘optimize’ feature.

6) PK-SHAVING: This feature allows to calculate and plot the minimum power that can be contracted by a prosumer with the utility grid, as long as the peak-shaving strategy is used. Depending on the sizes of both the PV and battery systems (between 25% and 200% of the initial size, as shown in Fig. 6.17) it is possible to determine which combination is the most suitable so that the electricity demand is always supplied.

Figure 6.17: Example of minimum contracted power varying PV and battery sizes.

7) LIFE BATTERY: This functionality uses the data of P_{bat} , battery cycling and T_{indoor} in order to calculate the battery lifetime. Fig. 6.18 shows the graph of the SoC along with the battery ageing process until the remaining capacity reaches 80%, value in which the battery should be changed.

Figure 6.18: Battery lifetime: SoC through the years (red), and battery remaining capacity (blue).

8) ECONOMIC: It opens a dialogue window that allows one to choose one of three electric markets available (Spanish, Ecuadorian or Portuguese). The Spanish scenario was shown as an example in [Fig. 6.11](#).

9) SETTINGS: It opens a new window ([Fig. 6.19](#)) to choose one of two battery control strategies (optimizing self-consumption or peak-shaving) and the battery operating schedule. It is also possible to combine both strategies, choosing specific days in which one strategy or another can work.

10) ANALYSE: An economic analysis is run, after correctly input the information of installation costs, tariff structure, self-consumption scheme and financial variables. The results show the annual electricity billing in three scenarios: if a PV-battery system is installed, if only PV system is installed; and, if no PV system is installed. It also calculates the LCOE derived from the PV system and the battery system, as well as the total investment and the payback-time. All these parameters will be analysed in detail in the next chapter.

Figure 6.19: Screenshot of control strategies settings.

11) PLOT and 12) SENSITIVITY: The last two functionalities of the tool, execute two different sensitivity analyses. The first one analyses the LCOE and the payback-time based on the variation of costs for the same PV-battery system. The second one calculates the self-sufficiency, the self-consumption and the billing saving, depending on the variation of the sizes, for both the installed PV power and the battery capacity. The figures 6.20 and 6.21 show an example of the results after executing the sensitivity analyses.

Figure 6.20: Sensitivity analyses of LCOE and payback-time varying both the PV and battery costs.

Figure 6.21: Sensitivity analyses of self-sufficiency, self-consumption and billing saving varying both the PV and battery sizes.

For more information on installation of PVbat and data input, please review [Appendix 3](#).

Chapter 7

Economic viability of PV-battery systems

7.1. Introduction

When making any investment in a grid-connected PV-battery system, there are many parameters that must be considered in addition to the solar potential to determine if the investment is worthwhile from a financial perspective. To assess the economic viability of case studies presented in this thesis, three important parameters are considered in this Chapter: Levelized Cost of Electricity (LCOE), Levelized Cost of Storage (LCOS) and payback-time.

LCOE is one of the most well-known cost metrics to analyse the economic potential of a PV system (Branker *et al.*, 2011; Breyer and Gerlach, 2013; CREARA, 2015; Lai and McCulloch, 2017). Generally speaking, the LCOE is calculated by accounting for all the PV systems' expected lifespan costs, including investment, operation & maintenance (O&M) and balance of system (BoS) (mounting structure, inverters, cables, etc.), which are then divided by the whole system's lifespan expected PV generation. The LCOE can also be regarded as the minimum cost at which electricity must be sold in order to achieve break-even over the lifespan of the project (Lai and McCulloch, 2017). All cost and benefit estimates are adjusted for inflation and discount rates to account for the time-value of money and investment risk. LCOE is important for assessing the proximity to the so-called 'grid parity' from the perspective of the prosumer, who is interested in comparing

the projected grid electricity cost with the projected cost of the PV electricity generated and levelized during the lifespan of the system. In this thesis, an adapted formulation of the LCOE metric, presented by [CREARA \(2015\)](#) and [Branker, Pathak and Pearce \(2011\)](#), is used to make it applicable to PV systems.

When a battery energy storage system (BESS) is added to a PV system, the LCOE of the new PV-battery system must also take into account the costs related to the BESS. The levelized cost of electricity derived specifically from the storage system — so-called ‘Levelized Cost of Storage’ — will depend on the amount of electricity that the BESS can supply during the lifespan of the PV-battery system. However, the amount of energy discharged from the battery is also dependent on the way in which the batteries are charged (they can be charged with the electricity grid, or only with PV electricity, as considered in the case studies mentioned in this thesis).

There are several studies on storage economics presenting different cost metrics definition about LCOS. For instance, Sandia National Laboratories ([SANDIA, 2013](#)) lists four cost metrics, which can be used to analyse the economic potential of different storage technologies: the installation cost, the levelized cost of capacity, the present value of life-cycle costs, and LCOS. In a similar way, [Jülch \(2016\)](#) presents a methodology for calculating the LCOS, which is used for comparing different storage technologies. [Zakeri and Syri \(2015\)](#) distinguish between an LCOE and an LCOS, where the latter excludes the cost of charging electricity; these metrics are then used to compare the life cycle cost of different storage technologies. Another important report is the one presented by [Lazard \(2016\)](#), which defines the LCOS taking into account different parameters: capital cost of technology, operating costs, and charging costs. This report principally describes capital costs in terms of discharged energy to calculate the duration of the relevant energy storage systems, as well as its capacity.

Although LCOS is obtained in a similar way as the LCOE, a generally accepted definition of LCOS used in PV systems does not yet exist ([Belderbos *et al.*, 2016](#)). For instance, [Pawel \(2014\)](#) suggested a method to calculate the LCOS in a similar manner as the traditional LCOE but has extended the formulation to analyse different renewable energy systems (RES) with storage. The World Energy Council ([WEC, 2016](#)) also proposed a formulation for the LCOS, where the cost for input energy, or the charging cost, is left out of the calculation to avoid obscuring the results with too many assumptions. However, during further analysis in the report, storage is coupled with RES, thus implicitly taking the levelized cost of RES as the cost of input energy. [Lai and McCulloch \(2017\)](#) use the LCOS formulation as provided by the WEC to analyse the cost component of storage in a PV-battery system. They come to a metric termed the ‘levelized cost of delivery’, which takes into account the cost for the fraction of PV electricity used to provide energy to

the BESS. All previous definitions are a starting point to calculate the LCOS; however, in this Chapter, a new formulation is proposed to calculate the LCOS as part of a PV-battery system.

Both, the LCOE and the LCOS, must take into consideration the degradation factor of PV modules. The electricity generated in a given year is multiplied by the degradation (d) factor, which decreases the energy with time. [Jordan and Kurtz, \(2013\)](#) conducted a review of degradation in different PV technologies, varying between 0.1 and 1%/year. It is important to note that this parameter must also be provided by the manufacturer, however, in this thesis the value of 0.5%/year is used, as a typical value of monocrystalline silicon PV modules.

Because of the importance of the discount rate (r) in calculating LCOE and LCOS, the discount rate can be expressed in nominal or real terms, resulting in nominal LCOE or real LCOE, respectively. Nominal LCOE is a constant value in nominal currency unadjusted for the relative value of money. Real LCOE is a constant value expressed in the local currency corrected for inflation, that is, constant currency of one year in particular. For cases study analysed in this thesis, the LCOE will be used to compare the cost of consuming PV-generated electricity with that of buying it from the grid from the viewpoint of a residential electricity consumer, therefore both alternatives (PV and grid electricity costs) should be expressed in the same terms (nominal or real currency per kWh).

Other important economic parameter and challenge of PV systems profitability is its cost-effectiveness, and therefore, its ability to generate profits ([Bernal-Agustín and Dufo-López, 2006](#); [Hosenuzzaman et al., 2015](#)). In this sense, ‘Payback-time’ is the time in years when the investment begins to generate economic benefits. It is a parameter derived from the Net Present Value (NPV) that is used to evaluate the ability of an investment to make a profit. Although the payback-time calculation is well known in many investment projects, many papers present adapted formulas for the economic analysis of PV systems ([Talavera et al., 2010](#); [Spertino et al., 2013](#); [Eicker et al., 2014](#); [Hoppmann et al., 2014](#); [Ciez and Whitacre, 2016](#); [Linssen et al., 2017](#)).

In this Chapter, the formulations to calculate the LCOE, LCOS and the payback-time of the PV-battery systems are presented, while considering the annual income from the economic savings associated to the PV hybrid system, including billing savings and selling of PV surplus (if applicable).

7.2. Levelized cost of electricity of PV systems without batteries

The general equation for calculating LCOE of PV systems is given in [Eq. 7.1](#), which takes into account all investment costs, $I_{pv} + C_{pv}$ (Initial; and, O&M and replacement) divided by the total PV electricity generated over the system lifespan (E_{pv}):

$$LCOE_{pv} = \frac{I_{pv} + C_{pv}}{E_{pv}} \quad (7.1)$$

where C_{pv} and E_{pv} , represent the sum of the values of C'_{pv} (annual O&M and replacement cost) and E'_{pv} (annual PV electricity generated), as follows:

$$C_{pv} = \sum_{t=0}^T \frac{C'_{pv_t}}{(1+r)^t} \quad (7.2)$$

$$E_{pv} = \sum_{t=0}^T \frac{E'_{pv}(1-d)^t}{(1+r)^t} \quad (7.3)$$

By replacing in [Eq. 7.1](#) by the [Eq. 7.2](#) and [7.3](#), the more formal equation for calculating the LCOE for a PV system is obtained, as shown in [Eq. 7.4](#):

$$LCOE_{pv} = \frac{I_{pv} + \sum_{t=0}^T \frac{C'_{pv_t}}{(1+r)^t}}{\sum_{t=0}^T \frac{E'_{pv}(1-d)^t}{(1+r)^t}} \quad (7.4)$$

7.3. Levelized cost of storage of BESS

In order to calculate the LCOS in a manner analogous to the LCOE, all costs associated with the BESS must be taken into account, which are then divided by the amount of electricity the BESS can supply. Both the costs and the electricity stored are considered throughout the PV-battery system's lifespan and not only for the battery lifetime. This implies that one must also consider the purchase of new batteries when they finish their life cycle if the PV-battery system to which the battery is incorporated requires so.

On the basis of the above explanation, the general equation for calculating the LCOS of a battery storage system, is given in Eq. 7.5, which represents all investment costs associated with the storage, $I_s + C_s$ (Initial; and, O&M and replacement) divided by the total electricity discharged from the battery over the PV-battery system lifespan ($E_{discharge}$):

$$LCOS = \frac{I_s + C_s}{E_{discharge}} \quad (7.5)$$

where C_s and $E_{discharge}$, represent the sum of the annual values of C'_s and $E'_{discharge}$ respectively:

$$C_s = \sum_{t=0}^T \frac{C'_{st}}{(1+r)^t} \quad (7.6)$$

$$E_d = \sum_{t=0}^T \frac{E'_{discharge_t}}{(1+r)^t} \quad (7.7)$$

By replacing in Eq. 7.5 by the Eq. 7.6 and 7.7, results in the more formal equation for calculating the LCOS for a BESS, as given in Eq. 7.8 below:

$$LCOS = \frac{I_s + \sum_{t=0}^T \frac{C'_{st}}{(1+r)^t}}{\sum_{t=0}^T \frac{E'_{dt}}{(1+r)^t}} \quad (7.8)$$

7.4. Levelized cost of electricity of PV-battery systems

The formulation for the LCOE of a PV-battery system is the same as for the LCOE of a PV system after adding the costs associated with the storage system. It should be noted that the electricity produced by the PV-battery system is the same as that produced by the PV system, that is, E_{pv} . This is because, in this thesis, the battery is charged only with not self-consumed PV surplus energy, and it is never charged from the grid²³.

²³ Although, in general, the batteries could be charged from the grid, the power exchanges between the grid and battery are not allowed in this thesis. The reason is that the battery charge regime would strongly depend on local electricity prices and might not be coherent with the objective of maximum efficient supply of HVAC load by PV electricity.

$$LCOE = \frac{I + C}{E_{pv}} \quad (7.9)$$

It should be taken into account that the costs of the whole investment are the sum of the individual systems cost, thus: $I = I_{pv} + I_s$, and $C = C_{pv} + C_s$

$$LCOE = \frac{I_{pv} + I_s + C_{pv} + C_s}{E_{pv}} \quad (7.10)$$

Accordingly, the LCOE for a PV-battery system is therefore given in [Eq. 7.11](#) below:

$$LCOE = \frac{I_{pv} + I_s + \sum_{t=0}^T \frac{C'_{pv,t} + C'_{s,t}}{(1+r)^t}}{\sum_{t=0}^T \frac{E'_{pv}(1-d)^t}{(1+r)^t}} \quad (7.11)$$

The general form of the LCOE given in [Eq. 7.11](#) is the most important in this Chapter since it is used to calculate the LCOE in general form (with or without storage). Also, from here, other equations that allow quantifying the cost of the kWh discharged from the battery can be deduced, as it is shown below.

From [Eq. 7.10](#), we can say that:

$$LCOE = \frac{I_{pv} + C_{pv}}{E_{pv}} + \frac{I_s + C_s}{E_{pv}} \quad (7.12)$$

And from [Eq. 7.1](#), we obtain the following:

$$LCOE = LCOE_{pv} + \frac{I_s + C_s}{E_{pv}} \quad (7.13)$$

By replacing [Eq. 7.5](#) in [Eq. 7.13](#), it can be concluded that:

$$LCOE = LCOE_{pv} + \frac{E_{discharge}}{E_{pv}} LCOS \quad (7.14)$$

[Eq. 7.14](#) indicates that only when $E_{discharge} = 0$, $LCOE = LCOE_{pv}$. The latter is a conclusion to analyse PV-battery systems. In fact, that means if a battery is never discharged, then it cannot be considered part of the PV-battery system because only the PV system would be working. Furthermore, [Eq. 7.14](#) shows that, although $LCOE$ takes into account all the costs and electricity produced by the PV-battery

system, the relationship that exists between $LCOE$, $LCOE_{pv}$ y $LCOS$ is not an algebraic sum, i.e: $LCOE \neq LCOE_{pv} + LCOS$. This is because the battery is charged only by PV system, so the E_d is part of the E_{pv} , being $E_{discharge}$ part of E_{pv} .

Therefore, in this Thesis, the ‘Levelized Cost of Discharged electricity’ (LCOD) is calculated in order to quantify the amount of $LCOE$ which is derived only from the BESS.

$$LCOD = \frac{E_{discharge}}{E_{pv}} LCOS \quad (7.15)$$

If E_d is unknown, $LCOD$ can be calculated from $LCOE$ and $LCOE_{pv}$ as follows:

$$LCOD = LCOE - LCOE_{pv} \quad (7.16)$$

Calculating the LCOD as part of the LCOE is useful when comparing different battery capacities that could be added to the PV system, as shown in an example of sensitivity analysis (see Fig. 7.1), where the LCOE increases from a certain value ($LCOE$ of the PV system without battery) until highest values corresponding to the $LCOE$ of the PV-battery system. This kind of sensitivity analysis is shown in the case studies presented in this Thesis (see Chapter 8).

Figure 7.1: LCOE sensitivity analysis of a PV-battery system.

7.5. Payback-time

The payback period or payback-time of an investment is the length of time required to recover the cost of an investment. The payback-time of a PV hybrid system is important for determining if the investment is profitable from an economic point of view. The methodology used in this Chapter to calculate payback-time takes into account the time value of money (using the discount rate) derived from the NPV parameter.

In order to calculate the NPV of PV investments (Spertino *et al.*, 2013), Eq. 7.17 is used as follows:

$$NPV = -I + \sum_{t=0}^T \frac{R_t - C_t}{(1 + r)^t} \quad (7.17)$$

where R represents the annual revenue at a year t

$$R_t = (S_{B_t} + \rho \cdot E_{exported_t}) \cdot (1 + r_e)^t \quad (7.18)$$

R depends on four main factors:

i) Billing savings (S_B). The annual billing saving is the difference between the annual electricity bill of the consumer (without a PV-battery system) and the new annual electricity bill of the prosumer (with a PV-battery system).

$$S_B = B - B_{pv} \quad (7.19)$$

ii) Depending on regulations in each country, the PV electricity that is not locally self-consumed nor used to charge the batteries can be exported to the electricity grid, and therefore, it can receive some kind of compensation (ρ).

iii) It is necessary to take into account that the electricity prices for consumers will change over time at a rate (r_e). For instance, according to EUROSTAT, (2017), for the EU countries from 2007 to 2017, the electricity prices have been increased an average of 5% per year (6.5% in Spain). It should be noted that for each location and each case of study a specific r_e should be considered.

iv) The annual PV electricity exported into the grid ($E_{exported}$).

Therefore, from Eq. 7.18 two extreme cases arise: *a*) if there is no compensation for the exported electricity ($\rho = 0$), then $R = S_B \cdot (1 + r_e)^t$; and, *b*) if PV electricity is not locally self-consumed but is exported into the grid instead, then $S_B = 0$ and $R = \rho \cdot E_{exp} \cdot (1 + r_e)^t$, where $E_{exp} = E_{pv}$.

Finally, in order to determine the year when the investment will begin to generate economic profits (τ), Eq. 7.17 is modified so that it can be used in iterations of year t until $NPV > 0$, as follows:

$$NPV(\tau) = -I + \sum_{t=0}^{\tau} \frac{R_t - C_t}{(1 + r)^t} \quad \forall \quad 0 \leq \tau \leq T \quad (7.20)$$

After iterations, the first value of τ for which $NPV(\tau) > 0$, is the payback-time, (*payback* = τ). If $NPV(\tau)$ never reaches a positive value, then the PV-battery system is not economically profitable, at least given the hypothesis considered (r, r_e, ρ). The aforementioned is shown with an example in Fig. 7.2, in which we can see that the payback-time varies depending on the annual increase in electricity price for prosumers.

Figure 7.2: Example of payback-time for a specific PV system, assuming three r_e .

In the example of Fig. 7.2, the evolution of the NPV according to three scenarios of r_e (1%, 3%, and 5%) is shown. As expected, from the PV prosumer's point of view, the higher the price of retail electricity increases, the shorter the payback-time will be. This is because the payback-time takes into account the billing savings, as indicated in Eq. 7.19.

7.6. PV grid parity

The ongoing cost reduction of PV-generated electricity, in addition to the constant increase in electricity prices (IEA PVPS, 2017), has been pushing the arrival of PV ‘grid parity’, which is the moment when the cost of generating own PV electricity for a prosumer is equal to the price for the electricity purchased from the grid. Once grid parity is reached, it would make sense — from an economic point of view — to self-consume the PV-generated electricity instead of purchasing electricity from the grid.

When analysing cost-competitiveness of PV systems against grid electricity, it should be noted that what is really being compared is the cost of PV electricity generated during the entire lifespan of a PV system against today’s retail price for the grid electricity. This reality has important implications because, while future grid electricity prices are likely to change, LCOE is fixed from the moment in which the PV system is bought. Consequently, to properly assess PV competitiveness against the grid, LCOE should ideally be compared against today’s electricity price, but the estimated future increase in retail electricity rates over the entire PV system lifespan should also be accounted for (CREARA, 2015).

