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Off-grid PV panel supply for a 2050 LEV fleet: Technical-economical analysis of Barcelona microgrids

TREBALL FINAL DE GRAU

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ABSTRACT

Low-emission vehicles (LEVs), represent a positive factor in mitigating greenhouse gas emissions, reducing atmospheric contamination and noise pollution. As the EU and other institutions promote the transition away from fossil fuels and the benefits of renewable energy, the question arises as to whether electric vehicles could be fully charged by renewable sources. In this study we project and analyze a scenario for 2050 for the city of Barcelona, where a fleet of electric vehicles is effectively and economically charged by solar energy, generated through a system of microgrids. These microgrids would feature solar panel installations, charging units and storage through batteries.

While a solar-powered microgrid could be connected to the main electrical grid (on-grid), this study proposes an independent, autonomous off-grid model, not connected to the general grid. Users installing a solar panel system, such as on their rooftops, would receive electrical energy from it to charge their LEVs and meet other energy needs. The off-grid model separates users from volatile energy markets, with unstable prices, provoked in part by geopolitical factors. Furthermore, an extended network of photovoltaic systems prepares Barcelona to meet forecast increases in electricity demand, driven in part by the growth of electric vehicle options.

Barcelona is an ideal site for solar-sourced electricity, with more than 2,500 hours of sunlight a year. Systems of solar panels on private rooftops are conceptualized to power LEVs, while generating positive externalities. Apart from incentivizing the purchase of LEVs, solar panel installations improve home energy efficiency, and with governmental incentives and technological advances are becoming increasingly accessible.

A technical-economic analysis is conducted to optimize costs based on panel cell, power capacity, location, efficiency, consumption, orientation, angle tilt and other variables. How many LEVs could Barcelona supply in 2050 with solar energy? Does the city have enough capacity to adapt to this emerging challenge? How many solar panels are necessary to carry out this task? How can solar panel efficiency be optimized? The study examines the projected reduction in CO_2 emissions. Finally, based on a budgetary analysis projected over time, the economic viability of such a system is established.

This study seeks respond to these concerns while proposing possible solutions based on different scenarios.

Key words: solar panels, electric vehicles, smart cities

RESUMEN

Los vehículos de bajas emisiones (LEV) representan un factor positivo en la reducción de gases de efecto invernadero, reduciendo la contaminación atmosférica y acústica. A medida que la UE y otras instituciones promueven la transición que reduce dependencia de los combustibles fósiles y los beneficios de las energías renovables, surge la pregunta si los vehículos eléctricos podrían cargarse completamente con fuentes renovables. En este estudio se proyecta y se analiza un escenario para el año 2050 en la ciudad de Barcelona, donde una flota de vehículos eléctricos se carga de manera efectiva y económica con energía solar, generada a través de un sistema de microrredes. Estas microrredes contarían a su vez con instalaciones de paneles solares, unidades de carga y el almacenamiento a través de baterías.

Si bien una microrred alimentada por energía solar podría conectarse a la red eléctrica principal (on-grid), este estudio propone un modelo autónomo, independiente, no conectado a la red general. Los usuarios que instalen un sistema de paneles solares, por ejemplo, en las terrazas de sus edificios, recibirán energía eléctrica para cargar sus LEV y satisfacer a otras necesidades energéticas. El modelo fuera de la red separa a los usuarios de la volatilidad de los mercados de energía, con precios inestables, provocados en parte por factores geopolíticos. Además, una red extendida de sistemas fotovoltaicos prepara a Barcelona para satisfacer los aumentos previstos en la demanda de electricidad, impulsados en parte por el crecimiento de vehículos eléctricos.

Barcelona es un lugar idóneo para la electricidad de origen solar, con más de 2.500 horas de sol al año. Los sistemas de paneles solares están conceptualizados para alimentar LEV, mientras generan algunas externalidades positivas. Además de incentivar la compra de LEV, las instalaciones de paneles solares mejoran la eficiencia energética de los hogares y, gracias a los incentivos gubernamentales y los avances tecnológicos, son cada vez más accesibles.

En este estudio se realiza un análisis técnico-económico para optimizar los costes en función de la placa solar, la capacidad de potencia, la ubicación, la eficiencia, el consumo, la orientación, el ángulo de inclinación y otras variables. ¿Cuántos LEV podría suministrar Barcelona en 2050 con energía solar? ¿Tiene la ciudad la capacidad suficiente para adaptarse a este desafío emergente? ¿Cuántos paneles solares son necesarios para llevar a cabo esta tarea? ¿Cómo se puede optimizar la eficiencia de los paneles solares? El estudio examina la reducción proyectada de las emisiones de CO_2. Finalmente, a base de un análisis económico proyectado en el tiempo, se determina la viabilidad económica de tal sistema.

Este estudio busca responder a estas cuestiones al tiempo que propone posibles soluciones basadas en diferentes escenarios.