Based on the aforementioned, Fig. 7.3 highlights the difference between the LCOE of a specific PV system (Fig. 7.3a) —which is calculated for the case studies presented in this thesis— and the LCOE of the PV technology (Fig. 7.3b), as is shown in most market technology reports.

Figure 7.3: (a) Example of the LCOE of a specific PV system, and (b) example of the LCOE evolution of the PV technology.

An interesting conclusion from Fig. 7.3 is that the LCOE has different meanings, depending on whether it is calculated for a specific installation, or is calculated for the PV technology. In the first case (Fig. 7.3a), it is a constant value throughout the lifespan of the PV installation because it is calculated with certain costs of the specific PV system. In the second case, the value of the LCOE varies each year because the costs of the installation of that year also vary (Fig. 7.3b).

One such report is a Deutsche Bank study (Shah and Booream-Phelps, 2015), which compared the retail price of electricity to that of PV system's, concluding that, in 30 markets, grid parity had already been reached in the residential sector (see Fig. 7.4).

Figure 7.4: Countries with PV grid parity in the residential sector. Source: Deutsche Bank Estimates (Shah and Booream-Phelps, 2015).

Other energy consultancy reports, such as ‘The PV Grid Parity Monitor’ series, analyse PV competitiveness with retail electricity prices for residential (CREARA, 2015) and commercial (CREARA, 2016) consumers, and assess local regulations for self-consumption in twelve countries. These reports concluded that nine countries had already achieved the PV grid parity in the residential sector and five in the commercial sector by 2015 and 2016 respectively, as shown in Fig. 7.5 and Fig. 7.6.

Figure 7.5: Comparison of grid electricity prices for the residential sector and PV LCOE. Source: Compiled by the author based on data of CREARA (2015).

Figure 7.6: Comparison of grid electricity prices for the commercial sector and PV LCOE. Source: Compiled by the author based on data of CREARA (2016).

As can be noted from Figures 7.4, 7.5 and 7.6, the LCOE is used in a high number of countries in order to compare the costs of PV electricity with the retail electricity prices. However, the concept of LCOE entails limitations. The main drawback lies in the need for assumptions about discount rate. These assumptions are difficult to make, especially for developing countries, and can thus limit LCOE's validity in regions where discount rates and costs of the PV hybrid systems are not well known. The same problem applies to payback-time, where in addition to discount rate, the annual increase of retail electricity prices must be assumed.

Consequently, due to the high sensitivity of the input assumptions, the sensitivity analyses developed in the PVBat software simulation tool (presented in [Chapter 6, Section 6.6](#)) allow one to have a broader view of the variability of the LCOE and payback-time depending on both the costs of the system and the discount rate, as will be presented in the case studies of [Chapter 8](#). In conclusion, LCOE, and payback-time should be evaluated together with a wide range of possible input values in order to have a better perspective of the PV hybrid systems investment.

Part IV

Results and conclusions

Chapter 8

Case studies

In the previous chapters, the state-of-the-art developments in the research about PV systems, battery energy storage systems, heating ventilation and air conditioning systems, have been presented. In the same way, an extensive experimental stage was carried out, from which a model and a software tool to simulate PV-battery systems have been developed. This tool also incorporates the formulations and concepts of the PV-battery systems economic viability. With all this background, this Chapter collects the particular case studies analysed in this Thesis, which reflect the use of PV hybrid systems for supplying HVAC loads in different environments (residential and commercial buildings) and different countries.

[Section 8.1](#) presents the experimental study on PV hybrid systems to supply the HVAC loads in a residential building located in Madrid. This study endeavours to give answers to the following questions:

- What is the HVAC electricity consumption of a residential building -under southern European climate conditions- to always maintain indoor comfort?
- Is it possible to supply the HVAC electricity consumption with a grid-connected PV-battery system? If yes, what is the optimal size of both the PV and battery systems?
- Under what conditions is it profitable for the prosumer installing PV hybrid systems to supply the HVAC loads?

Conversely, [Section 8.2](#) presents a theoretical study on PV systems to supply the HVAC electricity consumption in commercial buildings located in two Ecuadorian cities (Quito and Guayaquil) with different climatic characteristics. On the one hand, Quito is located in the Andes mountain and it has a subtropical highland climate, with many variations ranging from arid and temperate to humid and cold climates. On the other hand, Guayaquil, located on the Pacific coast, has a warm temperature during most of the year. Based on the above, this case study tries to answer the following questions:

- Could the electricity generated by a PV system installed in a commercial building in Ecuador cover the electricity demand needed for the HVAC system?
- Would there be a significant billing saving, when using the PV electricity instead of using the electricity from the grid?
- Under what conditions would the PV system installation be profitable?
- Would adding a storage system improve the profitability obtained with the PV system?

Finally, [Section 8.3](#) presents a theoretical study on electricity charges of a grid-connected PV-battery system, based on data of a dwelling located in Lisbon. Unlike the two previous cases, this study does not focus specifically on the HVAC demand but uses all the electricity consumption of the dwelling. This study analyses hypothetical electricity billing scenarios, and tries to answer the following questions:

- What is the impact of fixed charges on the viability of PV self-consumption?
- What is the most convenient tariff structure to encourage the use of PV-battery systems?
- Which combination of both tariff structure scenario and battery control strategy gives the best results from the technical and economic point of view?

In all the case studies, the *PVbat* simulation tool, developed in this doctoral thesis ([Section 6.6](#)), has been used.

8.1. Assessing the potential of PV hybrid systems to cover HVAC loads in a grid-connected residential building through intelligent control

8.1.1. Introduction

This case study presents theoretical and experimental work that was carried out in the grid-connected residential building demonstrator available at the *Instituto de Energía Solar* (IES) of the *Universidad Politécnica de Madrid* (UPM) presented in [Chapter 6](#). The house is provided with a building-integrated PV system of 7 kW_p coupled to a battery energy storage system (BESS: with a nominal capacity of 22 kWh and a battery inverter of 5 kW) and a heating, ventilation, and air-conditioning system (HVAC) based on two air-to-air direct expansion reversible heat pumps. Thermal loads, HVAC consumption, and PV generation are simulated using different dynamic models, and they are validated with actual data derived from monitoring of the experimental campaign.

This case study is the main topic of this thesis, and, therefore, the literature review was already presented in [Chapters 2, 3 and 4](#). Likewise, the experimental stage and modelling were exposed in [Chapters 5 and 6](#) respectively. Consequently, in this Chapter, the results of the technical and economic analyses are presented, together with the case study conclusions.

In [Section 8.1.2](#), the technical analysis is presented. The electrical consumption of HVAC is estimated from modelling experimental data. The behaviour of the PV hybrid system is simulated using the model and combined control strategies presented in [Chapter 6](#). Furthermore, in [Section 8.1.3](#), the economic analysis is presented, using three important parameters defined in [Chapter 7](#): LCOE, billing savings and payback time. In addition, a sensitivity analysis is performed to understand how the sizing of both PV and battery impacts the technical and economical performance of the hybrid system. Finally, discussion of the results and the most relevant conclusions are presented in [Sections 8.1.4 and 8.1.5](#) respectively.

8.1.2. Technical analysis

HVAC load estimation

In order to estimate the annual thermal loads of the building and the associated electricity demand of the HVAC system, an extensive measuring campaign has been conducted to measure the HVAC electrical consumption and thermal comfort conditions inside the building to assess whether it meets internationally accepted standards.

The two thermal comfort methods described in (Holopainen *et al.*, 2014) and presented in Chapter 4 have been analysed: Fanger's method and Adaptive Comfort method.

On the one hand, the Fanger's PMV method is a heat balance model that views the human being as a passive recipient of thermal stimuli. The resulting Predicted Mean Vote Index (PMV) and Predicted Percentage Dissatisfied (PPD) are calculated with the Fanger's equation (Fanger, 1970). These indices are widely used in international standards like ISO 7730 (ISO, 2005). Thus, variables such as clothing, physical activity, CO₂ concentration, relative humidity, outdoor and indoor temperature among others are involved in the assessment of the thermal comfort (Eq. 4.13).

On the other hand, the adaptive comfort model assumes that humans consciously or unconsciously modify their behaviour to adapt to thermal conditions. Therefore, the thermal balance equations cannot be strictly applied because the thermal adaptation is, by nature, a dynamic process (De Dear and Brager, 2002). The adaptive comfort formula does not directly take into account the classical comfort factors described above but simply establishes the indoor comfort temperature as a function of outdoor temperature (Nicol and Humphreys, 1973; EN15251, 2007; ASHRAE, 2013) (Eq. 4.14).

The Spanish 'Regulation for Thermal Installations in Buildings' (RITE, 2007), proposed the internal design conditions the values of temperatures as follows. For winter: 21-23°C; and, for summer: 23-25°C. Based on these values and contributing towards reducing the electricity consumption of the building, heat pumps have been configured to operate automatically at the following setpoint temperatures: 20°C for months October to March, and 26°C for months April to September. In total, 161280 one-minute samples have been collected, corresponding to 112 days covering all seasons from February 2016 to June 2017.

As mentioned in Chapter 4, Fig. 8.1 shows how samples are distributed inside of limits of comfort zones according to the two thermal comfort methods analysed. Fig. 8.1a corresponding to Fanger's method categories, which are defined by the PPD values below 6%, 10%, and 15% respectively. For instance, $PPD = 15\%$ indicates that 85% of 'theoretical' occupants inside of the house would be satisfied with the indoor temperature. Fig. 8.1b corresponding to the Adaptive method comfort zones categories: Category I, 90% acceptability; and Category II, 80% acceptability. The values of 'acceptability' indicate the percentage of occupants that would be satisfied with the indoor temperature. Table 8.1 shows a summary of the results from Fig. 8.1.

Figure 8.1: Evaluation of thermal comfort methods: (a) Fanger Method, and (b) Adaptive model.

Table 8.1: Results of thermal comfort categories for both Fanger and Adaptive methods: statistical distribution of indoor temperature measurements.

a) Fanger's method categories		b) Adaptive method categories	
Category A	39.3 %	Category I	77.0 %
Category B	71.4 %	Category II	91.2 %
Category C	92.4 %	Outside the categories	8.8 %
Outside the categories	7.6 %		

Note: 100% corresponds to 161280 one-minute samples of the indoor temperature measured.

A detailed analysis of the results shown in Fig. 8.1 and Table 8.1 reveals that, although both methods are very different, the results are similar. In both cases, more than 70% of the occupants would be satisfied with thermal conditions, by more than 90% of the time.

Once comfort conditions have been guaranteed inside the house, the heat pump's electrical consumption (P_{load}) is estimated — see Eq. 8.1 — depending on the main variables monitored: $T_{outdoor}$: outdoor temperature (°C); T_{indoor} : indoor temperature (°C); G_{hrz} : global horizontal irradiance (W/m²); and h : hour (from 1 to 24). Although these variables were monitored, in this first study a linear regression model was used to estimate P_{load} because it presents better adjustments compared to other existing simulation tools.

$$\begin{aligned}
 P_{load} = & a_0 + a_1 T_{outdoor} + a_2 T_{indoor} + a_3 G_{hrz} + a_4 h + \\
 & a_5 T_{outdoor} T_{indoor} + a_6 T_{outdoor} G_{hrz} + a_7 T_{outdoor} h + a_8 T_{indoor} G_{hrz} + \\
 & a_9 T_{indoor} h + a_{10} G_{hrz} h + a_{11} T_{outdoor}^2 + a_{12} T_{indoor}^2 + a_{13} G_{hrz}^2 + a_{14} h^2
 \end{aligned} \quad (8.1)$$

where coefficients a_x vary depending on the season of the year.

It is important to note that, the model of Eq. 8.1 was made to extend the analysis to the days for which the experimental data of HVAC electrical consumption were not available.

In Table 8.2, values of the coefficients and the associated p – value are reported for all seasons. A low p – value (< 0.05) in Table 8.2 indicates that the a_x has a meaningful addition to the model since changes in the predictor's value are related to changes in the response variable. On the contrary, a p – value greater than the common level of 0.05 suggests that changes in the predictor are not associated with changes in the response. As it can be noted, all the values are lower than the common statistical significance level of 0.05 with the exception of two values marked with an asterisk.

Table 8.2: Coefficients a_x of Eq. 8.1 and the corresponding p-value.

x	Winter		Spring/Autumn		Summer	
	a_x	$p - value$	a_x	$p - value$	a_x	$p - value$
0	6312.50	2.32E-131	-4346.00	2.67E-50	3827.58	0.00
1	134.77	2.18E-29	-188.69	2.79E-271	-328.18	0.00
2	-629.19	8.34E-91	508.47	1.28E-55	-108.80	1.79E-128
3	0.87	1.70E-19	2.42	2.08E-83	1.97	0.00
4	-21.20	1.64E-07	69.04	2.74E-91	-28.27	2.51E-19
5	-10.80	3.25E-48	4.42	6.72E-44	8.76	0.00
6	9.25E-3	1.05E-03	3.89E-02	4.79E-216	-4.46E-02	0.00
7	-0.35	5.46E-05	1.11E-02	0.73*	1.91	0.00
8	5.82E-3	0.34*	8.54E-02	6.50E-31	-4.73E-02	6.90E-74
9	1.11	1.43E-06	-3.12	1.84E-67	-1.28	2.97E-18
10	-7.18E-2	1.11E-168	-0.015	4.75E-12	1.53E-02	1.40E-67
11	1.34	1.14E-11	3.32	0.00	2.70	0.00
12	18.87	2.95E-89	-12.19	3.54E-41	0.26	1.87E-02
13	-1.91E-04	4.56E-13	9.07E-05	3.43E-04	-3.29E-05	1.79E-04
14	-0.28	6.24E-11	22.84E-02	2.55E-42	0.78	1.35E-184

*Coefficients a_x with p -value higher than 0.05 can be ignored because of poor correlation.

The output of the linear model was compared to the experimentally measured data (as mentioned above, minute samples over nine months covering all seasons of the year) in order to obtain a feedback on the reliability and accuracy of the model. The R-squared value of 0.8612 means that the model explains more than 85% of the variability in the response, showing a reasonably good agreement between the proposed linear-regression model and measured P_{load} , as it can be seen in Fig. 8.2.

Figure 8.2: Simulated and measured electricity demand for HVAC (P_{load}).

Based on the regression model above, a complete annual HVAC electricity demand with a minute-based resolution has been simulated, as shown in Fig.8.3a. Annual accumulated electricity required to cover the thermal loads is $E_{load} = 3807$ kWh.

Figure 8.3: (a) Annual HVAC consumption; (b) Annual PV energy generation

Fig. 8.3b shows the results from annual simulations of the PV system's electrical production according to the characteristics given in the Chapter 5, using validated tools and procedures (Masa-Bote and Caamaño-Martín, 2014) for the determination of the solar potential, which includes the effect of shadows and consideration of specific losses, such as optical and thermal losses in the generator, voltage drops, conversion losses in the inverter, among others. Due to the fact that the HVAC consumption in buildings is, in general, just a part of the total load and the objective of this study is the assessment of the potential of PV hybrid systems to cover HVAC loads, specific PV arrays from the building demonstrator have been selected (arrays 3 & 4 from Table 5.2) so that annual expected PV generation (Fig. 8.3b) is $E_{pv} = 3548$ kWh, comparable to the annual HVAC consumption ($E_{pv} \approx E_{load}$).

Likewise, the case study is simulated with a lead-acid battery bank coupled to the AC bus by means of a bidirectional inverter. In this study, the value of 6 kWh ($C_{10} = 125$ Ah, $V_{dc} = 48$ V), widely used and tested in other studies (Moseley *et al.*, 2004) will be simulated along with variations between 1.5 to 12 kWh for further sensitivity analysis. In addition, 60% of depth of discharge ($SoC_{min} = 0.4$) has been established, which is the value recommended by the manufacturer to extend the lifetime of the batteries and to avoid over-discharge stress.

In the specific case study, the simulation was performed with $P_{max} = 805$ W (the minimum level of power contracted so that there are no significant losses of load). Nevertheless, it is not the only possible value that can be used. In fact, in Spain, customers can choose different contracted power levels with the utility grid (BOE, 2006), as shown in Table 8.3. In this case, any value higher than P_{max} is

considered as a peak-load. According to the values in Fig. 8.3a, in some cases, the demand exceeds 2300 W. Therefore, if a PV-battery system is not used, the contracted power by the user should be at least 3450 W, according to the standardised power values. In the same Fig. 8.3a, seasonal periods with consumption peaks (winter and summer) can be identified. Consequently, it is reasonable to use strategy 2 (peak-shaving) in those periods. In order to determine the more appropriate new contracted power, several simulations were performed with the standardised P_{max} values lower than 3450 W, as shown in Table 8.3. For $P_{max} = 805$ W, the loss-of load (*LoL*) rate is 1.70%, i.e. 65 kWh of the annual HVAC consumption would not be supplied by the PV hybrid system. As P_{max} decreases, it increases self-sufficiency as well. However, it will also drastically increase the *LoL* rate, resulting in unsatisfying comfort conditions.

Table 8.3: Results of *LoL* and self-sufficiency parameters using combining of control strategies based on standard contracted powers for single-phase electricity supply systems in Spain.

P_{max} [W]	Reduction [%]	<i>LoL</i> [%]	Self-sufficiency [%]
3 450	0.00	0	39.28
2 300	33.34	5×10^{-4}	39.28
1 725	50.00	0.01	39.41
1 150	66.67	0.13	40.35
805	76.67	1.70	44.01
690	80.00	4.19	45.48
345	90.00	21.26	48.56

For the case study, the contracted power required for the HVAC system (according to the standardized levels of Table 8.3) is 3.45 kW. However, using PV hybrid system, the contracted power could be reduced to the smallest reasonable value: 0.805 kW (77% less).

Annual power flows

In order to perform the simulations, the following values have been assumed:

- PV generator nominal power: 2.68 kW_p
- Orientation and tilt angle: South, 25°
- BESS nominal capacity: 6 kWh ($V_{dc}=48V$; $C_{10}=125$ Ah)
- $SoC_{min}=0.40$; $SoC_{low}=0.45$; $SoC_{up}=0.95$; $SoC_{max}=1$
- Control strategies: strategy 2 in winter/summer; strategy 1 in spring/autumn

The simulation of both P_{grid} and P_{bat} are shown in Fig. 8.4a. In winter and summer months (from day 1 to 90, 181 to 243 and 334 to 365), the battery is discharged to supply power values higher than $P_{max} = 805$ W (strategy 2). For the rest of the year, P_{load} does not exceed the P_{max} . Therefore, the battery control strategy 1 is used to reduce energy consumption from the grid.

As shown Fig. 8.4b, the battery state of charge has a greater number of cycles during the strategy 1 due to the aim of this strategy is to import electricity from the grid as little as possible. In contrast, when strategy 2 is working, the battery only is discharged to reduce the peak-demand, and therefore the cycling is smaller than strategy 1.

Load duration curve

Load duration curve is a term for a demand frequency distribution graph. Such curves express the relationship between time and demand, showing the time the demand is greater or equal to a certain level (Poulin *et al.*, 2008). A load duration curve illustrates the variation of the load in a downward form such that the greatest load is plotted in the left and the smallest one in the right. On the time axis, the time duration for which the load continues during the year is given.

The load duration curves are shown in Fig. 8.5, these curves represent the grid electricity demand of the HVAC load under three different contexts: the first one (blue) is without neither using PV nor battery; the second curve (red) shows the case of using only PV (no BESS); the third curve (yellow) using PV and BESS.

Figure 8.4: (a) Annual power interaction in Magic Box. P_{pv} : PV power; P_{load} : HVAC load; P_{bat} : battery power; P_{grid} : grid power. (b) SoC: battery state of charge.

Figure 8.5: Load duration curve of imported energy from the grid to supply the demand for HVAC.

Using the PV system alone to directly supply the annual HVAC demand only reaches 27%, i.e. 73% of energy comes from the grid. When the BESS is added, the electricity from the grid can be reduced to 54%, as observed in Fig. 8.5.

In terms of power, Fig. 8.5 is of interest because it reveals the PV system does not cover the power peaks (red curve), indicating that the hours with the highest PV generation do not correspond to those with the highest demand. On the other hand, the PV-battery system along with control strategies make it possible to reduce power peaks by up to 65% during the first one thousand hours of maximum demand (yellow curve).

Self-sufficiency and self-consumption

According to Eq. 6.26 and Eq. 6.27, the annual values of self-sufficiency and self-consumption parameters have been calculated (see Fig. 8.6).

Therefore, the HVAC consumption (Fig. 8.6a) is supplied directly by the PV system (light green), the battery (dark green), or by the grid (light brown). In this figure, the origin of electricity to supply HVAC load is shown. The annual self-sufficiency is 44% since the PV electricity supplies the HVAC load (26.45% directly and 17.55% indirectly through the batteries). It could be inferred that increasing the BESS sizes would increase the self-sufficiency rate, but as it will be demonstrated later in the sensitivity analysis (Section 8.1.3), the increase of self-sufficiency is minimal.

Likewise, the PV electricity generated (Fig. 8.6b) flows toward the demand (light green), or to charge the battery (dark green), and finally, the PV surplus is exported to the grid (light brown). In this figure, the final use of PV electricity is shown, in which 28.37% instantly covers the HVAC demand, 24.60% is used to charge the batteries, and 45.46% is exported to the grid. Accordingly, in this case, the annual self-consumption is 49%. It is worth highlighting that if the system was used to supply not only the HVAC equipment but also other loads with different profiles, thus the annual self-consumption will significantly increase as it will be discussed in detail in the sensitivity analysis.

Figure 8.6: Annual energy accumulated: (a) Self-sufficiency and origin of electricity consumed by HVAC. (b) Self-consumption and final use of PV generation.

8.1.3. Economic analysis

Considering the cost of both PV and storage are constantly decreasing, an economic analysis was carried out to calculate the levelized cost of electricity (LCOE) and the payback-time —see equations in Chapter 7— with variations in PV system costing between 0.75 €/W_p and 2.25 €/W_p, and storage capacity cost ranging between 120 €/kWh – 360 €/kWh, which represent the current market conditions of small and medium-sized PV-battery systems (WEC, 2016; IEA PVPS, 2017).

To perform the economic analysis, it was necessary to assume some parameters, which are shown in Table 8.4:

Table 8.4: Economic input data used.

Nomenclature	Unit	Meaning	Assumed value
T	years	Economic lifetime of the PV system	30, according to (CREARA, 2015).
C_t	€	Operation & Maintenance (O&M) costs and equipment changes.	65 €/kW _p per year (CREARA, 2015) + PV Inverter replacement at 15 years (Hoppmann <i>et al.</i> , 2014; CREARA, 2015) + replacing batteries every 7.4 years.
I	€	Initial investment	PV: ranging from 0.75€ to 2.25 €/W _p . (IEA PVPS, 2017) + BESS: ranging from 120€ to 360 €/kWh.
r	%	Discount rate	4.9 % in Spain (CREARA, 2015).

The battery lifetime has been calculated using the Kinetic battery model presented in Chapter 3, Section 3.7. In addition, this model was implemented in the PVbat simulation tool presented in Chapter 6, Section 6.6.

LCOE

According to (IEA PVPS, 2017), the installed PV system price in the residential sector for Spain is between 1.4 and 1.5 €/W_p, including the price of modules, inverters, and the Balance of System (BoS). In this case study, 1.5 €/W_p is considered, assuming that the PV inverter also performs the BESS inverter function as an increasing number of manufacturers currently. Likewise, according to (Ciez and Whitacre, 2016; de Oliveira e Silva and Hendrick, 2016), the price of batteries ranges between 120 €/kWh and 360 €/kWh. For this case study, 243 €/kWh is assumed because it is the actual purchase price of the installed batteries. Consequently, the point (red lines: 1.5 €/W_p, 243 €/kWh) represents this case study in the Fig. 8.7, which results in 0.17 €/kWh.

Figure 8.7: Variation of LCOE depending on the cost of both PV and battery systems.

In Fig. 8.7 other possible future scenarios with different costs can be analysed. For example, if the PV system cost is reduced to 1.3 €/W_p (↓14%), and if incentives are applied in the purchase of storage systems, for example, 16% in the German case (PV magazine, 2017), the value of the LCOE (blue lines) is reduced from 0.17 €/kWh to 0.14 €/kWh.

Billing saving

In order to calculate the utility bill, the 2.0 DHA tariff period (residential tariff with two periods) was used (see Table 8.5). This is because the PV generation hours supply most of the HVAC demand in the 'peak period' tariff. It is reasonable, therefore, to use hourly discrimination where the 'off-peak period' tariff coincides with the higher HVAC demand, in accordance with the Spanish regulated prices currently in effect (Orden ETU/1282/2017).

Table 8.5: Electricity charges for residential buildings in Spain with two periods.

2.0 DHA	Fixed charge [€/kW/year]	Demand charge [€/kWh]			
		Peak period		Off-peak period	
		winter 12-22 h	summer 13-23 h	winter 22-12 h	summer 23-13 h
P ≤ 10 kW	38.04	0.062012		0.002215	

The cost in Euros that would be paid to the utility has been calculated over a year in the base case without PV-battery system and compared to two cases. In the first one, only the PV system is considered (no BESS), and in the second one, both PV and BESS systems are considered. The invoice is divided into three values: power, energy, and taxes, as shown in Fig. 8.8.

Figure 8.8: Cost of imported grid electricity under three scenarios: original demand (left); after using PV system (centre); and, after using PV - battery system (right).

From the Fig. 8.8, it can be seen that only using the PV system (2.68 kWp) would have 21% of annual billing reduction. However, the PV-battery system (2.68 kWp, 6 kWh) would enhance the annual savings in billing up to 56%.

Payback-time

To calculate the payback-time (Fig. 8.9), the annual income of the economic savings coming from the PV hybrid system is considered. In addition, three scenarios of the PV surplus value are considered: Scenario A, where PV surplus is not valued and is exported to the grid without receiving any monetary compensation (ir is the situation in Spain under current regulatory framework); Scenario B, where PV surplus is remunerated at the wholesale electricity market (around 0.17 €/kWh), and; Scenario C, where PV surplus is used to supply other loads into the house, which represents the maximum value in terms of market, corresponding to the retail electricity market price. Expenses correspond to the

operation and maintenance and replacement of equipment, considering that it has been assumed that the PV inverter must be changed after 15 years, and the batteries must be replaced at the end of their lifetime, i.e. after 7.4 years.

Figure 8.9: Payback-time. (a) Scenario A: PV surplus is not valued and is exported to the grid. (b) Scenario B: PV surplus is sold at the electric market price. (c) Scenario C: PV surplus is used to supply other loads.

The graphs presented in the Fig. 8.9 are used to evaluate any value of the payback-time (expressed in years) for the established price-ranges and for the mentioned scenarios of the PV surplus. For example, the payback-time for the reference case study (point 1.5 €/W_p, 243 €/kWh) can be obtained. Results are (red lines) 24, 18, and 15 years for scenarios A, B, and C respectively.

As seen in Fig. 8.9, the results depend quite significantly on the value of PV excess, which also depends on the political framework. In this respect, of the three scenarios considered, the most realistic scenario is C, where PV surplus supplies other demands within the home (lights, appliances, machinery, electric vehicles, etc.), where it is possible to combine battery storage with other control applications such as Demand Side Management (Castillo-Cagigal, Gutiérrez, *et al.*, 2011).

Fig. 8.9, also allows to directly assess the payback-time when the costs of both the PV and battery systems vary. For example, —as well as with Fig. 8.7— if other more favourable economic scenarios are assumed (blue lines: reduction of costs for both the PV system and the battery, 14% and 16% respectively), the payback time decreases between 3 and 4 years for each scenario.

Sensitivity analysis

The case study presented previously corresponds to a specific combination of PV and battery capacities (2.68 kW_p and 6 kWh). However, the variation of both PV and battery characteristics modifies the self-sufficiency (Fig. 8.10a), self-consumption, (Fig. 8.10b) and therefore, the billing savings (Fig. 8.10c). Thus, keeping the HVAC demand constant and using the same control strategies throughout the year (strategy 2 in winter/summer; strategy 1 in spring/autumn), multiple simulations were performed varying the battery size between 1.5 to 12 kWh (viable sizes for residential buildings), and the PV system size between 0.67 to 5.36 kW_p, which account for 25% and 200% of the reference value respectively.

Figure 8.10: (a) Self-sufficiency, (b) Self-consumption, and (c) Billing saving percentage with different battery size and different PV nominal power. HVAC load is constant.

This sensitivity analysis is useful to understand how the sizing of both PV and battery impacts the behaviour of the hybrid system. For example, setting a PV system of 2.68 kW, higher BESS sizes up 12 kWh does not significantly increase self-sufficiency (Fig. 8.10a). It is also worth noting that the small PV systems — less than 1kW— allow billing savings greater than 40%, even in cases where the battery is close to zero, mainly due to the combined effects of the two control strategies.

The self-sufficiency, self-consumption, and billing savings rate increments are not linear with the BESS capacity, suggesting that the optimal size of the PV-battery system is a crucial factor to be established, based on different energy and economic approaches (Weniger *et al.*, 2014).

8.1.4. Conclusions

In this case study, theoretical and experimental works that are being carried out in a grid-connected residential building prototype available at the IES-UPM have been presented. In particular, the following conclusions have been drawn from the analysis done on the influence of the specific application (to cover HVAC loads) and the BESS control strategy:

- a) The experimental measurements have confirmed that the comfort conditions are within the levels established by widely used standards. In the same way, these measurements allowed the elaboration of the HVAC electrical consumption for the entire year and to develop control strategies in order to increase self-consumption and decrease power demand.
- b) The battery control strategies used here allow an HVAC user to reduce consumption of both energy and power from the grid. Strategy 1 is useful in electricity markets whose value of energy (in kilowatt-hours) is high, while strategy 2 is useful in electrical markets, such as the Spanish one, where the contracted power (in kilowatts) has a high cost in billing (38.04 €/kW/year in 2018 for the residential sector, compared to 19.25 €/kW/year in 2007)
- c) It is important to know the annual distribution of electrical loads to determine which season or hourly periods with higher power demand justify the existence of some kind of battery electricity storage system strategy allowing consumption from the grid to be reduced. In this case study, two strategies have been used: the first helps to reduce energy consumption, and the second helps to reduce power peak demand from the grid. With the assumed values (Magic Box: 2.68 kW_p coupled to a 6kWh/48V lead-acid VRLA battery with a bidirectional inverter; annual PV generation comparable to HVAC demand), the combination of both strategies makes it possible to reduce both contracted power and energy consumption significantly (77% and 49% respectively).
- d) The implementation of local PV and electrical storage systems to power HVAC loads improves the self-sufficiency rate in varying degrees, depending not only on the PV power, but also on the HVAC load and storage control capacity. This behaviour implies that the optimal sizing of PV & BESS must be carried out in each case by considering both energy and economic aspects.
- e) It is clear that, at present, the billing saving by itself might not be enough to encourage the use of PV hybrid systems. On the one hand, the motivation strongly depends on the electricity tariff structure and energy policy in each country, in addition to PV and storage systems costs. This will determine whether the investment will be profitable from the financial point of view. On the other hand, the final decision will always depend on the user, his motivation and awareness in relation to a more efficient and sustainable use of energy.

8.2. HVAC systems using PV technology: Economic feasibility analysis in commercial buildings of Ecuador

8.2.1. Introduction

Based on the high solar irradiance ([CONELEC, 2008](#)) and in the great potential for investing in projects of renewable energies ([ECLAC, 2017](#)), the main interest of this case study is to assess the potential use of solar PV electricity to supply HVAC electricity demand.

Although in Ecuador, the technical requirements related to the connection of electricity from renewable energy generators to the distribution grid are established ([ARCONEL, 2015](#)), the technical aspects and/or incentives for PV self-consumption are not specified. This, combined with the fact that retail electricity prices are low compared to other countries in the region —the fourth cheapest tariff in Latin America ([Bloomberg, 2016](#); [ARCONEL, 2017](#))— the deployment and investment in this type of projects have not yet been deployed.

In this case study, the thermal loads of a reference commercial building (due to the great potential buildings have on the rooftop to install PV systems and generate their own consumption) were simulated in the Ecuadorian cities of Quito and Guayaquil (representing the mountainous and the coastal regions respectively) in order to determine the electrical consumption required for the HVAC system. In addition, the electrical generation of a PV system installed on the roof was calculated. Along with the consumption estimated, PV generation, and current electricity building structure in Ecuador, the annual electricity bill for HVAC demand was calculated in two scenarios: *i*) all the electricity required to guarantee the comfort conditions is supplied from the grid, and *ii*) the HVAC system is coupled to the PV generator and connected in self-consumption mode.

The present case is organized into the following sections: [Section 8.2.2](#) shows the simulations carried out in a reference building, both to characterize the HVAC load and the PV system performance for a suitable building integration. [Section 8.2.3](#) shows the results of the simulations and the billing saving analysis under different building orientations. [Section 8.2.4](#) shows the economic analysis, calculating the LCOE and the payback-time under different PV prices and different discount rates. In [Section 8.2.5](#), a sensitivity analysis was performed to evaluate the impact of adding a battery energy storage system on the PV system already proposed. Finally, the conclusions can be found in [Section 8.2.6](#).

8.2.2. Simulation of the reference building

The reference office building used in this case study was defined in the Solar Heating and Cooling program of the International Energy Agency (IEA) within tasks 25, 27 and 31 (Van Dijk, 2001). It is a medium-sized office building consisting of approximately 6,500 m² distributed over 7 floors. On each floor, there are 30 offices that are equally divided between the two main façades separated by a central corridor. Fig. 8.11 shows a schematic of the building used in the simulation and the dimensions of one of the 210 offices that form a part of it. It has been considered of interest for PV technology integration in the past, for example, Olivieri *et al.* (2014) simulated the thermal behaviour of the reference building to determine the potential for energy savings in the integration of semi-transparent PV modules.

The building was considered not affected by shadows. It was simulated considering the inherent factors of each city, such as temperature and solar irradiance, over a year.

Figure 8.11: (a) Reference building, and (b) dimensions of an individual office.

Thermal simulation

The simulations of the thermal behaviour of the building were performed using *DesignBuilder*²⁴ software, based on the *EnergyPlus*²⁵ calculation code. To carry out the simulations, the following hypotheses have been made:

- Setpoint temperatures of the HVAC system: heating, $T_{indoor} = 20\text{ }^{\circ}\text{C}$; and, refrigeration, $T_{indoor} = 26\text{ }^{\circ}\text{C}$.
- Coefficient of performance of the heat pumps, $\text{COP} = 3$
- Total internal loads are 10W/m^2 (lighting, office equipment, occupation, and so on).
- Schedule of action of internal loads for working days: 08h00 until 19h00 (on holidays, internal loads are not considered).

PV system

The PV system was simulated on the roof of the reference building, which has dimensions of $66\text{ m} \times 14\text{ m}$. To simulate PV production for each location, the data of solar irradiance on a horizontal surface and air temperature were used (see Fig. 8.12). In addition, the specific variables of latitude, longitude, and the technical parameters of monocrystalline silicon PV modules with 20% efficiency were used.

Annual simulations were carried out on an hourly basis of the expected electrical PV production, using tools and procedures validated for both the determination of electricity PV generation and estimation of the expected losses, considering optical and thermal losses in the PV arrays, voltage drops, conversion losses in the inverter, and so on (Masa-Bote and Caamaño-Martín, 2014).

²⁴ More information in: www.designbuilder.co.uk

²⁵ Available in: <http://apps1.eere.energy.gov/buildings/energyplus/>

Figure 8.12: Monthly averaged irradiance on a horizontal surface and monthly averaged air temperature for (a) Quito (Latitude: -0.225, Longitude: -78.524): data were obtained from The International Weather for Energy Calculation (IWECC); and, (b) Guayaquil (Latitude: -2.144, Longitude: -79.966): data were obtained from the weather station of the ESPOL (*Escuela Politécnica del Litoral, Guayaquil*).

As HVAC loads and PV generation depend significantly on the building orientation, the four main orientations were simulated, as shown in Fig. 8.13. Likewise, for each building orientation, the PV modules were distributed in parallel rows respecting the main axes of the building and tilted with three possible inclination angles (0° , 5° , 10°). This range of inclinations covers the optimum from the perspective of the latitude in Ecuador (0°), the minimum recommended to favour the self-cleaning of the modules (5°), and a higher value (10°) that considers non-horizontal building roofs (Cronemberger *et al.*, 2012).

Figure 8.13: Simulated orientations in the reference building and row arrangement of PV modules in each case.

8.2.3. Results

The dimensioning criterion considers that the annual electricity required for HVAC (E_{hvac}) must be as equal as possible to the annual electricity generated by the PV system (E_{pv}). The nominal PV power (P_{nom}) under standard test conditions, the E_{hvac} , and the E_{pv} , for the different orientations of the reference building in each city are shown in Table 8.6.

Table 8.6: Nominal PV power and corresponding annual both PV electricity and HVAC consumption for different building orientation. Tilt of PV modules: 5° .

City	Building orientation	P_{nom} [kW _p]	E_{pv} [MWh/year]	E_{hvac} [MWh/year]
Quito	E-W	30	44	42
	NW-SE	44	63	62
	N-S	59	84	83
	NE-SW	44	63	62
Guayaquil	E-W	84	110	112
	NW-SE	105	138	139
	N-S	154	201	203
	NE-SW	105	137	139

As shown in Table 8.6, Guayaquil city, being a coastal one and having average temperatures around 30 °C throughout the year, requires between two and three times more electricity for the same building compared with Quito city, whose average temperature is 18 °C. Likewise, in both cities, the east-west orientation is more energy efficient than other orientations, mainly due to the better management of passive solar gains, which allow maintaining the building at a comfortable temperature for most days of the year. In this respect, Fig. 8.14 shows monthly electricity HVAC consumption (E-W building orientation) versus monthly PV generation for Quito ($P_{nom} = 30 \text{ kW}_p$) and Guayaquil ($P_{nom} = 84 \text{ kW}_p$).