Palabras clave: paneles solares, vehículos eléctricos, ciudades inteligentes

RESUM

Els vehicles de baixes emissions (LEV) representen un factor positiu en la reducció de gasos d'efecte d'hivernacle, reduint la contaminació atmosfèrica i acústica. A mesura que la UE i altres institucions promouen la transició que redueix la dependència dels combustibles fòssils i els beneficis de les energies renovables, sorgeix la pregunta si els vehicles elèctrics es podrien carregar completament amb fonts renovables. En aquest estudi es projecta i s'analitza un escenari per a l'any 2050 a la ciutat de Barcelona, on una flota de vehicles elèctrics es carrega de manera efectiva i econòmica amb energia solar, generada mitjançant un sistema de microxarxes. Aquestes microxarxes comptarien alhora amb instal·lacions de panells solars, unitats de càrrega i l'emmagatzematge a través de bateries.

Si bé una microxarxa alimentada per energia solar podria connectar-se a la xarxa elèctrica principal (on-grid), aquest estudi proposa un model autònom, independent, no connectat a la xarxa general. Els usuaris que instal·lin un sistema de panells solars, per exemple, a les terrasses dels seus edificis, rebran energia elèctrica per carregar els seus LEV i satisfer altres necessitats energètiques. El model fora de la xarxa separa els usuaris de la volatilitat dels mercats d'energia, amb preus inestables, provocats en part per factors geopolítics. A més, una xarxa estesa de sistemes fotovoltaics prepara Barcelona per satisfer els augments previstos a la demanda d'electricitat, impulsats en part pel creixement de vehicles elèctrics.

Barcelona és un lloc idoni per a l'electricitat d'origen solar, amb més de 2.500 hores de llum solar a l'any. Els sistemes de panells solars estan conceptualitzats per alimentar LEV, mentre generen algunes externalitats positives. A més d'incentivar la compra de LEV, les instal·lacions de panells solars milloren l'eficiència energètica de les llars i, gràcies als incentius governamentals i els avenços tecnològics, són cada cop més accessibles.

En aquest estudi es fa una anàlisi tècnic-econòmica per optimitzar els costos en funció de la placa solar, la capacitat de potència, la ubicació, l'eficiència, el consum, l'orientació, l'angle d'inclinació i altres variables. Quants LEV podria subministrar Barcelona l'any 2050 amb energia solar? La ciutat té la capacitat suficient per adaptar-se a aquest desafiament emergent? Quants panells solars són necessaris per dur a terme aquesta tasca? Com podríem optimitzar l'eficiència dels panells solars? L'estudi examina la reducció projectada de les emissions de CO_2. Finalment, a base d'una anàlisi econòmica projectada en el temps, es determina la viabilitat econòmica del sistema.

Aquest estudi busca respondre aquestes qüestions alhora que proposa possibles solucions basades en escenaris diferents.

Paraules clau: panells solars, vehicles elèctrics, ciutats intel·ligents

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LIST OF ABBREVIATIONS

a-Si	amorphous silicon
AC	alternating current
BCN	Barcelona
BEV	battery electric vehicle
BH_2O_2	boron dioxide
BIM	Building Information Modelling
CC	Codi Civil
CO_2	carbon dioxide
CO2eq	carbon dioxide equivalent
DC	direct current
DER	distributed energy resources
DHI	Diffuse Horizontal Irradiance
DIF	Diffuse Horizontal Irradiance
DLID	Direct Light-Induced Degradation
DNI	Direct Normal Irradiance
EEA	European Environment Agency
EU	European Union
EV	electric vehicle
EVA	ethyl vinyl acetate
FF	fill factor
GDP	Gross Domestic Product
GHG	greenhouse gas emissions
GHI	Global Horizontal Irradiance
GSA	Global Solar Atlas
HV	hybrid vehicle
Hz	hertz
IAE	Impuesto de actividades económicas
IBI	Impuesto de Bienes Inmuebles
ICIO	Impuesto sobre Construcciones, Instalaciones y Obras
IDAE	Instituto para la Diversificación y Ahorro Energético
IEE	Impuesto Especial de Electricidad
IRPF	Impuesto sobre la Renta de las Personas Físicas
IRR	Internal Rate of Return
I-V curves	current voltage characteristic curves
IVTM	Impuesto sobre vehículos de tracción mecánica
kW	kilowatt-hour
LCD	liquid crystal display
LCOE	levelized cost of energy
LeTID	Light and Elevated Temperature-Induced Degradation
LEV	low emission vehicle
LID	Light-induced degradation
MITECO	Ministry for the Ecological Transition and the Demographic Challenge
MPPT	Maximum Power Point Tracking
MTD	Memoria Técnica de Diseño
MW	megawatt
n-type	negatively charged solar cell
NG	Next Generation
NOCT	nominal operating cell temperature
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
p-type	positively charged solar cell
PHEV	Plug-In Hybrid Electric Vehicle