Figure 8.14: Monthly electricity HVAC consumption versus monthly PV generation for Quito and Guayaquil.

As representative days of these configurations, in Fig. 8.15, a typical week of the HVAC demand and PV generation is shown, with a PV module tilt of 5°, for Quito city (Fig. 8.15a) and Guayaquil city (Fig. 8.15b).

Figure 8.15: PV generation and HVAC demand in a typical week type for a) Quito, and b) Guayaquil.

The data obtained in the simulation stage for the whole year can be analysed more clearly with the load duration curve of HVAC demand with and without coupled PV system, as shown in [Fig. 8.16](#).

Figure 8.16: HVAC grid load duration curves when there is no PV system (blue), and after simulating the PV system installed (red). a) Building in Quito city, orientation E-W, $P_{nom} = 30 \text{ kW}_p$; and b) building in Guayaquil city, orientation E-W, $P_{nom} = 84 \text{ kW}_p$.

As Fig. 8.16a shows, in the case of Quito, the HVAC demand is reduced 62 % after using the PV system. This means that only 38 % of the total electricity required for HVAC is supplied by the grid, resulting in billing savings. On the other hand, in the case of Guayaquil (Fig. 8.16b), the HVAC demand is reduced 57 % after using the PV system, meaning that 43 % of the total electricity required for HVAC is supplied by the grid. In addition, in the Guayaquil case, although there is no reduction of power peaks (as 52% for the case of Quito) the PV electricity supply a considerable reduction of power during the two thousand hours of peak demand (reduction of 68%). In both cases, comparing PV generation with HVAC demand, it is possible to evaluate the electric balance, where the hours of higher demand coincide reasonably with the hours of PV generation.

According to the characteristics of the reference building, the terms established in the official document known as ‘Tariff specification for electrical companies of Ecuador’ (ARCONEL, 2017) were considered, for medium voltage tariff with time discriminating, as indicated in Table 8.7.

Table 8.7: Electricity charges in Ecuador for commercial buildings connected to medium-voltage.

	Marketing charge USD/consumer	Power charge [USD/kW]	Energy charge 07-22 h [USD/kWh]	Energy charge 22-07 h [USD/kWh]
Quito	1.414	4.129	0.095	0.095
Guayaquil	1.414	4.576	0.077	0.077

With this information, the annual bill that the consumer would pay was calculated in two contexts: with no PV system (all the required electricity is supplied from the grid), and with PV system installed in the building. Comparing both results, the billing savings (expressed in percentage) obtained by using the PV system, with respect to the first scenario, as shown in Table 8.8.

Table 8.8: Billing savings for each orientation and inclination used in the simulations.

		Annual billing saving [%]							
		Quito				Guayaquil			
	Tilt	E-W	NW-SE	N-S	NE-SW	E-W	NW-SE	N-S	NE-SW
Total	0°	54	58	56	58	54	57	55	57
Energy charges	0°	63	68	67	68	59	61	61	61
Power charges	0°	14	08	08	15	10	16	04	13
Total	5°	54	58	56	58	54	57	55	57
Energy charges	5°	64	68	67	68	59	61	61	61
Power charges	5°	14	08	08	15	10	16	04	23
Total	10°	55	58	56	58	54	57	54	57
Energy charges	10°	64	68	67	68	59	61	61	61
Power charges	10°	14	08	08	15	10	16	04	23

Although the PV system was designed to supply annually 100% of the building's HVAC demand on an annual basis, the annual billing savings ranged between 54%–58%. This is because the PV generation does not always coincide with the HVAC demand, as can be seen in [Fig. 8.15](#).

As [Table 8.8](#) shows, the highest values of billing savings occur in the energy charges (approximately 70%), compared to the power charges, where the billing savings are minimal (lower than 16%). This is basically because the tariff structure in Ecuador is based mostly on the electricity consumed than on the power contracted, unlike the Spanish case analysed in [Section 8.1](#).

The [Table 8.8](#) also shows that the billing savings vary by less than 8% between different building orientations, nevertheless, the minimum values are given for the most advantageous orientation in terms of HVAC demand, i.e. E-W.

Another conclusion that emerges from [Table 8.8](#), is about the PV modules tilt. Because both cities are located very close to the equator, the PV generation is not affected by the PV modules tilt between 0° and 10°.

8.2.4. Economic analysis

Considering the price of PV technology is constantly decreasing and the discount rate is a difficult forecast variable, a sensitivity analysis was carried out to calculate LCOE ([Fig. 8.17](#)) and the payback-time ([Fig. 8.18](#)) –see [Equations 7.11](#) and [7.20](#)– with variations in PV system costing between 1 USD/W_p and 3 USD/W_p, and discount rate variations ranging between 3.5 %–10.5 %. According to [CREARA, \(2016\)](#), the discount rate in international markets ranges between 5 %–11 %, e.g. Spain (5 %), Chile (8.4 %), Mexico (9.2 %) and Brazil (10.4 %). Therefore, taking into account the data of the Central Bank of Ecuador ([BCE, 2017](#)), in this study variations between 50 % and 200 % of the referential value of 7 % were used.

Figure 8.17: LCOE values based on both the PV system cost and discount rate, compared with the limits of current electricity charges in Ecuador (dashed red lines).

In Fig. 8.17, it is possible to compare the PV LCOE with the current electricity grid prices (dashed red line). For instance, in Quito city, if the PV system cost is lower than 1.6 USD/W_p and if the discount rate is lower than 7.7%, the grid parity is achieved. In contrast, in Guayaquil city, these values are reduced and the grid-parity, for this specific application, is reached if the PV system cost and the discount rate are lower than 1.4 USD/W_p and 6.3 % respectively.

For payback-time analysis, three scenarios were considered. Scenario A: PV surplus is not valued, Scenario B: Net-metering scheme, where PV surplus is valued at the retail electricity prices; and, Scenario C: Feed-in tariff scheme, where PV surplus is valued with a special tariff of 0.40 USD/kWh according to ‘REGULACIÓN No. CONELEC – 004/11’ (currently abolished). In this last scenario, it is assumed that all the PV electricity is exported to the national interconnected grid system (no self-consumption scheme). Although this regulation is no longer in effect, the results clearly indicate that this kind of incentives allows for very short payback-time, as shown in Fig. 8.18.

Figure 8.18: Payback-time based on both the price of PV technology and discount rate.

From Fig. 8.18, the following conclusions are highlighted. In scenario A, the PV cost should be lower than 1.4 USD/kWh, in order to have a payback-time of about 15 years on average, a value comparable with those PV installations of this type in Europe (Casademont, 2014). Likewise, the discount rate should also be lower than 9 %, otherwise, the payback-time will increase by more than 20 years, which is not attractive from the investors' point of view. Scenario B is more feasible, although there is currently no legislation for PV systems in buildings, the consumer can use the PV surplus to supply other building loads. If scenario C is used (the most optimistic), the investment in PV systems is guaranteed, with recovery times of less than 10 years in the majority of the cases. However, at this point, it may be more convenient exporting all PV electricity into the grid for the prosumer instead of using the PV system in self-consumption mode. For any of the above scenarios, it is important that there should be a legislation in Ecuador for distributed PV systems. Thus, the present study hopes to make a contribution to this approach.

8.2.5. Adding a battery energy storage system

A new analysis was carried out in order to assess the impact of adding a BESS on the PV system already proposed. In addition, to evaluate the LCOE, billing savings and payback-time, a sensitivity analysis was performed varying the PV system sizes from 25 % to 200 % of the reference size: 30 kW_p for Quito, 84 kW_p for Guayaquil. Likewise, the battery capacity size ranges from 25 % to 200 % of the reference size: 20 kWh in both cases, which is a reasonable value for this type of buildings (Ru, Kleissl and Martinez, 2013; Stadler *et al.*, 2013).

To perform the sensitivity analysis, it was necessary to assume some parameters, which are shown below:

Table 8.9: Assumed values of technical and economic parameters used in the PV-battery system.

Parameters	Assumed values
Scenario of PV surplus	A: PV surplus is not valued
Discount rate	7 % (BCE, 2017)
Lifespan of PV-battery system	30 years (CREARA, 2015)
Degradation of PV modules	0.5 %/year (Jordan and Kurtz, 2013)
PV system cost	2 USD/W _p (IEA PVPS, 2017)
Inverter replacement	15 years (Hoppmann <i>et al.</i> , 2014; CREARA, 2015)
BESS cost	400 USD/kWh (IRENA, 2015)
O&M	4.5 USD/kW (CREARA, 2015)
Battery	Lithium, 80% of DoD. Simulated with kinetic battery model (Section 3.7).

Figure 8.19: LCOE, billing saving and payback-time based on both PV and battery sizes. For Quito (upper) and Guayaquil (bottom)

The scenario A was assumed because the PV surplus is currently not valued and it makes sense storing the non-self-consumed PV electricity. As shown in the sensitivity analysis of Fig. 8.19, the LCOE is higher than 0.14 USD/kWh in all possible combinations of both the PV and the battery sizes. This value is not yet competitive with the current retail electricity prices in Ecuador, which is approximately 0.09 USD/kWh for commercial buildings. Likewise, although the billing savings increase by 58% without storage (Table 8.8) to more than 70% with BESS, the payback-time is too extensive (over 20 years). Therefore, it can be concluded that Quito and Guayaquil, adding a BESS, are not profitable from the economic point of view, mainly due to the extremely low electricity price which results in a low profitability of the investment even though the billing savings in percentage are very high.

8.2.6. Conclusions

In this case study, technical and economic analyses on PV systems integrated into buildings to supply the HVAC electricity consumption in commercial buildings located in two Ecuadorian cities were analysed. A reference commercial building located in both Quito and Guayaquil cities was used. The electricity demand for HVAC loads of the building and the PV generation was simulated with an hourly resolution.

The results showed that the HVAC demand is reduced (62 % for Quito, and 57% for Guayaquil) after using the PV system. This means that 38 % and 43%, respectively, of the total electricity required for HVAC, is supplied by the electricity grid. From the economical point of view, the results showed that the annual billing savings ranged between 54 %–58 %, depending on external parameters such as the building orientation, the PV modules' tilts, and the PV power installed. In addition, the economic profitability of the PV system was analysed, calculating the LCOE and payback-time according to different scenarios of the PV system cost and discount rate. On the one hand, the results show that the investment of PV systems will be profitable when net-metering or feed-in tariff schemes are used. On the other hand, the PV LCOE – if the price of PV technology is lower than 1.4 USD/W_p and the discount rate is lower than 9%— will be competitive with the electricity charges. Finally, adding a BESS was also analysed, concluding that the addition of a storage system will increase the costs, and therefore increase the payback-time of the investment.

8.3. Impact of fixed charges on the viability of PV self-consumption

8.3.1. Introduction

The traditional electricity market is built upon the concept of the marginal cost of electricity (Glachant and Ruester, 2014; Ito, 2014; Herrero *et al.*, 2015). Marginal costs, from a consumer point of view, are those prices that consumers pay for their last kilowatt-hour of electricity consumed. For utilities, marginal electricity costs are the costs experienced for the last kilowatt-hour of electricity produced. A utility's marginal cost can be higher or lower than its average price, depending on the relationships between capacity, generation, transmission, and distribution costs (Greer, 2012). In order to maximize system efficiency, the cost of electricity is determined by the marginal cost of the generated electricity required to satisfy, in every instant, the total demand. The large-scale integration of Renewable Energy Sources (RES) in the electricity system leads to a disruption of this energy market. When a significant portion of the demand is satisfied by zero marginal cost —with RES— generation, the wholesale electricity prices will be reduced (Haas *et al.*, 2013; McConnell *et al.*, 2013; Gullì and Balbo, 2015; Lund *et al.*, 2015). On the other hand, fixed costs (or so-called power term, price per kilowatt) are rising due to many factors including grid modernization —smart grid technologies—, maintenance of the ageing transmission and distribution infrastructures and environmental regulation (Laws *et al.*, 2017). Utilities worldwide are therefore in a situation of decreasing revenue, due to increasing levels of zero marginal cost generation, and increasing fixed costs. The answer is usually an increase in the customer electricity bills.

Due to its zero-marginal-cost, the high penetration of renewable energy sources in the electricity markets threatens incumbents' business models who are gradually shifting towards fixed power charges instead of the traditional volumetric rates (or also called energy term or demand charges, price per kilowatt-hour).

The purpose of this case study is to assess the impacts of these fixed power charges on the economics of PV systems under self-consumption schemes. Using real demand from a household located in Lisbon and PV generation data according to solar irradiance variability in Lisbon, simulations were performed with the *PVbat* software tool (see Section 6.6) and include detailed computation of the annual billing savings, the payback-time, the self-consumption, the self-sufficiency and the

load factor²⁶ of a dwelling coupled with PV-battery system. A range of PV array and battery sizes are explored for different storage control strategies. Billing scenarios include: *i*) only demand charges, *ii*) Portuguese case (high demand charges and low fixed charges), *iii*) Spanish case (low demand charges and high fixed charges), and *iv*) only fixed charges.

This situation is particularly evident in the case of residential rooftop PV systems. For situations with net-metering schemes, or to a less extent whenever the retail rate has a relevant volumetric component (cost per kilowatt-hour consumed), the PV customers avoid paying their full share of fixed infrastructure costs which leads to higher retail prices for all other consumers (Brown and Lund, 2013; Eid *et al.*, 2014). This could be rightly perceived as unfair since the have-nots would be paying higher bills whilst those with the financial ability to invest in a PV system would benefit the most. Furthermore, it may be argued that this situation will lead to further adoption of rooftop PV systems, and grid defection, which will reinforce the burden on the grid, in a positive feedback mechanism that has become popularized as ‘utility death spiral’ (Laws *et al.*, 2017). Another study (Cai *et al.*, 2013) analyses the impact of residential PV adoption on retail electricity rates; authors found that the most important parameter that determines whether the feedback (between PV adoption and electricity rates) has an effect is the fraction of customers who adopt PV based solely on the money saved. For the particular case of rooftop PV systems, Naïm R. Darghouth *et al.*, (2016) notes that this utility death spiral is hindered by an opposing feedback loop, as PV deployment becomes less economically attractive as the time of peak period—and higher electricity price—shifts away from times with high insolation. In another study, Naim R. Darghouth *et al.*, (2016) also argues that moving from demand charges to two-part tariff rate with fixed charges severely erodes the bill saving under the net-metering scheme because PV only displaces the volumetric portion of the total bill.

The emerging reaction to this disruption of the electricity markets and utilities’ business models is the redesign of electricity bills (Jenkins and Pérez-Arriaga, 2017). The argument is that there should be an alignment between costs of electricity generation, now mostly based on electricity demand (energy consumed), and installed capacities (power contracted) (CEER, 2017). Hence, the most common proposed approach is to change the structure of the electricity retail rate, reallocating a fraction of cost recovery from volumetric rates into fixed charges.

²⁶ Load factor (LF) is the ratio of the total imported electricity from the grid in a given period (annual in the present case study) divided by the total possible electricity that could have been imported in the same period, at the peak kilowatt level established by the customer during the billing period (see Section 6.3).

Higher ‘fixed charges’ are a straightforward and guaranteed mechanism to collect revenues to cover utility fixed costs but can negatively impact low-income customers and discourage energy efficiency or self-generation. Other bill designs include minimum bills and demand charges. In (McLaren *et al.*, 2015), authors argue for the use of ‘minimum bills’, which ensures that all grid-connected customers pay a specified minimum amount each month, regardless of the amount of electricity they purchase from the utility. This approach captures the revenue requirement whilst addressing the concerns about efficiency—and/or excess of non-productive use of electricity—and low-income customers. Analysis of annual residential PV (5 kW_p, without any batteries) customers’ bills for various rate structures for six different utilities in the US showed that fixed charges and minimum bills increase customer costs, regardless of system size.

A different approach is ‘demand charges’, based on a customer’s energy consumed over a specified time period, typically the monthly billing cycle. Hledik, (2014) has shown that demand charges may result in higher annual utility payments for PV customers and lower annual payments for non-PV customers. On the other hand, Borenstein, (2016) argues for a combination of higher fixed charges and an adder for time-varying volumetric rates, showing that minimum bills are inferior both in terms of efficient use of energy or equity—in the sense of fairness across different consumption levels.

Some electricity markets have already witnessed a relevant increase of the retail price of electricity, with a significant increase of its fixed component. In Spain, for instance, since 2007 until 2016, the fixed component (which is proportional to the contracted power) increasing 100% for the residential sector (38.04 €/kW/year in 2018, compared to 19.25 €/kW/year in 2007) (Orden ETU/1282/2017, RD 1634/2006). Also in Europe, fixed charges are significant in the electricity bill of Sweden (about 80%) and Netherlands (100%) (European Commission, 2015).

The increase of fixed costs of the electricity bill is expected to negatively affect the profitability of PV systems since the decrease in demand due to self-consumption will not usually be reflected in a reduction in the contracted power. Indeed, for typical residential customers, peak demand occurs in winter evenings whilst peak solar supply occurs at midday in summer. However, if the PV system is accompanied by some battery energy storage system (BESS), the impact of increased fixed costs on PV economics is not straightforward. The battery—as a part of a PV-battery system—may be controlled in order to provide some benefits to the consumers, such as: time-of-use bill management (Nottrott *et al.*, 2012; Hanna *et al.*, 2014), optimizing PV self-consumption (Castillo-Cagigal, Caamaño-Martín, *et al.*, 2011; Widén, 2014; Moshövel *et al.*, 2015; Quoilin *et al.*, 2016; Linssen *et al.*, 2017), and peak-shaving (Palensky and Dietrich, 2011; Leadbetter and Swan, 2012; Purvins *et al.*, 2013; Yang *et al.*, 2014). BESSs can also offer important benefits to

the utility grid by solving issues arising from the injection of electricity into the distribution grid. For example: distribution deferral (Wu *et al.*, 2015; Garcia-Garcia *et al.*, 2017), frequency and voltage regulation (Tant *et al.*, 2013; Von Appen *et al.*, 2014), and reducing ramp rates (Cormode *et al.*, 2013; Lam and Yeh, 2015).

The organization of this case study is as follows. Section 8.3.2 shows the input data and compares the results of the simulations under different scenarios. Section 8.3.3 discusses the results and exposes questions for future research. Finally, Section 8.3.4 includes a summary of most important conclusions.

8.3.2. Methodology

8.3.2.1. Input data

Electrical consumption

In Portugal, annual electrical consumption in the residential sector averages about 3500 kWh, according to a study that analyses data from 17 dwellings between 2004 to 2013 (Fonseca, 2014), well below of 10000 kWh in the US (EIA, 2016).

In this study, representative data of electrical consumption (measured 15-minute resolution load profile) of a household located in Lisbon with the contracted power of 3.45 kW was used —selected among 18 possible cases described in Reis, (2017). Data were taken between January and December 2013, resulting in the E_{load} equal to 3082 kWh/year with a mean power of 351 W and maximum value of 2809 W.