PID	Potential Induced Degradation
PNIEC	Plan Nacional Integrado de Energía y Clima
PPW	price per watt
PP	performance ratio
PRTR	Plan de Recuperación, Transformación y Resiliencia
PSA	Peak Sunlight Hour
PV	photovoltaic
PVGIS	Photovoltaic Geographic Information System
RAC	Registre d'Autoconsum a Catalunya
RHI	Refracted Horizontal Irradiance
REBT	Reglamento Electrotécnico para Baja Tensión
RITSIC	Registre d'Instal·lacions Tècniques de Seguretat Industrial de Catalunya
ROI	return on investment
SAV	Solar Access Value
STC	Standard Test Condition
T	tons
TOF	Tilt and Orientation Factor
TSI	total solar irradiance
UAE	United Arab Emirates
ULS	ultimate limit state
UN	United Nations
US	United States
UV	Ultra Violet
UVID	Ultra Violet Induced Degradation
VAT	Value Added Tax
VSA	Vertical Shadow Angle
V	volt
WAC	Weighted Average Cost of Capital
WHO	World Health Organization
ZBE	Zona de Baixes Emissions

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1. PREFACE

1.1 INTRODUCTION

1.1.1 Motivation

Rising energy bills, motivated by the uncertainty of the war in Ukraine and other global supply factors, has generated an outburst of reactions worldwide. After energy sanctions were enacted, Russia decreased exports towards the EU by 80%. A decrease in supply set off an electricity bill price surge of up to 30% in Spain (Fariza, 2022) [17]. Electricity is a necessary good that is becoming less affordable. The European Union is now being forced to find other methods of obtaining energy without depending on non-EU countries, in the path to becoming energy self-sufficient.

Gasoline prices have spiked since the war started and have been in a volatile state since. Gas-powered vehicles represent around 12% of global greenhouse gas emissions worldwide (Ritchie et al., 2020) [140]. Therefore, other transport alternatives have to be developed. Moreover, the EU has marked 2035 as a possible year by which only low emission vehicles (LEVs) can be sold on the market, and by 2050 no high-emissions vehicles will be able to circulate. It is probable, therefore, that low-emission vehicles powered by electricity will become more popular in the future. If this occurs, society will be met by an influx of electricity demand that could generate deficits if supply were not to be met.

Implementation of renewable energy sources is on a constant growth curve, due to their economic and environmental implications. Climate change concerns, coupled with high oil prices and peak oil, alongside the mitigating factor of increasing governmental support, are together driving a rise in renewable energy legislation, incentives and commercialization.

I am motivated to pursue this project to seek possible solutions to high electricity prices and the negative effects of fossil fuels, such as gasoline, while facilitating the reduction of CO_2 emissions. This project studies the possibility of installing private PV panel systems that capture energy from a never-ending source, the sun. This energy can then be used to power LEVs. The model I have opted to study is off-grid, where PV panel systems are not connected to the general electrical grid. By implementing PV panels in an urban context to run LEVs, many of the major issues cited here could be addressed.

This final degree project responds to my interests in exploring the nexus of energy infrastructure, renewable sources and urban transport from the perspective of civil engineering. Since I have a penchant for economics, I sought to include economical aspects in the final degree project, as it is one of the fields that I might be interested in pursuing in the future.

Finally, I am also motivated to conduct this project to learn more about renewable energies overall. I believe it is a major industry that has direct implications for civil engineers, which will affect us in the coming century. I believe we are still in the early stages of this transition. As a future engineer, it is paramount to be prepared for possible changes in how renewable energies might alter the world. Before starting this project, I knew little about solar panel systems; hopefully this will have changed with the project's completion.

1.1.2 Scope of the Study

High energy costs caused by global uncertainties are making energy less available worldwide; gasoline prices are in a volatile state while CO_2 emissions are jeopardizing the planet. If LEVs took a more dominant role in the vehicle market, how would society supply enough energy to power an electrical fleet by 2050? This project seeks to give plausible solutions to these problems.

Solar power energy generation is underrepresented in Barcelona, accounting for a small percentage of energy obtained. However, Spain has ideal conditions to obtain solar energy due a high amount of sunlight hours and solar irradiation conditions. Solar panels have existed for many decades now, but solar energy is still in development phase. Solar panels have improved their characteristics but it is still a technology being developed.

The project analyzes why going solar is a viable option as opposed to other alternatives. It also accounts for other positive externalities, such as economic, environmental and availability in the world. Solar power is considered a leading option due to its constant and never-ending flux of energy.[1]

A decentralized model of capturing energy is proposed in order to reach levels of self-sufficiency. As seen repeatedly, over-reliance on the existing power grid as well as the limitations of an aging infrastructure pose a significant threat to energy supply (Grid Systems, n.d.) [2]. Off-grid microgrids are able to mitigate grid disturbances and integrate renewable energy sources for each community.

A model is proposed whereby each city building installs the solar panels necessary to supply energy to the system. Individual city housing or commercial blocks are controlled via microgrids. A microgrid is a small-scale version of the national grid. It includes renewable power generation, distribution and control.