PV generation

Annual simulation of the PV system's electrical production was carried out according to solar irradiance variability in Lisbon. The design criterion used is that the E_{pv} is approximately equal to E_{load} . Therefore, the reference installed power of the PV system is 2.2 kW_p, resulting in $E_{pv} = 3066$ kWh/year. In addition, PV data were normalized to enable the sizing of the different PV systems in order to make sensitivity analysis (variations between 0.55 kW_p and 4.4 kW_p were simulated).

Battery capacity

According to Hoppmann *et al.*, (2014), the optimal nominal storage capacity (under the assumption that the consumer cannot sell electricity on the wholesale market) for residential buildings using PV systems was about 4.5 kWh in 2013. It is expected to increase significantly to 7 kWh in 2021 under different scenarios of

electricity costs. As reference installed capacity, a Li-ion battery bank of 5 kWh (nominal capacity) was simulated along with variations between 1.25 to 10 kWh for further sensitivity analysis. An 80% of depth of discharge ($SoC_{min} = 20\%$) was considered.

8.3.2.2. Simulation stage

Based on the proposed control strategies presented in Chapter 6, four main simulations were carried out: one with strategy 1 (Optimizing self-consumption) and three with strategy 2 (peak-shaving, considering different levels of contracted power). Four different bill charging scenarios were tested, depending on the energy term (demand charges) and the power term (fixed charges). In all scenarios, the numerical value of the annual electricity bill is the same. Table 8.10 and Table 8.11 and Fig. 8.20 summarise the test conditions of the simulations.

Table 8.10: New assumed contracted power if the dwelling uses a PV-battery system. The value of 3.45 kW is the contracted power level prior to the installation PV-battery system.

Control strategy	Case	Power contracted with no PV-battery system [kW]	Power contracted with PV-battery system, P_{max} [kW]
Strategy 1: Optimizing self-consumption	1	3.45	3.45
	2	3.45	1.15
Strategy 2: Peak-shaving	3	3.45	0.805
	4	3.45	0.690

Table 8.11: Billing scenarios. The combination of charging values in each scenario results in the same value for the annual billing of a dwelling with the demand of 3082 kWh/year and 3.45 kW of contracted power.

Scenario	Demand charges [€/kWh]	Fixed charges [€/kW/year]	Comments
A	0.184	0	Hypothetical scenario with no fixed charges. An extreme case of volumetric rate bill.
B	0.166	16.47	It is the present Portuguese scenario. The annual bill was calculated from these values.
C	0.130	49.41	Based on the present Spanish bill structure, with relatively higher costs for fixed charges.
D	0	164.70	Hypothetical scenario with no demand charges. An extreme case of fixed charges.

Figure 8.20: Percentage of electricity bill components for the reference dwelling with the demand of 3082 kWh/year and 3.45 kW of contracted power (568.23 € is the 100%), under different tariff scenarios of Table 8.11.

8.3.3. Results

Fig. 8.21 presents the minimum contracted power that the dwelling could achieve without any loss of load for different PV system configurations when considering a peak-shaving battery control strategy. The installed PV power ranges from 25% to 200% the reference installed power of 2.2 kW. The battery capacity has equivalent range regarding the reference battery capacity of 5kWh and 80% of deep of discharge.

Figure 8.21: Minimum contracted power for different PV-battery system configurations.

Fig. 8.21 shows that in every situation there is a significant improvement (i.e. lower contracted power) when compared to a scenario without any PV system. Indeed, the contracted power may be reduced from 3.45 kW to almost 1.4 kW, even for very small PV-battery systems (battery capacity lower than 1.25 kWh, and PV size lower than 0.55 kW). This is a 2.5-fold reduction in the fixed charges. Fig. 8.21 also shows that a large PV system with little storage capacity or a large battery with little PV generation also leads to lower contracted power (around 0.8 kW). It ought to be noted that in this study the battery only stores electricity from the PV system, not from the grid. Hence, in order to minimize the contracted power, the PV system configuration has to be well balanced with the storage capacity, which should be about 2 kWh/kW_p.

In order to perform the sensitivity analysis in this case study, it was necessary to assume some parameters, which are shown below:

Table 8.12: Assumed input values of technical and economic parameters.

Parameters	Assumed values
Scenario of PV surplus	‘Decreto-Lei n.º 153/2014’
Discount rate	4% (Camilo et al., 2017)
Lifespan of PV-battery system	30 years (CREARA, 2015)
Degradation of PV modules	0.5 %/year (Jordan and Kurtz, 2013)
PV system cost	1.45 USD/W _p (IEA PVPS, 2017)
Inverter replacement	15 years (Hoppmann <i>et al.</i> , 2014; CREARA, 2015)
BESS cost	400 USD/kWh (IRENA, 2015)
Battery	Lithium, 80% of DoD. Simulated with kinetic battery model (Section 3.7).

Fig. 8.22 and Fig. 8.23 present the billing savings and payback-time for PV-battery system with different bill structures (cases and scenarios described in Table 8.10), from 100% costs based on demand charges (left column) to 100% costs based on the fixed charges (right column). The intermediate columns refer to intermediate cases, Portugal and Spain respectively.

LCOE was not taken into consideration for economic analysis of this case study because it is not influenced by the retail electricity prices.

Figure 8.22a: Billing savings using battery control strategies in Scenarios A and B. Case 1 corresponds to strategy 1 (optimizing self-consumption). Cases 2, 3 and 4 correspond to strategy 2 (peak-shaving with maximum contracted power of 1.15 kW, 0.805 kW and 0.690 kW respectively). Blank spaces belong to results that have loss of load, therefore, they are not considered.

Figure 8.22b: Billing savings using battery control strategies in Scenarios C and D. Case 1 corresponds to strategy 1 (optimizing self-consumption). Cases 2, 3 and 4 correspond to strategy 2 (peak-shaving with maximum contracted power of 1.15 kW, 0.805 kW and 0.690 kW respectively). Blank spaces belong to results that have loss of load, therefore, they are not considered.

Figure 8.23a: Payback-time using battery control strategies in Scenarios A and B. Case 1 corresponds to strategy 1 (optimizing self-consumption). Cases 2, 3 and 4 correspond to strategy 2 (peak-shaving with maximum contracted power of 1.15 kW, 0.805 kW and 0.690 kW respectively). Blank spaces belong to results that have loss of load, therefore, they are not considered.

Figure 8.23b: Payback-time using battery control strategies in Scenarios C and D. Case 1 corresponds to strategy 1 (optimizing self-consumption). Cases 2, 3 and 4 correspond to strategy 2 (peak-shaving with maximum contracted power of 1.15 kW, 0.805 kW and 0.690 kW respectively). Blank spaces belong to results that have loss of load, therefore, they are not considered.

These results are quite interesting. One can observe that the peak-shaving control strategy (cases 2 to 4) may lead to quite positive economic performance of PV-battery systems even when the bill structure is based on fixed charges (scenario D). Indeed, for a 100% fixed charge bill (scenario A), a small PV system with a couple of PV modules and a small battery, may reduce the contracted power by a third, hence a reduction $> 66\%$ in the annual bill (Fig. 8.22b, case 2-D), whilst featuring payback-times below 5 years (Fig. 8.23b, case 2-D). Further decreases of contracted power (cases 3-D and 4-D) have a significant impact on the billing savings (from 76% to almost 80%) but require larger systems in order to warrant 0% loss of load, with somewhat upper payback-times.

When the electricity bill has a significant energy component (scenario A) the most economic return is achieved for higher levels of self-sufficiency rate. This can be achieved using a control strategy that maximises self-sufficiency (strategy 1), presently the most common control strategy for PV-battery systems on residential rooftops. Again, the system economic return (or its payback-time) is rather sensitive to the balance between PV and battery sizes, as the economic performance is eroded for systems from too large batteries (which are not fully used as often) to very small (which will lead to significant amounts of excess electricity to be fed into the grid). Finally, it can be also observed that this strategy would have very poor results with a billing structure valuing the contracted power (case 1-D).

Fig. 8.24 presents the self-consumption, self-sufficiency and load factor rates of different PV-battery systems for different control strategies and various levels of contracted power. Here, the tariff scenarios are not shown because they do not affect the results. In general, one may observe that in cases 2, 3 and 4 (peak-shaving objective), self-consumption, self-sufficiency and load factor rates are not very sensitive to the battery capacity. This insensitivity to the size of the battery is a direct result of the storage control strategy.

On the other hand, the case 1 uses control strategy for maximizing self-sufficiency. In this case, PV systems greater than 3 kW_p with batteries of more than 7 kWh (sizes very common in the current market) achieve self-sufficiency rates about 90%. Theoretically, in this strategy, the sizes of both PV system and BESS could be increased to achieve a self-sufficiency of 100%, hence no power import power from the grid. However, large systems also involve greater costs of investment.

Regarding the load factor rates, the opposite effect is observed when using strategy 1. This is due to the fact that power demand peaks (normally outside PV generation periods) do not decrease. Thus, the load factor only improves when the peak-shaving strategy is used. If the contracted power is lower then the LF will be higher.

Figure 8.24: Self-consumption, self-sufficiency and load factor for different battery control strategies. Case 1 corresponds to strategy 1 (optimizing self-consumption). Cases 2, 3 and 4 correspond to strategy 2 (peak-shaving with maximum contracted power of 1.15 kW, 0.805 kW and 0.690 kW respectively). Blank spaces belong to results that have loss of load, therefore, they are not considered.

8.3.4. Discussion

What is the optimal battery size?

The reference PV system (2.2 kW_p) with no storage leads to a self-sufficiency rate of 34%, hence 66% of the electricity comes from the grid. From the prosumer's point of view, it is important to decide if the PV system needs to add a storage system, and what would be the minimum battery size, for the desired self-sufficiency rate. Full self-sufficiency (100%) would be achieved increasing storage (a nominal battery capacity of 146 kWh with 80% DoD) but the cost of electricity and payback-time would be unacceptably high. Therefore, at this point, it is important to consider two approaches. The first refers to the economic point of view, where the prosumer could take into account the payback-time (see Fig. 8.23) below n years ($n = 5$ or 7 or 10 , or what prosumer considers appropriate). The second refers to the self-sufficiency rate that the prosumer wants to reach. For example, in case 1 of Fig. 8.24, for a 2.2 kW PV system, if the battery capacity is increased from 5 kWh to 10 kWh, self-sufficiency only increases from 70% to 80% respectively. So, the prosumer should evaluate if this increase is worth it.

Do PV-systems degrade the load factor?

The default LF for the dwelling (without any installed PV-battery system) is 12.52% (demand of 3082 kWh/year and a peak demand of 2.81 kW). When a PV system is added without storage, this value decreases to 8.24% (2026 kWh/year with the same peak demand of 2.81 kW). Adding storage will increase LF , as shown in Fig. 8.24 (right column) up to 39% (using peak-shaving control strategy). From the point of view of the grid, which of course appreciates lower net load variability and hence higher LF , it is interesting to note that the higher LF is achieved with high penetration of renewable energy, when appropriately managed.

How changing billing structure affects behaviours?

The present study assumes unchanged consumer behaviour whilst changing the billing structure. However, it is reasonable to believe that if consumers are not charged for accumulated electricity demand, they could increase the consumption, adopting habits such as leaving appliances on unattended²⁷. On the other hand, if

²⁷ The bundling of telecom services ought to have a similar impact to fixed charges in the electricity bill, since customers pay for the access to the service not the duration of the phonecalls themselves. In Portugal, on average, the total duration of phonecalls for bundled costumers is about 20% higher than standard customers (ANACOM, 2017).

consumers are not charged for fixed charges, there would be strong incentives to energy efficiency, reducing energy consumption without curtailing social welfare (De Boeck *et al.*, 2015) and scheduling of appliances through Demand Side Management solutions (Castillo-Cagigal, Gutiérrez, *et al.*, 2011). These possibly emerging trends are not yet observed, although the relative weight of the fixed charges in the Spanish electricity bill has increased about 100% in the last 10 years. There seems to be a complete lack of literature on these effects, which open the opportunity for further study.

8.3.5. Conclusions

The purpose of this chapter has been to assess the impact of changes in the electricity bill structure on the economics of residential rooftop photovoltaics. Modelling has considered real demand and supply data for a range of bill structures, PV-system sizes and different storage control strategies.

Results show that the peak-shaving control strategy may lead to quite positive economic performance of PV-battery systems even when the bill structure is based on fixed (power) charges. When the electricity bill has a significant energy component (demand charges) the highest economic return is achieved for higher levels of self-sufficiency rate. This can be achieved using a control strategy that optimizes self-consumption.

The billing saving, payback-time, self-consumption, self-sufficiency and load factor are rather sensitive to the balance between PV and battery sizes when optimizing self-consumption control strategy is used, unlike peak-shaving control strategy, which presents no significant differences between high battery capacities and small ones. An interesting result is the high load factor reached using the peak shaving strategy. This shows that low net load variability can be achieved with high penetration of renewable energy when appropriately managed.

When PV-battery systems use optimizing self-consumption control strategy, systems greater than 3 kW_p with batteries of more than 7 kWh (sizes very common in the current market) achieve self-sufficiency rates about 90%, but with very low load factor rate. This is due to the fact that the power demand peaks (normally outside PV generation periods) do not decrease when this battery control strategy is used.

These results show that, regardless of the billing structure, residential PV may always be an interesting investment for prosumers, as long as the system is adequately sized, and the suitable storage control strategies are implemented.

Chapter 9

Conclusions and future works

This Chapter summarizes the main conclusions of this Thesis. It is divided into eleven sections. The first ten sections refer to the main conclusions and findings obtained in this Thesis. [Section 9.9](#) shows some proposals of future research lines. [Section 9.10](#) presents the contributions and publications in scientific journals over the course of his doctorate. Finally, [Section 9.11](#) presents the prize awarded to the author for his study proposed, as well as the acknowledgements to the institutions that supported this research.

9.1. General overview

This research work is a contribution to assess the potential of PV hybrid systems to supply the electrical consumption in the heating, cooling and air-conditioning (HVAC) systems of buildings.

The hypothesis of this thesis suggested that a grid-connected PV-battery system is capable of supplying the necessary electricity to maintain the comfort conditions inside of a building, being technically and economically profitable from the consumer point of view.

In order to contrast the hypothesis, an extensive experimental campaign was carried out in a residential demonstrator (prototype of the nearly zero-energy building, so-called ‘Magic Box’ at the *Instituto de Energía Solar - Universidad Politécnica de Madrid*). The campaign was divided into two stages, on the one

hand, HVAC electrical consumption (two heat pumps to maintain the comfort conditions), indoor temperature, carbon dioxide concentration, relative humidity, global horizontal irradiance and outdoor temperature were measured through controlled conditions (HVAC settings), performing a considerable number of tests in 112 days, covering all seasons. On the other hand, a battery energy storage system was coupled to the PV system already existing in the ‘Magic Box’. In this way, the grid-connected PV-battery system parameters (PV generation, HVAC electrical consumption, imported/exported grid power, discharged/charged battery power, and battery state of charge) were analysed in 44-day experimental measurements between January and June 2017.

In order to control the battery, two control strategies were implemented, being the first one focused on optimizing the PV self-consumption and the second one on decreasing the grid-peak demand (peak-shaving). With the data collected, a model was developed that reproduces the control strategies implemented. This model served as the basis for the development of a simulation software tool that allows one to evaluate —under various hypothesis— the main parameters of a grid-connected PV-battery system. This tool, called *PVbat*, also implements a detailed economic analysis that includes the levelized cost of electricity, the payback-time and the billing savings, as well as a range of useful parameters, inter alia, self-consumption, self-sufficiency, load factor and battery lifetime (for both lead-acid VRLA and lithium manganese oxide batteries), which allow the user to size a PV-battery system and to determine whether the PV hybrid system is technically and/or economically profitable or not.

With the developed model, three case studies presented in this thesis have been studied. The first one presents an experimental study on PV hybrid systems to supply the HVAC loads in a residential building located in Madrid. Conversely, the second one presents a theoretical study on PV systems to supply the HVAC electricity consumption in commercial buildings located in two Ecuadorian cities (Quito and Guayaquil) with different climatic characteristics. A third case study also was evaluated with the *PVbat* tool (Portuguese scenario), where the economic impact of changing fixed charges (or also called power term, price per kilowatt contracted) in the bill electricity using PV-battery systems to supply total electricity consumption in a residential building in Lisbon was analysed, suggesting that the peak-shaving control strategy may lead to quite positive economic performance of PV-battery systems especially when the bill structure is based on fixed charges.

9.2. About the state of the art

Around the world, many countries have adopted different schemes to regulate the self-consumption. Some schemes compensate electricity consumption and the PV electricity production, some compensate real energy flows, while others are compensating financial flows. For instance, in the U.S. typically is used the net-metering, FiT and PPA schemes. In most cases, the financing of these measures is done through indirect public funding and/or absorbed by utilities. Another region that encourages the PV self-consumption is Europa. For instance, Germany has introduced a FiT scheme for PV electricity that is rewarded in the consumer electricity bill. In other countries, traditional schemes have been modified and new models have been created. In Italy, for instance, the net-billing mechanism was modified in which electricity fed into the grid is remunerated through an ‘energy quota’ based on electricity market prices. In Spain, the current self-consumption regulation establishes significant restrictions on the exported electricity into the grid and on the operation of energy storage systems. These restrictions reduce considerably the benefits and savings of the prosumers.

Regarding PV-battery and PV-hybrid systems, in some regulatory frameworks where incentives for the installation of BESS exist, the storage is clearly profitable. In other countries, where retail electricity prices are relatively high, these systems are able to compete head to head with the grid, even if they do not have favourable regulatory frameworks to the self-consumption. Despite the BESS costs are still high, a reduction of more than 50% is expected in the next ten years. This fact, along with the cost-reduction of PV technology, the installation of grid-connected PV-battery systems would become more attractive for the prosumers.

In relation to HVAC systems, in recent years, an increase in the market for air-conditioning and heat pumps has been observed worldwide, especially in developing countries. Regarding energy use for space heating, according to the studies, it still represents the most energy-intensive use in the buildings, more than 40%.

Despite the importance of thermal systems in the energy balance of buildings, the studies indicate that specific strategies for combining local PV generation with electricity-powered air-conditioning equipment, especially reversible heat pumps, are still under examination. In addition, the implementation of the battery systems into the PV systems to supply HVAC, along with control strategies, is quite interesting because these systems have not been analysed in detail in order to determine whether or not they are competitive with the electricity grid, from both the technical and economical point of view.

9.3. About comfort conditions

The experimental measurements have confirmed that the comfort conditions are within the levels established by widely used methods: The Predicted Mean Vote (PMV) or the so-called the Fanger's method, and the Adaptive Comfort method.

On the one hand, according to the Fanger's method, there are three comfort zones (categories A, B, and C), which are defined by the ranges of PMV values from -0.2 to 0.2 , -0.5 to 0.5 , and -0.7 to 0.7 , which correspond to PPD (Predicted Percentage Dissatisfied) values below 6%, 10%, and 15%, respectively. On the other hand, according to the Adaptive method, the limits of the comfort zones are given by the following two categories: Category I, 90% acceptability; and Category II, 80% acceptability. In both methods, the values of 'acceptability' indicate the percentage of occupants that would be satisfied with the indoor temperature, and occupants also have the opportunity to adapt by adjusting their clothing, opening/closing. Regarding the reliability of methods, the PPD method needs many input variables (air temperature, air velocity, mean humidity, clothing insulation and activity level) and when any parameter is not available, it is necessary to assume values that could lead to erroneous results. In contrast, the adaptive method has fewer variables (only the ambient temperature is needed), however, the same formula is used to measure comfort in various environments (residential, commercial, with or without ventilation, different latitudes, etc.) which also could lead to errors of interpretation. Nevertheless, in my opinion, the adaptive method is more reliable because the formulation was defined by empirical field studies.

Results shown that, with the Fanger's method, 92% of the samples measured of indoor temperature are within Category C; similarly, 71% of samples are within Category B limits; and 39% are within Category A. Furthermore, according to the Adaptive model, 91% of the samples are within Category II; likewise, 77% of samples are within Category I limits. In both cases, the main conclusion is that — when the heat pumps were working— more than 80% of the possible occupants would be satisfied with the indoor temperature, by more than 90% of the time.

Once comfort conditions were guaranteed inside the house, the heat pump's electrical consumption was estimated with a regression model, which depended on the main variables monitored: outdoor temperature, indoor temperature and global horizontal irradiance. The linear regression model was used to estimate HVAC electrical consumption because it presented better adjustments compared to other existing simulation tools based on physic models and Typical Meteorological Years (TMY). In fact, these models can be very powerful and accurate to estimate average

consumption of the building under the conditions defined in the TMY, but they are not so much adequate tools when the user wants to assess the behaviour of the building under specific climate conditions, as is the case here. The simulated data were compared with the experimentally measured data in order to obtain a feedback on the reliability and accuracy of the model. The R-squared obtained was of 0.86, which means that the model explains about 86% of the variability in the response, showing a reasonably good agreement between the proposed linear-regression model and measured HVAC loads.

9.4. About grid-connected PV-battery model

The mathematical modelling was developed to simulate the behaviour of the PV hybrid system with different sizes of both PV and battery systems. This model also allows designing PV-battery systems for a specific consumption. In order to develop the formulation, it was necessary to have experimental campaign to validate the model. In this sense, 44-day experimental measurements between January and June 2017 was carried out. The data obtained were used as the basis for developing the model that allows one to replicate and simulate a grid-connected PV-battery system. This model allows the user to determine the state of charge of the batteries and exchange of power between the PV generation, the loads, the grid and the battery.

On the one hand, the simulated battery state of charge had errors around 2% compared with measured data from the battery inverter (Sunny Backup), which indicates that the model can predict with an accuracy higher than 98% the behaviour of this variable; this is very useful when calculating the cycling, ageing, and battery lifetime.

On the other hand, comparing simulated values (exported/imported electric grid power and charge/discharge battery power) with measured data from electricity meters, the model has an error lower than 7 % for power levels > 500 W in absolute terms. For low power values (near zero) the error increases (between 10% - 100%), but, the high percentage error does not necessarily indicate that the model does not correspond to reality. This has been verified by the RMSE and the standard deviation, which show that the residuals on average are < 60 W, which are acceptable values, considering that the absolute values range between 2000 and 6000 W. In energy terms, the model has an error lower than 10% and with absolute differences lower than 15 kWh (around 600 kWh over 44-days period), which is equivalent to an average difference of 14.20 W in each measurement, which is a negligible value, considering that only the load of battery inverter in silent mode

is about 35 W. With all these considerations, the model presented in this thesis was considered valid, and it was used to develop the *PVbat* simulator software tool.

The *PVbat* tool implements the battery control strategies presented in this Thesis. Strategy 1 (optimizing PV self-consumption) is useful in markets whose value of electricity (in kilowatt-hours) is high, while strategy 2 (peak-shaving) is useful in electrical markets, such as the in Spain, where the contracted power (in kilowatts) has a high cost in billing.

This tool can also assess economic parameters presented in this Thesis: the Levelized cost of electricity (LCOE), and the Payback-time. An adapted formulation was presented in order to calculate the payback-time while considering the annual income from the economic savings due to the grid-connected PV-battery system, including billing savings and, if applicable, the incomings for selling of the PV surplus. Also, in this Thesis, a new ‘Levelized Cost of Discharged electricity’ (LCOD) is proposed in order to quantify the amount of *LCOE* which is derived only from BESS.

The economic analysis of *PVbat* enables the user to assess three scenarios about excess of PV electricity (not self-consumed nor used to charge battery). The first scenario is when the consumer does not receive bonus for exporting PV surplus into the grid. In the second one, is net-metering scheme, where PV surplus is valued at the current retail electricity prices. The third scenario is when the consumer would be considered a prosumer, who is able to sell the PV surplus (Feed-in tariff scheme). The simulation tool enables these scenarios to provide evidence of the potential benefit that the PV-battery systems would have under different market conditions.

The model and battery control strategies presented in this thesis are also applicable for other realistic situations, where HVAC power consumption is only a part of the total building load. Another important aspect to be considered in a realistic situation is the quality of data. The input data can be obtained from simulations from software tools (typically hourly values) or measured data. Time resolution is a very important factor in the accuracy of the model, where the results will be more reliable with sub-hourly data, especially to capture the high-peak powers.

9.5. About residential building in Spain

The results of this case study show that in a typical residential building —with high electrification level and a PV system (without a battery system) that annually generates the expected annual consumption— the self-consumption rate is 27%; however, with the implementation of the BESS and the proposed control strategies, it could achieve approximately 50%, depending on the BESS capacity and the PV

generator nominal power. Likewise, with the assumed values (PV nominal power of 2.68 kW_p coupled to a 6kWh lead-acid battery with bidirectional inverter; and, annual PV generation comparable to HVAC demand), the combination of both strategies made it possible to reduce both contracted power and electricity consumption (77% and 49% respectively for case study).

The combination of both strategies enabled to limit the power from the grid in the months of peak demand (winter and summer) and to reduce grid electricity imports for the rest of the year. The electricity and economic savings are related to the contracted power required for the HVAC system. According to the different standardized levels of contracted power with the grid, 3.45 kW should be contracted for the house. However, using PV hybrid system, this value could be reduced to the smallest reasonable value: 0.805 kW (77% less) without significantly worsening the quality of the thermos-hygrometric conditions in the house.

The implementation of PV system and electrical storage systems to power HVAC loads has demonstrated to improve both the self-sufficiency (>50%) and billing savings (>60%), depending not only on the PV power but also on the storage capacity. This behaviour implies that a specific sizing of PV and storage must be carried out in each case by considering technical and economic aspects.

9.6. About commercial building in Ecuador

In order to determine the electrical consumption required for the HVAC system, the thermal loads of a reference commercial building were simulated in two Ecuadorian cities: Quito and Guayaquil (representing both the mountains and the coast region respectively). In addition, the electrical generation of a PV system installed on the roof of a typical medium-sized office building was calculated. Along the consumption data, PV generation, and current electricity charges in Ecuador, the annual electricity bill for HVAC demand has been calculated in two scenarios: *i*) all the electricity required to guarantee the comfort conditions is supplied from the grid; and, *ii*) the HVAC system is coupled to the PV generator and connected in self-consumption mode. The results showed that under different PV modules' tilts and building orientation, the annual billing savings for HVAC demand ranges reached between 54 % – 58 %.

Results showed that in Quito city, if the PV system cost is lower than 1.6 USD/W_p and if the discount rate is lower than 7.7%, the grid parity could be achieved. In contrast, in Guayaquil city, these values should be reduced to 1.4 USD/W_p and 6.3 % respectively in order to be the PV system profitable. This is

due to the fact that in the Quito city there is (on average) more solar irradiance and lower environment temperature (15°C on average) compared to the Guayaquil city, making it possible to obtain more PV electricity per unit area of the building roof. In addition, the HVAC electricity consumption is lower in Quito (60% minor) due to the temperate climate and the altitude of the city.

About payback-time in both cities, if PV surplus is not valued, the PV system cost must be lower than 1.4 USD/kWh to be competitive. Likewise, the discount rate should also be reduced (lower than 7 %), otherwise, the payback exceeds 20 years, which is not attractive from the investors' point of view.

Finally, adding a battery storage system (Lithium-ion battery) was also analysed, concluding that the addition of a storage system increases the annual billing savings up to 65%, but the payback is about 30 years in most cases. The same happens with the LCOE, where the minimum value using PV-battery system is 0.14 USD/kWh (almost twice as current retail price). Therefore, it can be concluded that in Quito and Guayaquil cities, adding a BESS, are currently not profitable from an economic point of view.

9.7. About case study in Portugal

In this case study, the economic impact of changing fixed charges in the bill electricity using PV-battery systems was analysed using Portuguese and Spanish regulatory frameworks as references. The study included annual billing savings, payback-time, self-consumption, self-sufficiency and the load factor of a dwelling coupled with PV-battery system, located in Lisbon. Data used in the study included annual electrical consumption (real data measured at 15-minute resolution load profile) and simulation of PV generation using real data of global solar irradiance.

In order to compare different PV-battery sizes, several simulations were carried out with PV power ranging from 0.5 kW to 4.4 kW. Also, the battery capacity (Lithium-ion battery) ranged from 1.25 kWh to 10 kWh with 80% of deep of discharge. Based on the two battery control strategies proposed in this Thesis, four main simulations were analysed: one corresponding to optimizing self-consumption strategy, and three corresponding to peak-shaving strategy, considering three possible values of contracted power reduction. Likewise, four different scenarios of bill charging were assumed: *i*) only demand charges (price per kilowatt-hours), *ii*) Portuguese case: high demand charges and low fixed charges (price per kilowatt), *iii*) Spanish case: low demand charges and high fixed charges; and *iv*) only fixed charges.

According to sensitivity analyses performed, the self-sufficiency, payback-time and billing saving were assessed with a variety of both PV and battery sizes. When PV-battery systems use optimizing self-consumption control strategy, systems greater than 3 kW_p with batteries of more than 7 kWh (sizes very common in the current market) achieve self-sufficiency rates about 90%, payback-time lower than 14 years, and billing saving up to 80%. In contrast, when peak-shaving control strategy is used, the balance between PV and battery sizes presents no significant differences between high battery capacities and small ones, suggesting that the main factor to obtain technical and economic benefits occurs when contracted power can be reduced. In fact, the peak-shaving control strategy may lead to quite positive economic performance of PV-battery systems even when the bill structure is based on fixed charges. For instance, for a 100% fixed charge bill scenario, a small PV system with a couple of PV modules and a small battery, may reduce the contracted power by a third, hence a reduction > 66 % in the annual bill, whilst featuring payback-times below 5 years. Further decreases of contracted power have a significant impact on the billing savings (from 76% to almost 80%) but require larger PV-battery systems in order to warrant 0% loss of load, with somewhat upper payback-times.

Finally, the results suggest that the control strategies can generate billing savings and a quick return on investment depending on the tariff structures. In general, when the fixed charge is low (as the Portuguese case), it is recommended to implement control strategies to reduce electricity consumption (optimizing self-consumption). On the contrary, in tariff structures such as the Spanish, the peak-shaving control strategy is the best solution.

9.8. General conclusions

According to the results obtained in this Thesis, the starting hypotheses of the thesis have been demonstrated, suggesting that a grid-connected PV-battery system is capable of supplying the electricity required to maintain the comfort conditions inside of a building, being technically and economically profitable from the consumer point of view.

Regarding technical analysis, in terms of energy, the proposed PV systems (without battery), which in annual terms generate the same amount of consumed electricity, are capable of supplying between 27% and 62% (self-sufficiency) of the HVAC electrical consumption (in the Spanish and Ecuadorian case studies), depending in each case on the PV and HVAC load profiles. Adding a battery storage system, the self-sufficiency increases between 50% and 80%, up to theoretically 100%, depending on the PV power, the battery capacity and the

selected control strategy. In terms of power, when the optimizing self-consumption strategy is used, the PV-battery system does not always cover the power peaks, indicating that the hours with the highest PV generation do not correspond to those with the peak load, notably in the case of residential buildings. In contrast, in the case of commercial buildings, the hours of higher demand coincide reasonably with the hours of PV generation, obtaining about 50% of power peak reduction. On the other hand, the PV-battery system along with peak-shaving control strategy makes it possible to reduce power peaks depending on battery capacity and load profile (up to 65% in the residential case study).

About economic parameters used in all case studies, on one hand, LCOE is used to compare the costs of PV electricity with the retail electricity prices, and on the other hand, the payback-time is used to know the time in years when the investment begins to generate economic benefits. In this sense, the LCOE in the case studies ranges from 0.10 USD/kWh to 0.20 USD/kWh, depending mostly on the costs of the PV and battery systems, as well as the discount rate in each country. Likewise, regarding the billing savings, despite analysing different electricity markets, values above 50% are achieved. As for the payback-time, in the residential building in Spain and Portugal, the range oscillates between 15 - 20 years. In the case of commercial buildings in Ecuador, the scenario is less advantageous, obtaining values higher than 20 years. In all cases, lower payback-times could be achieved if self-consumption schemes and/or political frameworks were more favourable.

The economic parameters used to analyse the economic impact of the PV-battery systems entail limitations. The main drawback lies in the need for assumptions about discount rate and the annual increase in retail electricity prices. These assumptions are difficult to make, especially for developing countries, and can thus limit validation in regions where discount rates and costs of the PV hybrid systems are not well known. Therefore, due to the high sensitivity of the input assumptions, the sensitivity analyses developed in the *PVbat* tool allow the user to have a broader view of the variability of the economic parameters depending on both the costs of the PV-battery system and the discount rate. In conclusion, LCOE, and payback-time should be evaluated together with a wide range of possible input values in order to have a better perspective of the PV hybrid systems investment.

It is clear that, at present, the LCOE, the billing saving or payback-time by itself might not be enough to encourage the use of PV-battery systems. On the one hand, the motivation strongly depends on the electricity tariff structure and energy

policy in each country, in addition to PV and storage systems costs. These factors will determine whether the investment will be profitable from the financial point of view. On the other hand, the final decision will always depend on the user, his motivation and awareness in relation to a more efficient and sustainable use of energy.

9.9. Future works

On the basis of the activities carried out within this research and in the light of the results, the following research lines are proposed.

a) To optimize the battery control strategies for PV-battery systems presented in this Thesis, by implementing forecast-based operation which has the capability of use optimizing PV self-consumption and/or peak-shaving strategies, depending on battery storage capacity available. The control algorithm should take real PV power and load forecasts into account, in order to optimize the battery and reducing the imported power from the grid as well.

b) In the model presented in this Thesis, power exchanges between grid and battery were not allowed. A new model which incorporates this functionality would be very useful to analyse other tariff scenarios. Although in this approach, there are already many investigations carried out, it would be possible to analyse new control strategies and to incorporate other systems, such as electric vehicle, domestic hot water, solar thermal, among others. Likewise, it would be interesting to implement energy efficiency programmes and other energy efficiency measures, such as demand side management and forecasting as mentioned above.

c) In this thesis, ageing battery models proposed by other authors to calculate the battery lifetime have been used. In further studies, news validated models for calculating battery lifetime could be incorporated. Likewise, future works could prove or not (based on the actual battery capacity) the accuracy of the ageing models used. It is clear that in the future, the PV-battery systems will use new storage technologies or will improve existing ones. Therefore, research in this field would be of great interest.

d) In this thesis, two air-to-air direct expansion reversible heat pumps have been used to maintain comfort conditions, with set temperatures (20°C in winter and 26°C in summer), and although the comfort conditions have been satisfactory, it would be very useful to incorporate automatic temperature control, taking into

account new variables such as number of people, work schedules, automatic switching on/off of HVAC equipment, etc., that make it possible to optimize the electrical consumption without diminishing the thermal comfort.

e) The analyses carried out in this thesis only focused on PV-battery systems installed in the same building. Further studies could analyse housing complex and microgrids. These communities can share PV generation, electrical consumption and storage, in order to optimize resources, reduce expenses and achieve better short- and medium-term investment returns.

f) It is imperative that future research related to renewable energies in Ecuador can propose an adequate regulation for the promotion of distributed PV systems given the excellent solar potential of the country. The impact of grid-connected PV systems in self-consumption mode (with or without storage) on the distributed grid, would be an interesting topic of research. Also, making proposals about the best scenarios to assess the PV surplus in such a way that it is beneficial from both the consumer and the utility grid point of view.

9.10. Dissemination of results

Scientific Journals

Solano, J. C., Olivieri, L., & Caamaño-Martín, E. **Assessing the potential of PV hybrid systems to cover HVAC loads in a grid-connected residential building through intelligent control.** *Applied Energy*, 206, 249–266. Received 24 March 2017; Received in revised form 3 August 2017; Accepted 20 August 2017.
<https://doi.org/10.1016/j.apenergy.2017.08.188>

Almeida Dávi, G., López de Asiain, J., **Solano, J.C**, Caamaño-Martín, E., & Bedoya, C. **Energy Refurbishment of an Office Building with Hybrid Photovoltaic System and Demand-Side Management.** *Energies*, 10(8), 1117. Received: 16 June 2017; Accepted 26 July 2017; Published 1 August 2017. <https://doi.org/10.3390/en10081117>.

Almeida Dávi, G., Caamaño-Martín, E., Rüther, R., & **Solano, J.C**. **Energy performance evaluation of a net plus-energy residential building with grid-connected photovoltaic system in Brazil.** *Energy and Buildings*, 120, 19–29. Received: 25 November 2015; Received in revised form 16 February 2016; Accepted 22 March 2016.
<https://doi.org/10.1016/j.enbuild.2016.03.058>

Solano, J.C, Olivieri, L., & Caamano-Martín, E. **HVAC systems using PV technology: Economic feasibility analysis in commercial buildings of Ecuador.** *IEEE Latin America Transactions*, 14(2), 767–772. Date of Publication 21 March 2016.
<https://doi.org/10.1109/TLA.2016.7437221>

Submitted to Journal

Solano, J.C, Brito M.C, & Caamano-Martín, E. **Impact of fixed charges on the viability of self-consumption photovoltaics.** *Energy Policy*.

International Conferences

Oral presentation:

J.C. Solano, L. Olivieri, E. Caamaño-Martín, G. Almeida-Dávi. **Assessing the potential of hybrid PV–battery systems to cover HVAC loads under southern European climate conditions.** *32nd European Photovoltaic Solar Energy Conference and Exhibition.* International Congress Center Munich, Germany. June 20 – 24, 2016.

Poster presentation:

G. Almeida-Dávi, M. Castillo-Cagigal, E. Caamaño-Martín, **J.C. Solano**. **Evaluation of load matching and grid interaction indexes of a net plus-energy house in Brazil with a hybrid PV system and demand-side management.** *32nd European Photovoltaic Solar Energy Conference and Exhibition.* International Congress Center Munich, Germany. June 20 – 24, 2016.