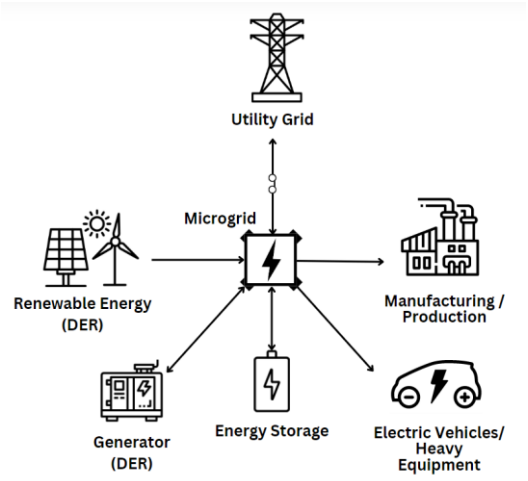

Figure 1: *Microgrid system representation. Steps towards Smart City communities* (Ingle, 2023) [12]

[1] Solar energy will be available for as long as the sun shines, which is estimated to be for 5 billion years.

A microgrid is a small network of electricity with a local source of power that is able to work independently. A microgrid can often be attached to a central grid (on-grid model). It is a smaller version of a larger grid, but it is smarter, cleaner and more efficient. It allows to tailor specific needs to each community.

Microgrids also include energy storage that enables to work under adverse conditions. For example, battery storage makes it possible to store excess power generated during times of high generation and use the surplus power when in times of low energy production. This is done by installing high quality panels and batteries in a central location, also called a "hub".

An estimation of solar panels is calculated to supply a potential LEV fleet by the year 2050. Since it is hard to estimate the necessary energy of a building block microgrid, the study is done for each household individually.

The project considers systems of 8 panels. The systems connected in series are of 8 panels, because they can supply enough energy for a single average LEV throughout the year.

A technical-economic analysis is carried out aided by an Excel sheet. The Excel sheet serves as a data base where certain variables can be changed based on personalized conditions. The Excel sheet allows to make different hypotheses and analyze scenarios based on the variables chosen. A micro and macro-scale analysis is carried out to see if it this target is possible in Barcelona by 2050. The project will consider a standard case, resembling the most typical conditions. Further hypotheses can be made to estimate individual case scenarios.

Output can change based on panel characteristics, such as cell type, power output or dimensions of the panel. Other aspects affect the economical side, such as aesthetics or even the weight of the panels, which can affect the rooftop configuration.

Further analysis is done based on panel efficiency and performance. It is essential to ensure the panel is in optimal conditions to produce maximum energy. Temperature effects, heat conditions, annual degradation, shading, angle tilt and panel direction all have direct effect on panel output potential. For example, high temperatures are actually counterproductive for the PV panel, but more energy is produced in summer due to having higher solar irradiation and sunlight hours. Solar panels are affected by a reduction of efficiency when objects intervene with sunlight rays. To optimize panel disposition, several applications are used to select the best tilt and direction. Several options are available for each case.

Based on the available area in the city from rooftop terraces, inside city blocks or public facilities, an estimation of necessary solar panels is calculated. Moreover, an estimated number of gigawatts able to be produced is done considering an average day in Barcelona (average solar irradiation and panel performance).

The project will refer to LEV, which includes different categories of electricized vehicles, including Electrical vehicles (EV), Battery Electric Vehicles (BEVs), Plug-In Hybrid Electric Vehicles (PHEVs) or Hybrid Electric Vehicles (HEVs). The project considers a standard LEV consumption rate, using data from the US Department of Transportation (Vehicle Types, 2023) [5] and industry sources. Moreover, when the project refers to vehicles, it mainly includes four-wheel cars. It does not consider other types of transport such as motorcycles, which represent a high number of vehicles in Barcelona. The Excel sheet allows to include these nuances but the project studies a general case.

Given it is not possible to know how many vehicles Barcelona will have by 2050, three hypotheses are posed that define possible scenarios: a case where vehicle rate is constant, another where vehicles decrease by one third by 2050, and a third with an increase of 10%. Given the number

of vehicles, their required energy, and the possible production, an estimation of vehicle fleet is established.

An economic analysis is done by considering the investment cost, the operation cost of maintaining a PV panel system and accounting for many incentives set out by the government. The investment cost is done by selecting the components of a PV panel system and assembling them together independently. A hypothesis on whether a PV panel system is economically viable is done by taking into account government incentives. Economic variables are obtained that help decide if it would be a worthwhile investment. The analysis is carried out over a 25-year period, which resembles a typical lifespan of a solar panel.

Next, a comparison of transitioning towards a LEV or a fuel vehicle is done over a 25-year period. Considering two cars are purchased during this period, what would their costs be? Car price is a major concern: if society wants to transition towards LEV, is it compensated by other costs such as a reduction of gasoline expenses or maintenance costs? Is it more effective if coupled with a solar panel system?

Converting to PV panel system generation could potentially generate economic benefit, and also has positive environmental implications. Transitioning towards a LEV fleet by 2050, as opposed to fuel vehicles, would enable drastic reductions in emissions. A case is studied for the city of Barcelona, also accounting for the monetary value of CO_2.