Oral presentation:

J.C. Solano, L. Olivieri, E. Caamaño, M. Egido. **Climatización eficiente mediante bombas de calor y tecnología solar fotovoltaica: Análisis de viabilidad en edificios comerciales en Ecuador.** *VIII Conferencia Internacional de Energía Renovable, Ahorro de Energía, y Educación Energética.* La Habana, Cuba. May 25-28, 2015.

Poster presentation:

J.C. Solano, L. Olivieri, E. Caamaño, M. Egido. **Climatización eficiente mediante bombas de calor y tecnología solar fotovoltaica: Análisis de viabilidad en edificios comerciales en España.** *XIII Congreso Ibero-Americano de Climatización y Refrigeración.* Madrid, Spain. April 28-30, 2015.

Local Conferences

Oral presentation:

J.C. Solano. **Gestión activa de la demanda con estrategias de control en el sistema de almacenamiento: tecnologías de Lead-acid Vs. Li-Ion.** *Universidad de la Batería.* Madrid, Spain, June 29-30, 2017.

Oral presentation:

J.C. Solano. **Integración de los sistemas de autoconsumo con almacenamiento en la edificación.** *JORNADA TÉCNICA UNEF: Almacenamiento para Autoconsumo Fotovoltaico.* Madrid, Spain, January 30, 2018.

Accepted contributions

J.C. Solano, L. Olivieri, E. Caamaño-Martín. **PV hybrid systems to cover HVAC loads in a grid-connected residential building through optimized control strategies.** CYTEF 2018 – *IX Congreso Ibérico / VII Congreso Iberoamericano de las Ciencias y Técnicas del Frío*. Valencia, Spain, June 19-21, 2018.

9.11. Awards and acknowledgements

Awards

To: **J.C. Solano**. Project title: **Efficient HVAC of public buildings in Ecuador using PV systems.** Award of the best project in the Engineering, Industry and Construction Area within the research component, in the Scientific Research Contest of the *III Encuentro de Estudiantes Ecuatorianos en Europa*. Oficio Nro. SENESCYT-SESCOT-2015-0098-CO. Quito, Ecuador, February 05, 2015.

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Appendices

1. Battery monitoring script
2. Battery inverter controlling script
3. Installation and user guide of the *PVbat* tool
4. Scientific articles and International congresses

APPENDIX 1

Battery monitoring

Script

```
1  #include "SBU_monitoring.h"
2
3  CSBU_monitoring::CSBU_monitoring(char* inputDevice){
4
5      //Divide device name and code
6      size_t nSepPos, nSlength;
7      string str1, str2;
8      sDeviceC = string(inputDevice);
9      nSepPos = sDeviceC.find(':');
10     nSlength = sDeviceC.length();
11     str1.assign(sDeviceC, 0, nSepPos);
12     str2.assign(sDeviceC, nSepPos + 1, (nSlength - nSepPos - 1));
13
14     pcWebboxCom = new CwebboxCom (str1, str2);
15     cout << str1 << ":" << str2 << endl;
16     loadVariables();
17 };
18
19
20 int CSBU_monitoring::communicationMain ( void ){
21
22     char batteryfile[256];
23     time_t current_time;
24     tm      *current_hour;
25
26     time(&current_time);
27     current_hour = localtime(&current_time);
28
29     sprintf(batteryfile, "/home/magicbox/data/SBU/SBU_datas-%04d-
30 %02d-%02d", (current_hour->tm_year + 1900), (current_hour->tm_mon
31 +1), current_hour->tm_mday);
32     ofstream Out_file (batteryfile, ios::app);
33     int auxpos;
34     auxpos = Out_file.tellp();
35     if (auxpos == 0){
36         Out_file << "#Time";
37         for (int i = 0; i < pcWebboxCom->readSizeNum() ; i++){
38             Out_file << " " << pcWebboxCom->readNumName(i);
39         }
```

```

40         for (int i = 0; i < pcWebboxCom->readSizeChar() ; i++){
41             Out_file << " "<< pcWebboxCom->readCharName(i);
42         }
43         Out_file << endl;
44     }
45
46     pcWebboxCom->updateVariables();
47
48     Out_file << current_hour->tm_hour << ":" << current_hour->
49     tm_min << ":" << current_hour->tm_sec;
50     for (int i = 0; i < pcWebboxCom->readSizeNum() ; i++){
51         Out_file << " "<< pcWebboxCom->readNumValue(i);
52     }
53     for (int i = 0; i < pcWebboxCom->readSizeChar() ; i++){
54         Out_file << " "<< pcWebboxCom->readCharValue(i);
55     }
56     Out_file << endl;
57
58     return 0;
59 };
60
61
62
63 int CSBU_monitoring::loadVariables(void){
64
65     ifstream inputfile
66     ("/home/magicbox/programs/WebBox_RPC/parametersFiles/SBUvariables"
67 );
68     char newline[16];
69     int numNum,numChar;
70
71     inputfile >> numNum;
72     inputfile >> numChar;
73     inputfile.ignore(256, '\n');
74
75     for(int i= 0;i<numNum;i++){
76         inputfile.getline(newline, 256);
77         pcWebboxCom->includeNumParam (newline);
78     }
79     for(int i=0;i<numChar;i++){
80         inputfile.getline(newline, 256);
81         pcWebboxCom->includeCharParam (newline);
82     }
83
84     return 0;
85 };

```


APPENDIX 2

Battery inverter controlling

Script

```
1  #include "maxSelfConsumption_5.h"
2
3  CmaxSelfC_5::CmaxSelfC_5(void) {
4
5      time_t new_time;
6      tm      *c_t;
7      time(&new_time);
8      c_t = localtime(&new_time);
9
10
11      Maximun_Charge = 100.0;
12      Minimun_Charge = 95.0;
13
14      Maximun_Discharge = 40; // (%) Se considera 5% de diferencia
15      entre la máxima descarga y la mínima descarga
16      Minimun_Discharge = 45;
17
18      Charge_overload_coef = 0.5;
19      Charge_self_coef     = 1.0;
20
21      // ESTRATEGIAS DE CONTROL
22      strategy = 1; // (1) Optimizing self-consumption; (2) Grid
23      Peak-shaving
24      demand = 1; // (1) La batería actuará sobre todas las cargas.
25      (2) La batería actuará sólo sobre HVAC
26
27
28      sprintf(batInfoFile, "/home/magicbox/data/SBU/SBU_datos-
29      %04d-%02d-%02d", (c_t->tm_year + 1900), (c_t->tm_mon + 1), c_t-
30      >tm_mday);
31      sprintf(outputFile,
32      "/home/magicbox/data/batController/batController-%04d-%02d-
33      %02d", (c_t->tm_year + 1900), (c_t->tm_mon + 1), c_t->tm_mday);
34
35
36
37
38
39
```

```

40     // Datos de los contadores
41
42     sprintf(hvacInfoFile,      "/home/magicbox/data/HVACs/HVAC-%04d-
43 %02d-%02d", (c_t->tm_year + 1900), (c_t->tm_mon + 1), c_t->tm_mday);
44     sprintf(hvactmpInfoFile,  "/home/magicbox/data/HVACs/HVAC-
45 tmp");
46     sprintf(meterInfoFile,
47 "/home/magicbox/data/METER/meter_3phase-%04d-%02d-%02d", (c_t-
48 >tm_year + 1900), (c_t->tm_mon + 1), c_t->tm_mday);
49
50
51     // Dato del estado de carga anterior
52
53     sprintf(SOCTmpInfoFile,
54 "/home/magicbox/data/batController/batController-tmp");
55
56     int auxpos_p;
57     ofstream outputFile (outputFile, ios::app);
58     auxpos_p = outputFile.tellp();
59     if (auxpos_p == 0)
60         outputFile << "#Time Bat_SoC ChargeCur GridCur PV_power
61 Consum_power Pgrid Pbat Pload_sbu Phvac Pbuilding0" << endl;
62 };
63
64 int CmaxSelfC_5::controllerMain(void){
65     time_t new_time;
66     tm      *c_t;
67
68     float Bat_SoC, FeedCur, ChargeCur, GridCur, GridVtg,
69 Consum_power, PV_power, aux_power, ExtCur, Pgrid, Pbat,
70 Bat_SoCtmp;
71     float Ppv, Pload, Pload_sbu, Ehvac, Ehvactmp, Phvac, Pmax,
72 Pbuilding, Pbuilding0;
73     float aux_cur1, aux_cur2;
74     float Limit_Charge_coef;
75     char StateInfo[3];
76
77
78     /* COMMUNICATION */
79     m_bComError = false;
80     /* SBU read */
81     Bat_SoC = batSoC_Calc(batInfoFile);
82     GridVtg = VtgCA_Calc (batInfoFile); //Lectura de tensión de red
83     ExtCur = ExtCur_Calc(batInfoFile);
84     Pload_sbu = LodPwr_Calc(batInfoFile);
85     ChrgState (batInfoFile, StateInfo);
86
87     Webbox.readConfiguration(ChargeCur, GridCur); // Estas
88 variables están como InvChrgCurMax y GdCurNom en el manual de
89 usuario del SBU5000 y en la interfaz web del WebBox
90
91     Pload_sbu = ((1000*Pload_sbu) + 60); // Watt. Se suma 60 W por
92 el autoconsumo del inversor
93
94

```

```

95     /* Contador HVAC */
96
97     Ehvac = Ehvac_Calc(hvacInfoFile); // Consumo actual de
98 climatización, en Wh
99     Ehvactmp = Ehvactmp_Calc(hvactmpInfoFile); // Consumo anterior
100 de climatización, en Wh
101
102
103     /* Contador METER */
104
105     Pgrid = Pgrid_Calc(meterInfoFile); // Potencia de red actual,
106 en W
107     Ppv = Ppv_Calc(meterInfoFile); // Potencia fotovoltaica actual,
108 en W
109     Pload = Pload_Calc(meterInfoFile); // Potencia de consumo
110 actual, en W
111
112     /* Dato del fichero batController-tmp
113
114     Bat_SoCtmp = batSoCtmp_Calc(SOCtmpInfoFile); // Estado de carga
115 anterior
116
117     // Obtener potencia en W, a partir de datos de energía Wh
118
119     if(Ehvac==0 || Ehvactmp==0 || ((Ehvac-Ehvactmp)*60)>0.5*Pload){
120 // En caso de que haya error de comunicación en el contador se
121 usará el valor del sunny backup
122         Phvac = 0.5*Pload;
123     }
124     else{
125         Phvac = (Ehvac-Ehvactmp)*60; // Watt
126     }
127
128     /* PV, Pload y Pbat */
129
130     PV_power = 0.5*Ppv; // Se multiplica por 0.5 debido a la
131 utilización de un trafo 25/5 en lugar de uno 50/5
132     Consum_power = 0.5*Pload; // idem
133     Pbat = Consum_power - PV_power - 0.5*Pgrid; // Se calcula Pbat,
134 solo es aplicable cuando Pgrid es positiva y se importa de la red,
135 debido a que el trafo no da valores negativos cuando exporta a la
136 red
137     Pbuilding0 = Consum_power - Phvac; // Potencia del resto de
138 cargas de la casa, diferentes de HVAC
139
140     // ESTRATEGIAS DE CONTROL
141     if(demand==1){
142         Pbuilding = 0;
143     }
144     else{
145         Pbuilding = Pbuilding0;
146     }
147
148
149

```

```

150     if(strategy==1){
151         Pmax = Pbuilding;
152     }
153     else{
154         Pmax = 805; // [Watt] Potencia máxima que entrega la red
155         eléctrica para abastecer la demanda. Si la demanda es mayor que
156         Pmax funciona la batería. En caso de Pmax = 0 funciona la
157         estrategia 1.
158     }
159
160
161     /* MAIN CONTROL */
162
163     if(!m_bComError){
164
165         // BATTERY DISCHARGE
166
167         if (Consum_power >= PV_power){
168             // Si la batería (SoC) está entre Maximun_Discharge y
169             Minimun_Discharge, sólo se descargará si viene descargando, es
170             decir el SoC anterior es mayor a SoC presente.
171             // Lazo de histéresis. La batería necesitará cargarse hasta
172             Minimun_Discharge para poder descargar nuevamente.
173             if (Bat_SoC >= Maximun_Discharge && Bat_SoC <=
174             Minimun_Discharge){
175                 if ((Bat_SoCtmp - Bat_SoC)>0){
176                     if (Consum_power >= Pmax){
177                         aux_curl = (PV_power + Pmax)/GridVtg;
178                         aux_curl = (float(int(aux_curl*100.0)))/100.0;
179                         if (aux_curl >= 16.0){ // Nominal Grid Current Default
180                             value = 16A.
181                             aux_curl = 16.0;
182                         }
183                         if (GridCur != aux_curl){
184                             Webbox.setGridCur(aux_curl); // La potencia que
185                             alimenta las cargas proviene de la red sólo hasta el valor de
186                             aux_curl, el resto proviene de la batería.
187                         }
188                         if (ChargeCur != 20.0){
189                             Webbox.setChrgCur(20.0);
190                         }
191                     }
192                     else {
193                         if (GridCur != 16.0){
194                             Webbox.setGridCur(16.0); // Entrega toda la energía
195                             de la red para cubrir la demanda. Nominal Grid Current Default
196                             value = 16A
197                         }
198                         if (ChargeCur != 0.15){
199                             Webbox.setChrgCur(0.15); // Corriente de carga de
200                             batería es 0.3 A para obtener 32W que es la potencia de
201                             autoconsumo del inversor SBU en silent mode
202                         }
203                     }
204                 }

```

```

205         else{
206             if (GridCur != 16.0){
207                 Webbox.setGridCur(16.0); // Entrega toda la energía de
208 la red para cubrir la demanda. Nominal Grid Current Default value
209 = 16A
210             }
211             if (ChargeCur != 0.15){
212                 Webbox.setChrgCur(0.15); // Corriente de carga de
213 batería es 0.0
214             }
215         }
216     }
217     else{
218         if (Bat_SoC > Minimun_Discharge){
219
220             if (Consum_power >= Pmax){
221                 aux_curl = (PV_power + Pmax)/GridVtg;
222                 aux_curl = (float(int(aux_curl*100.0)))/100.0;
223                 if (aux_curl >= 16.0){ // Nominal Grid Current Default
224 value = 16A.
225                     aux_curl = 16.0;
226                 }
227                 if (GridCur != aux_curl){
228                     Webbox.setGridCur(aux_curl); // La potencia que
229 alimenta las cargas proviene de la red sólo hasta el valor de
230 aux_curl, el resto proviene de la batería.
231                 }
232                 if (ChargeCur != 20.0){
233                     Webbox.setChrgCur(20.0);
234                 }
235             }
236             else {
237                 if (GridCur != 16.0){
238                     Webbox.setGridCur(16.0); // Entrega toda la energía
239 de la red para cubrir la demanda. Nominal Grid Current Default
240 value = 16A
241                 }
242                 if (ChargeCur != 0.15){
243                     Webbox.setChrgCur(0.15); // Corriente de carga de
244 batería es 0.3 A para obtener 32W que es la potencia de
245 autoconsumo del inversor SBU
246                 }
247             }
248         }
249     }
250     else{
251         if (GridCur != 16.0){
252             Webbox.setGridCur(16.0); // Entrega toda la energía de
253 la red para cubrir la demanda. Nominal Grid Current Default value
254 = 16A
255         }
256         if (ChargeCur != 0.15){
257             Webbox.setChrgCur(0.15); // Corriente de carga de
258 batería es 0.3 A para obtener 32W que es la potencia de
259 autoconsumo del inversor SBU
260         }
261     }

```

```

260     }
261 }
262 }
263
264 // BATTERY CHARGE
265 else{
266     if(Bat_SoC < Maximun_Charge ){
267         aux_cur2 = (PV_power - Consum_power)/GridVtg;
268         aux_cur2 = (float(int(aux_cur2*100.0)))/100.0;
269         if (aux_cur2 >= 20.0){ // Maximum device charging current =
270 20 A.
271             aux_cur2 = 20.0;
272         }
273         if (GridCur != 16.0){
274             Webbox.setGridCur(16.0); // Entrega toda la energía de la
275 red para cubrir la demanda. Nominal Grid Current Default value =
276 16A
277         }
278         if (ChargeCur != aux_cur2){
279             Webbox.setChrgCur(aux_cur2); // La corriente de carga de
280 batería sólo admite el excedente entre PV_power y Consum_power.
281         }
282     }
283     else{
284         if (GridCur != 16.0){
285             Webbox.setGridCur(16.0); // Entrega toda la energía de la
286 red para cubrir la demanda. Nominal Grid Current Default value =
287 16A
288         }
289         if (ChargeCur != 20.0){
290             Webbox.setChrgCur(20.0); // Se queda en 20 A, a pesar de
291 que ya no seguirá cargando la batería.
292         }
293     }
294 }
295 }
296
297 /* FILE REPRESENTATION */
298 ofstream output (outputFile, ios::app);
299
300 time(&new_time);
301 c_t = localtime(&new_time);
302 output << c_t->tm_hour << ":"<< c_t->tm_min << ":"<< c_t-
303 >tm_sec << " " << Bat_SoC << " " << ChargeCur << " " << GridCur
304 << " " << PV_power << " " << Consum_power << " " << Pgrid << " "
305 << Pbat << " " << Pload_sbu << " " << Phvac << " " << Pbuilding0
306 << endl;
307
308 output.close();
309 return 0;
310 };

```

APPENDIX 3

Installation and user guide of the *PVbat* tool

PVbat is a software tool (developed in MATLAB®) designed to simulate the power flows between the PV system, the loads inside the building, the battery (charging and discharging), and the grid (imported and exported). Besides, *PVbat* uses ageing battery modelling in order to calculate the battery lifetime. After the technical analysis is performed, an economic analysis is made taking into account three electrical market scenarios, namely Spain, Ecuador and Portugal.

Figure A.1: Logo of *PVbat*

A3.1. Download

The folder that contains the installer files, user guide and example of Excel files for data entry, can be downloaded from the following web link:

https://1drv.ms/f/s!AsjZn9N6J1s_gqx6Q6GvUVhMnmdF1A

Once the folder is downloaded, the simulator can be installed in two ways: *i*) online installation, through the PVbat_online.exe file, or *ii*) offline installation, through the PVbat_standalone file.exe.

Nombre	Fecha de modificación	Tipo	Tamaño
ficheros excel listos para PVBat	20/12/2017 20:03	Carpeta de archivos	
About_PVBat.pdf	08/06/2017 15:36	Adobe Acrobat Document	707 KB
PVbat_online.exe	20/12/2017 19:43	Aplicación	65.849 KB
PVbat_standalone.exe	20/12/2017 19:41	Aplicación	1.063.378 KB

Figure A.2: Files in the folder

A3.2. Preparing the Excel file

Before using the simulator, an Excel file ready with data of PV generation and electricity consumption of the building must be entered, as can be seen in the Fig. A3.

	A	B	C	D
1	Ppv [W]	Specific load [W]	Other loads [W]	
2	0,00	640,46	60,00	
3	0,00	640,42	60,00	
4	0,00	642,98	100,00	
5	0,00	652,24	120,00	
6	0,00	665,81	120,00	
7	0,00	683,64	120,00	
8	0,00	722,47	60,00	
9	0,00	740,94	60,00	
10	15,19	719,77	300,00	
11	52,78	701,23	360,00	
12	101,72	673,20	400,00	
13	153,81	622,41	420,00	
14	287,09	552,49	500,00	
15	383,86	491,62	450,00	
16	334,21	450,29	600,00	
17	291,74	418,48	1100,00	
18	110,67	410,85	100,00	

Figure A.3: Example of Excel file data, worksheet *Data*

The worksheet 1, called '**Data**', must contain three columns: P_{pv} , *Specific load*, and *Other loads* (in watts), these annual data have a specific size depending on the time interval. Time intervals and data number accepted in this worksheet are:

Table A.1: Time interval and data number accepted in the Excel file.

Time interval	Data number
1 hora	8760
30 minutes	17520
20 minutes	26280
15 minutes	35040
10 minutes	52560
5 minutes	105120
2 minutes	262800
1 minute	525600

The simulator can be configured to simulate the supplying of electricity consumption of a specific load (for example HVAC, lights, etc.) or to whole electricity demand of a building. If specific load data are not available, ‘*Specific load*’ column must be filled with zeros and the data available must be located in ‘*Other loads*’ column.

The worksheet 2, called ‘**Ta**’, should contain hourly annual temperature data. If temperature data inside the batteries room is not available, air temperature data will be enough.

Unlike worksheet 1, worksheet 2 only supports annual hourly data, i.e. the number of data for column **Ta** will always be 8760.

	A	B	C	D
1	Ta (Air temperature) Annual hourly data			
2	9,7			
3	9,7			
4	9,5			
5	9,2			
6	8,8			
7	8,3			
8	7			
9	7,3			
10	7,7			
11	8			
12	9,3			
13	10,7			
14	12			
15	12,2			
16	12,5			
17	12,7			

Figure A.3: Example of excel file data, worksheet *Ta*

For more information on how PVbat works, please review [Chapter 6, Section 6.6](#).

APPENDIX 4

Scientific articles and International congresses

Hereafter, the first page of the papers published in scientific journals is attached, as well as the certificate of participation in the international congresses. In all these publications, the results obtained through the doctoral studies of the Thesis author have been presented and exposed.

Assessing the potential of PV hybrid systems to cover HVAC loads in a grid-connected residential building through intelligent control

J.C. Solano^{*}, L. Olivieri, E. Caamaño-Martín

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HIGHLIGHTS

- A grid connected PV-battery system model is proposed to supply HVAC loads.
- Two optimized control strategies for the battery energy storage system are proposed.
- Simulations are validated with actual data coming from the monitoring campaign.
- An economic assessment of the strategies, including sensitivity analysis are included.

ARTICLE INFO

Keywords:

PV hybrid
BESS
Battery control strategies
HVAC
PV-battery

ABSTRACT

This paper presents theoretical and experimental work that is being carried out in a grid-connected residential building demonstrator available at the *Instituto de Energía Solar* (IES) of the *Universidad Politécnica de Madrid* (UPM) in Madrid, Spain. The house is provided with a building-integrated photovoltaic (PV) system coupled to a battery energy storage system (BESS), and a heating, ventilation, and air-conditioning system (HVAC) based on two air-to-air direct expansion reversible heat pumps. Thermal loads, HVAC consumption, and PV generation are simulated using different dynamic models, and they are validated with actual data derived from monitoring the experimental campaign. A model of intelligent control of BESS is proposed, which aims to supply the selected application (HVAC load) with two control strategies: increasing PV self-consumption and grid-peak shaving. This model has been validated with experimental data (error < 10%). Furthermore, the study includes aging and degradation effects on the batteries to make allowance for realistic lifetime assessment. The results of the case study show that in a building without a BESS, the self-consumption rate is about 30%; however, with the implementation of the proposed control, it could achieve approximately 50%, depending on the BESS capacity and the PV generator nominal power. Likewise, by using a combination of both strategies, it is possible to reduce both contracted power and energy consumption (77% and 49% respectively for case study).

1. Introduction

Heating, Ventilations, and Air Conditioning systems (HVAC) represent between 40% and 60% of energy demand for buildings in Europe [1], and are also of increasing importance for buildings worldwide [2]. Despite the importance of thermal systems in the energy balance of buildings, existing research indicates that specific strategies for combining local photovoltaic (PV) generation with electricity-powered air conditioning equipment (especially reversible heat pumps) are still under examination [3–5].

In fact, the IEA Solar Heating and Cooling Programme has shown interest in these kinds of systems, particularly within its Task 53 [6]. Its main objective is to analyse the use of solar driven systems for cooling

and heating, including PV driven systems, from both technical and economic points of view.

In a previous study by the authors [7], it was shown that annual billing for HVAC demand in commercial buildings could be reduced by up to 50% using PV solely without storage systems, primarily because thermal loads match reasonably well with PV energy production. In contrast, most of the HVAC consumption in the residential sector is time-shifted with respect to the PV generation. Therefore, the addition of a Battery Energy Storage System (BESS) is required in order to decouple generation and consumption, increasing the self-consumption rate.

Many studies simulating PV systems coupled to HVAC equipment have been published [8–12], demonstrating the interest of using PV

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Article

Energy Refurbishment of an Office Building with Hybrid Photovoltaic System and Demand-Side Management

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Abstract: On-site photovoltaic (PV) and battery systems intend to improve buildings energy performance, however battery costs and monetary incentives are a major drawback for the introduction of these technologies into the electricity grids. This paper proposes an energy refurbishment of an office building based on multi-objective simulations. An innovative demand-side management approach is analyzed through the PV and battery control with the purpose of reducing grid power peaks and grid imported energy, as well as improving the project economy. Optimization results of load matching and grid interaction parameters, complemented with an economic analysis, are investigated in different scenarios. By means of battery use, the equivalent use of the grid connection is reduced by 12%, enhancing the grid interaction potential, and 10% of load matching rates can be increased. Project improvements indicate the grid connection capacity can be reduced by 13% and significant savings of up to 48% are achieved on yearly bills. The economy demonstrates the grid parity is only achieved for battery costs below 100 €/kWh and the payback period is large: 28 years. In the case with only PV system, the grid parity achieves better outcomes and the payback time is reduced by a half, making this a more attractive option.

Keywords: energy refurbishment; hybrid photovoltaic system; load matching; cost analysis

1. Introduction

Office buildings are one of the most energy consuming building types [1] and consequently are in need of energy refurbishment actions. In 2014, a total of 226 TWh of electricity was consumed in Spain, where office buildings consumed about 10% [1]. In a typical office building, artificial lighting and Heating, Ventilation and Air Conditioning (HVAC) systems are considered as major contributors to the building's energy consumption, making these loads the best targets for energy savings [2]. Office buildings have the advantage that the electrical demand occurs mainly during the day so that load supply can also be performed by on-site photovoltaic (PV) solar system. Moreover, hybrid renewable energy systems can combine several technologies, such as photovoltaics, thermal photovoltaic, wind turbine and electrical storage [3]. Photovoltaics is one of the most promising renewable energy technologies because it provides electricity locally, is free of greenhouse gas emissions and pollution during operation and can be widely applied in the urban context. As PV generation is an intermittent power source, Demand-Side Management (DSM) with electrical storage becomes increasingly challenging. The added value of power and energy services that can be provided by PV hybrid systems combined with intelligent management strategies is an interesting topic,

Energy performance evaluation of a net plus-energy residential building with grid-connected photovoltaic system in Brazil

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Load matching and grid interaction (LMGI)

ABSTRACT

The proposition of Net Plus-energy Buildings (NPEB) leads to the need to carry out studies of load matching in contrast with the grid impacts of distributed generation (DG). This paper performs simulations with the EnergyPlus software tool concerning a NPEB operating in four Brazilian metropolitan areas. The analyses include photovoltaic (PV) performance parameters and Load Matching and Grid Interaction indicators (LMGI). New grid impact indicators are defined in order to study the impacts of DG in the power grid. In the second stage, the work investigates economic aspects under net metering supporting. Results show the annual amount of electrical demand covered by PV varies from 29 to 51% with more potential in situations with higher PV production and higher cooling load, and the annual PV electricity that supplies the loads varies from 24 to 36% according to the seasonal variations of PV-load correlation. The levels of exported electricity into the grid are high in Brazil with annual mean power peaks surrounding 0.7 but can surpass 0.8 in the sunniest periods. The economy demonstrates the building achieves grid parity from 6 to 18% discount rates and the payback time is given for different scenarios of investment costs, discount rates and electricity tariffs.

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1. Introduction

In recent years, building designs are undergoing major changes with energy efficient use and strategic electricity supply through passive design studies and thermo-energetic simulations. These buildings must be sustainable, reasonably priced for construction and maintenance, and with high life cycle [1]. In this context, Photovoltaics (PV) is one of the most promising renewable energy in achieving sustainable building design [2] because it is the only electricity generation technology that can be widely integrated in the urban environment. The life-cycle greenhouse gas emissions per GWh is far lower than conventional fossil-fuel-based electricity generation technologies because PV does not require any fuel to operate [3], even as during operation, photovoltaics have zero emissions of CO₂ and pollution.

Net Plus-energy buildings are typically characterized by low energy consumption through passive energy design strategies. In general, in single-family residential buildings, electricity demand can be met on an annual basis, from a roof-mounted PV

generator. As the amount of electricity produced by a PV system in a residential building is constrained by the size of the roof, it is also advisable to reduce electricity demand. This minimizes the requirement for power generation and the required area for PV modules [4]. The net-plus balance means that the annual electrical energy surplus fed-in to the grid is greater than the annual electrical energy imported from the grid [4]. The main advantage of the NPEB is that it produces more electricity than it consumes in annual terms, so that the PV electricity surplus is used to supply nearby buildings and infrastructure (public lighting, etc.), contributing to a sustainable distributed power generation in urban areas. Many interesting examples of PV integration in residential buildings can be found in the Solar Decathlon (SDE) international competition [5].

In general, the combination of high residential tariffs with high solar radiation availability suggests that PV electricity can reach economic feasibility for grid-connected roof top installations [6]. In this respect, a building with a PV system achieves grid parity when PV electricity costs are equal to retail electricity price (considering revenues, savings, cost, taxes and depreciation). However, the ways to reach grid parity are not straightforward due to the influence of many non-technical and uncontrollable factors (i.e. investment costs, loan discount rate), which means that, in practical terms, political support and financial incentives are still needed [7–9]. In countries where feed-in tariffs (FiT) are applicable, the PV

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HVAC systems using PV technology: Economic feasibility analysis in commercial buildings of Ecuador

J. Solano, *Member, IEEE*, L. Olivieri and E. Caamaño

Abstract— In this paper, the electricity demand for heating, ventilation, and air conditioning (HVAC) systems of an office building located in two Ecuadorian cities (Quito and Guayaquil) has been analyzed. To perform the analysis, two scenarios have been considered: in the first, energy required for HVAC is entirely supplied from the grid; in the second, the thermal equipment are coupled to a grid connected photovoltaic (PV) system installed on the building roof. The PV system has been supposed to be connected in self consumption configuration and has been sized to cover the electricity demand for HVAC. Results show that the PV system could provide annual billing savings ranging between 54% and 58% depending on the building orientation. Moreover, the profitability of the investment and the solar electricity cost have been analyzed under different scenarios. The conclusions show that the facility has a payback time between 10 and 30 years, while the levelized cost of electricity ranges between 4 and 24 cents/kWh.

Keywords— self consumption, heat pump, HVAC, PV system, cost saving.

I. INTRODUCCION

LOS SISTEMAS de climatización o *Heating, Ventilation and Air-Conditioning* (HVAC), son utilizados a nivel mundial tanto en edificios comerciales, como residenciales para el acondicionamiento ambiental. En particular, estos sistemas representan entre 40% y 60% del total de la demanda de edificios en Europa [1], más del 50% en Estados Unidos [2], y en regiones subtropicales de Asia alrededor del 35% [3]. Simulaciones realizadas en este artículo, indican que, en ciudades de la sierra ecuatoriana como Quito, la energía requerida para climatizar un edificio es aproximadamente el 20% del total del consumo eléctrico, y en ciudades costeras como Guayaquil, estos sistemas representan alrededor del 45%.

La energía necesaria para climatizar los edificios se puede suministrar utilizando distintas tecnologías que emplean el recurso solar como fuente de energía primaria renovable. Diversos estudios se han realizado para determinar cuál solución es más rentable técnica y económicamente. En [4] se comparó la rentabilidad económica de dos sistemas de climatización basados en energía solar: uno eléctrico (de compresión) alimentado por un sistema fotovoltaico y otro térmico (de absorción) alimentado por un sistema solar térmico, los resultados mostraron que, utilizando el sistema

fotovoltaico se puede lograr un ahorro de hasta el 50% en términos de energía primaria, mientras que el ahorro proporcionado por el sistema térmico presenta un máximo del 37%.

La disminución de precios de los módulos fotovoltaicos, un 85% en los últimos 7 años [5], unida al incremento de precios de la electricidad, han modificado sustancialmente la rentabilidad de esta tecnología y, por tanto, su uso en aplicaciones hasta ahora poco consideradas como es la climatización en edificios. Sin embargo, una revisión de las investigaciones realizadas en el ámbito de control de los equipos de acondicionamiento alimentados por energía eléctrica (en particular las bombas de calor reversibles) permite concluir que aún no han sido propuestas estrategias específicas destinadas a la combinación de dichos equipos con la generación local de origen fotovoltaico [6]. En este sentido, y con el objetivo de minimizar la demanda energética del edificio, la combinación de bombas de calor alimentadas directamente con sistemas fotovoltaicos, presenta un gran potencial en el diseño de edificios eficientes energéticamente.

En el presente trabajo, se ha realizado una simulación en régimen dinámico del comportamiento térmico de un edificio comercial situado en dos ciudades ecuatorianas: Quito y Guayaquil (representativas de la sierra y de la costa respectivamente) determinando la demanda eléctrica requerida para la climatización del inmueble con bombas de calor. Además, se ha calculado la potencia horaria que un generador fotovoltaico instalado en la cubierta puede entregar a lo largo de un año. Con los datos horarios de consumo, de generación fotovoltaica, y las tarifas horarias de la electricidad vigentes, se han calculado los gastos para climatizar el edificio en dos escenarios: en el primero, toda la energía requerida para garantizar las condiciones de confort se suministra desde la red de distribución, mientras que, en el segundo, el sistema de climatización está acoplado al generador fotovoltaico y conectado en modalidad de autoconsumo.

En base a lo señalado anteriormente, en este artículo se trata de responder a las siguientes preguntas:

- La energía generada por un sistema fotovoltaico instalado en un edificio comercial, ¿podría cubrir la demanda eléctrica necesaria para climatización?
- ¿Se tendría un ahorro significativo en la facturación anual, al utilizar la energía del generador fotovoltaico para climatizar el edificio, en lugar de utilizar la energía proveniente de la red de distribución?
- ¿En qué condiciones sería rentable la inversión económica a realizar en la instalación fotovoltaica?

El presente trabajo está organizado en las siguientes

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Munich, 27/06/2016

Confirmation of Attendance

We hereby confirm that

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has participated in the 32nd European Photovoltaic Solar Energy Conference and Exhibition taking place from 20/06/2016 to 24/06/2016 in Munich, Germany. His/her below mentioned scientific work has been presented in the frame of the conference.

Session	Title
6AV.4.31.	Evaluation of Load Matching and Grid Interaction Parameters of a Net Plus-Energy House in Brazil with a Hybrid Grid-Connected Photovoltaic System and Demand-Side Management
6CO.12.4.	Assessing the Potential of Hybrid PV-Battery Systems to Cover HVAC Loads under Southern European Climate Conditions

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Appendices

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Por su participación como ponente en la VIII Conferencia Internacional
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Con el trabajo titulado: CLIMATIZACIÓN EFICIENTE MEDIANTE TECNOLOGÍA

SOLAR FOTOVOLTAICA: ANÁLISIS DE VIABILIDAD ECONÓMICA EN
EDIFICIOS COMERCIALES DEL ECUADOR

Dado en La Habana a los 28 días del mes de mayo de 2015

Tania Carbonell Morales
Dra. Tania Carbonell Morales
Presidenta Comité Organizador

Fundación
de la Energía
de la
Comunidad
de Madrid

LA FUNDACIÓN DE LA ENERGÍA DE LA COMUNIDAD DE MADRID

CERTIFICA:

Que, **D. Juan Carlos Solano Jiménez**, con NIF. [REDACTED] perteneciente a la **INSTITUTO DE ENERGÍA SOLAR - UPM** ha asistido al **XIII Congreso Ibero-Americano de Climatización y Refrigeración - CIAR 2015**, organizado por la Dirección General de Industria, Energía y Minas, ATECYR y la Fundación de la Energía de la Comunidad de Madrid, celebrado en el Complejo Duques de Pastrana, ubicado en Paseo de La Habana, 208 de Madrid, los días 28, 29 y 30 de abril de 2015.

Asimismo, que ha participado en la Sesión de Pósters del citado Congreso celebrada el día 30 de abril, con el trabajo titulado **"Climatización eficiente mediante bombas de calor y tecnología solar fotovoltaica: análisis de viabilidad en edificios comerciales en España"** - Autores: **Juan Carlos Solano, Lorenzo Olivieri, Estefanía Caamaño Martín, Miguel Ángel Egido Aguilera**. Instituto de Energía Solar - Universidad Politécnica de Madrid; Av. Complutense 30; 28040 Madrid.

Y para que conste, a petición del interesado, se firma en Madrid a 7 de mayo de 2015.

Dpto. Administración

Nota: Este certificado no acredita la asistencia íntegra al evento, pudiendo haber sido la misma total o parcial.

La Universidad
de la **Batería**

Universidad de la Batería 29 y 30 de
junio de 2017

CERTIFICA

La participación de D. Juan Carlos Solano,

Impartiendo la ponencia "Gestión activa de la demanda con estrategias de control en el sistema de
almacenamiento: tecnologías de Pb-Ácido Vs. Litio-ión", en el curso sobre sistemas de almacenamiento
energético electroquímico, celebrado los días 29 y 30 de junio de 2017,

Dr. Joaquín Chacón
Director General
ALBUFERA ENERGY STORAGE

Madrid a 3 de Julio de 2017

Dña. María Jesús Magro
Directora General
PONS ESCUELA DE NEGOCIOS

La Asociación Unión Española Fotovoltaica (UNEF)

CERTIFICA

Que **D. Juan Carlos Solano**, Investigador en el Instituto de Energía Solar de la Universidad Politécnica de Madrid, IES-UPM, ha participado como ponente en la Jornada técnica "Almacenamiento para autoconsumo fotovoltaico", organizada por UNEF, el día 30 de enero de 2018 en Madrid, en la sesión sobre *"Integración de los sistemas de autoconsumo con almacenamiento en la edificación"* (13:00-13:30).

Madrid, 16 de Febrero de 2018.

UNEF

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