1.1.3 Renewable Energies Debate: Why Go Solar?

In 2020, the International Energy Agency declared that "Solar is the new king of the electricity markets" (World Energy, 2020, 34) [195].

Currently, 1.65% of worldwide energy is obtained from solar power. Meanwhile, solar energy is set to expand globally in the coming years due to its proven potential. By the year 2030, solar power is expected to reach 10% of global power generation.[2]

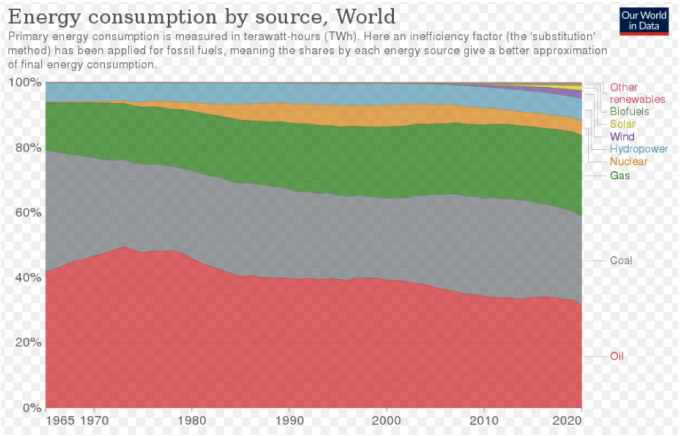

Figure 2: *Energy consumption share by source 1965-2020* (Energy Consumption, n.d.)

[2] In relation to this data, the Extremadura region in Spain recently reported that it is currently obtaining up to 25% of its total energy from solar energy (Rentero, 2022) [190].

The following is a list of positive externalities of why going solar is favorable, as opposed to promoting other energy sources:

- Economical cost

The following chart highlights the levelized cost of energy-by source. It is a measure of electricity from utility-scale solar photovoltaics. Cost was 359 $/MWh in 2009, which since then has dropped 89% to 40 $/MWh, in data from 2019.

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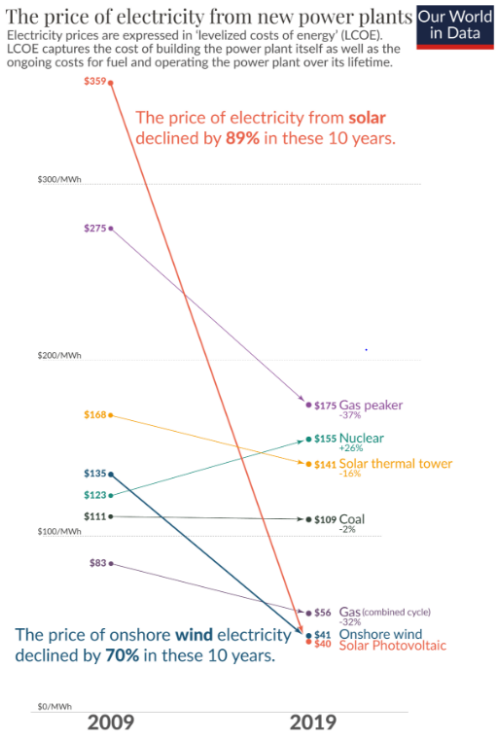


Figure 3: *Levelized cost of energy (LCOE) by energy source from 2009-2019* (Roser, 2020)

Solar panels make it possible to save on electricity bills. In turn, the amortization period of solar panel installation is reduced, given government incentives and subsidies of an economic character to assist purchase of the initial system.

- Greenhouse gas emission reduction

The quantity of greenhouse gas emissions in the atmosphere continues to increase, causing damaging consequences to the planet and its people. As a result, widespread changes are happening to marine currents, affecting atmospheric breeze, terrestrial fluctuations, rising sea levels, melting ice or the continuity of biodiversity. Accumulation of gases creates a layer around the earth that increases temperature. preventing heat from escaping from the ozone layer. Overall global temperature averages will increase 3.4ºC by the end of the century.

Unlike fossil fuels, which emit harmful byproducts like carbon dioxide, nitrogen dioxide, sulfur dioxide, mercury, and particulate dust, increased use of solar panels to produce energy will reduce the number of emissions from fossil fuels. This in turn will help alleviate the damaging effects of smog, acid rain, climate change and contaminated water sources (Brookenally, n.d.) [194].

Solar power is one of the sources with the least greenhouse gas emissions considering lifecycle emissions based on energy generated.

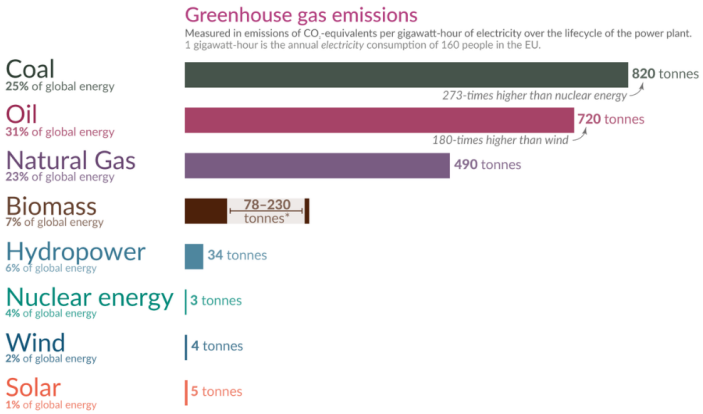


Figure 4: *Greenhouse gas emissions by energy source* (Solar Power, 2023) [31]

- Decarbonization and air quality improvements

Installing a PV system contributes to the decarbonization of energy and improvement of air quality. The air we breathe can help or hinder our wellbeing. Instead of relying on fossil fuels, solar panels provide a clean and clear alternative. A typical residential solar panel system will eliminate three to four tons of carbon emissions that would otherwise be generated each year, the equivalent of planting over 100 trees annually. It is estimated that for every PV panel system installed, a reduction of 100 T of CO_2 along the lifespan of the solar panel (Aggarwal, 2023) [34].

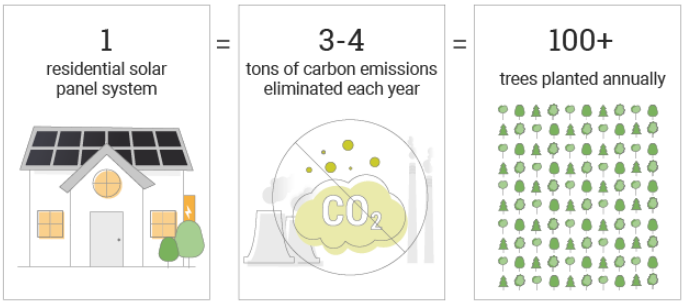


Figure 5: *Trees planted equivalent to panel system installation* (Aggarwal, 2023) [34]

- Reduction of Noise Pollution

If photovoltaic panels are installed to propel LEVs, cities will become quieter. Cities have become an epicenter of pollution acoustics, an invisible threat that affects the quality of life of citizens and wildlife. The World Health Organization (WHO) defines noise above 65 decibels as noise

pollution. To be precise, noise becomes harmful when it exceeds 75 decibels and is painful above 120 dB. Generally, noises lower than 45 dB are imperceptible and do not affect city life (Noise pollution, n.d.) [141].

Figure 6: *Noise pollution (dB) in Barcelona* (Sanchis, 2023) [39]

Effects of noise pollution are damaging for our hearing (Noise pollution, n.d.). It is especially harmful to very young and older individuals. Consequences of noise pollution include physical problems (respiratory agitation, racing pulse, high blood pressure, headaches), psychological issues (noise can cause attacks of stress, fatigue, depression, anxiety and hysteria in both humans and animals), sleep and behavioral disorders (noise above 45 dB stops you from falling asleep or sleeping properly) and memory and concentration. Noise may affect people's ability to focus, which can lead to low performance over time. It is also negative for the memory, making it hard to study.

Traffic noise accounts for the most prevalent noise in cities. For example, a car horn produces up to 90 dB. Fuel vehicles generate 80 dB and motorcycles can produce up to 100 dB. Since LEVs generate around 50 dB, transitioning to LEV will allow cities to reduce noise pollution. LEVs are quieter because they do not have noise-producing combustion engines. It should be noted here that a LEV should emit at least 40 dB, so that pedestrians can hear the vehicle for their own safety.

Usually, creating electricity generates noise. However, solar panels go audibly unnoticed, without creating noise pollution. Unlike other renewable energy sources, PV panels are completely silent.

- Safety concerns

Solar energy is a safe and reliable way of obtaining energy without provoking deaths from accidents or air pollution.

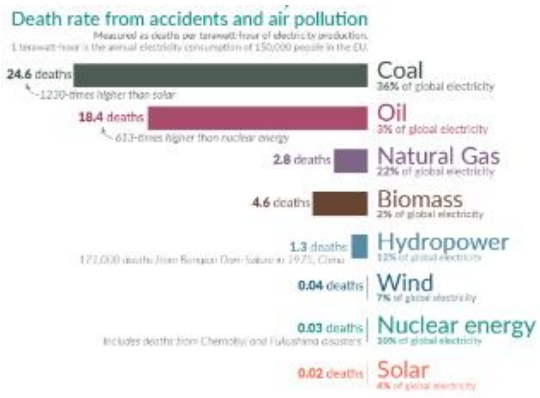


Figure 7: *Weighted death rate from accidents and air pollution by energy source* (Roser, 2020)

- Employment Creation

PV installations favor new business models, encouraging job creation. Jobs represent a tangible benefit that gives people a stake in this transformation, and therefore employment creation promises to raise its political acceptance, according to a report by the International Renewable Energy Agency (IRENA, 2022a) [28]. In 2020, there were 58,892 new jobs related to the photovoltaic sector created in Spain, according to the "Informe Annual UNEF 2022" (Empleo en el sector, 2022) [26]. It is estimated that 90,742 direct jobs were created in the country in 2021. This shows a clear, upward-moving trend.

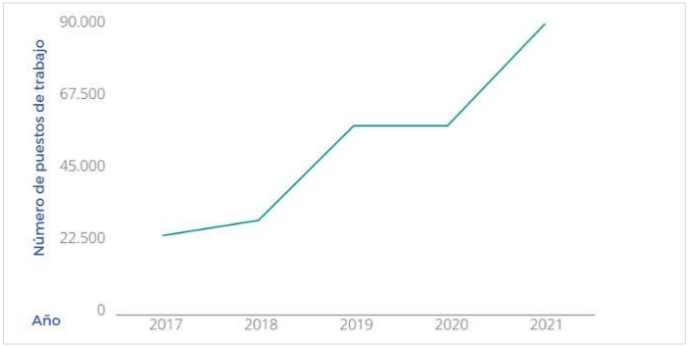


Figure 8: *Evolution of jobs created in Spain due to solar energy sector between 2017 and 2021* (Empleo en el sector, 2022) [26]

It is estimated that a total accumulated sum of 468,000 direct jobs will be created in the upcoming decade in Spain. This account for direct jobs related to fabrication, transportation, installation and maintenance, as well as indirect jobs such as material fabrication. It should be noted that solar sector jobs employ 40% of women, the highest percentage of any renewable energy sector.

The PNIEC will generate more than 250,000 new jobs and increase the GDP in Spain by 1.8% (between 16.5 billion and 25.7 billion euros), by 2030 (De las Heras, 2020) [84].

- Improve home efficiency

Solar panels add value to housing and other built facilities, socially and economically. The reason why PV installation increases home value is because the energy consumption is cheaper over the longer term. Moreover, by installing PV energy supply, a privately held property will have better environmental certifications and thus, make it more attractive on the market.

Homes with solar panels are on average 4% more expensive. It is important to note that PV lifespan is about 25 years, so the older they are the less valuable they will be to potential new customers. Homes with PV installations are also sold quicker (on average 14% faster) than homes without PV installations. More than 80% of potential buyers consider energy efficiency an important component when making a purchase (Revalorización de las viviendas, n.d.) [35]

Another economic incentive is that by installing PV systems, charging LEV will become more accessible. This makes having LEV plug-in chargers more common, thus lowering charger price.

Energy efficiency is a classification of 7 categories (from A to G). Higher categories A, B and C mean the building is more energy efficient. Depending on PV efficiency, the system will improve its classification (Certificado energético, 2023) [53].

Figure 9: *Energy efficiency classification* (Certificado energético, 2023) [53]

- Public acceptance

Public support for solar panels is highest among all energy generation procedures. Across Europe, 86% of people questioned say they would support solar project near where they live. A majority of people in Spain (84%) say they would support requiring all new building to have installed solar panels, according to the European Climate Foundation (Europeans support, 2021) [176].

- Availability

Solar energy is available on every spot of the globe, being one of the most available and sustainable energy sources on the planet. An inconvenience, however is that energy supply can sometimes be intermittent.

PV panel systems are quick to install compared to other renewable energy sources. They can be made available in remote areas with insufficient infrastructure. Moreover, they are the best option if users do not want to deal with noisy and polluting generators.

Solar panels can also provide multiservice opportunities. This project focuses on photovoltaic panels, but there are also thermal panels on the market and in implementation. Thermic panels take advantage of the thermic heat of the sun to warm water or air. They are designed to take sun irradiation and convert it into heat (Tipos de Paneles, 2023) [69]. Hybrid panels combine both systems, electrical and thermal supply, into a single panel, having a multifaceted purpose.

PV installation reduce energy dependency on other countries and helps achieve self-reliance in relation to other energy sources. Uncertainties seen in recent years, such as the Covid-19 lockdowns or the war in Ukraine, can sometimes cause energy price fluctuations. Off-grid systems that include a battery storage can be independent from the central grid, even in the case of a power outage.

1.2 A Solar Era

1.2.1 History

Nowadays, we think of solar energy as a new technology that emerged from the renewable energy boom. However, solar energy has been used and developed throughout history to be where we are now (Timeline of solar, 2023; Kutcha, 2021) [25] [116]. Solar energy was first used in 7th century BC to create fire by reflecting light rays into shiny objects. Later, in the 3rd Century BC, the Greeks and Romans harnessed solar power with mirrors to light torches for religious ceremonies or used sun power to heat homes. Long after, Leonardo da Vinci used a solar system to heat water in the 15th century.

In 1839, and just at the age of 19, French physicist Edmond Becquerel discovered the photovoltaic effect while experimenting with a cell made of metal electrodes. It was used in a conducting solution using selenium coated by a thin layer of gold. He noted that the cell produced more electricity when it was exposed to light, as it generated voltage and electric current.

In 1873, Willoughby Smith found that selenium had photoconductive properties. Photoconductivity is an electrical phenomenon by which a material becomes electrically conductive, due to the absorption of electromagnetic radiation.

The first solar panel was installed in 1884 in New York City by American inventor Charles Fritts. This solar module consisted of a wide, thin selenium wafer covered by an even thinner sheet of gold. Although energy efficiency was only around 1%, this demonstrated that obtaining energy from the sun was a possible option. Fritts reported solar panels produce a current "that is continuous, constant, and of considerable force." (Brief History, n.d.) [117]

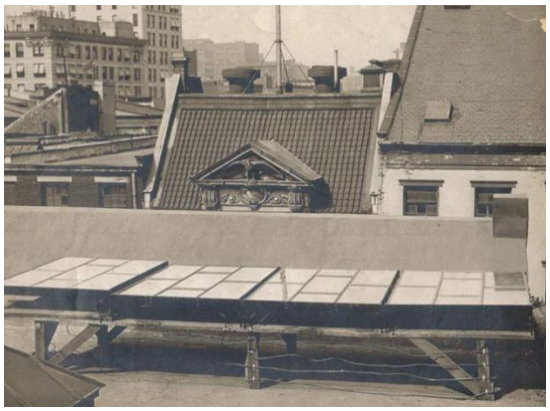


Figure 10: *Charles Fritts installed the first solar panels on New York City rooftop in 1884* (Brief History, n.d.) [117]

In 1905 Albert Einstein published "On a Heuristic Viewpoint Concerning the Production and Transformation of Light," which discovered that light could behave as a photon or particle by knocking electrons out of the atoms in certain metals. He predicted that photons above a certain energy level could eject electrons from a semiconductor material. Afterwards, Einstein earned the Nobel Physics prize in 1921 after discovering the photoelectric effect. The emergence of modern theoretical physics helps create a foundation for a greater understanding of photovoltaic energy.

In 1941, Bell Laboratories engineer Russell Ohl patented the first monocrystalline silicon solar cell. Bell Laboratories realized that semiconductors, such as silicon, were more efficient than selenium.

In 1954, PV technology was born when Daryl Chapin, Calvin Fuller and Gerald Pearson developed the first silicon monocrystalline PV cell at Bell Labs. This was the first solar cell capable of absorbing and converting enough of the sun's energy into power to run every day electrical equipment (How does solar power, n.d.) [24].

Their demonstration inspired a *The New York Times* article, which forecast that "solar cells will eventually lead to a source of limitless energy from sun". In 1961 the United Nations sponsored a conference in favor of the use of solar energy.

In the early 1960s, satellites from the American and Soviet space program were powered by solar cells. Soyuz 1 is the first manned spacecraft powered by solar cells. Although solar panels remained unaffordable for the average customer, they were being incentivized in the 1970s, in the wake of the energy crisis occurring at the time.

In 1979 solar panels arrived at the White House for installation under the Jimmy Carter administration. It was a symbolic act to promote solar panel usage.

Figure 11: *Solar panels in White House facilities, 1979* (Lila, 2017) [115]

The first batteries to store solar energy were developed in 1985, and were made from lithium-ion.

The total installed production of photovoltaic power reached 1000 MW worldwide in 1999.

Today, solar models are used in residential, commercial, and utility-scale systems in most regions across the globe. They are found in homes, cars, aircraft, and a variety of other applications.

Moving forward with a view to 2024, new technologies are being developed every year, improving efficiency. Solar panel price follows what is known as Swanson's law, named after Richard Swanson. It states that the price of solar photovoltaic modules tends to drop 20% for every doubling of cumulative shipped volume. This is the learning rate of solar modules. This means that every 10 years, the prices should drop by 75%.

Solar panels should become more affordable for a greater public as time evolves, since demand increases and supply chains improve (History of Solar, n.d.) [118], while mandatory targets are set across the EU and grants are awarded to promote PV consumption.

It is undoubtedly clear that PV systems will continue to grow as the world transitions into a renewable energy economy.

1.2.2 State-of-the-Art

1.2.2.1 State-of-the-Art: Barcelona

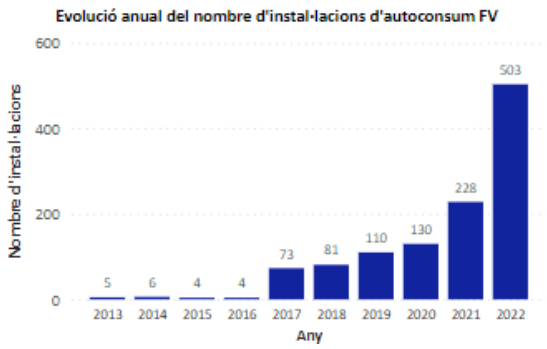
Spain is among the European countries with most hours of irradiation a year. The majority of Spain has an irradiation between 1,600 and 1,950 W/m^2, which makes the country an ideal powerhouse for solar power generation.

Further, with more than 2,500 hours of sunlight a year, Barcelona is a suitable place to install solar panels, due to its geographical location and climate.

Nevertheless, Germany has ten times more investment in solar energy; this means that Spain still has a lot of potential to invest and grow in the future. For example, it is estimated that 85% of buildings are suitable for PV systems in Barcelona (Instalación de placas solares en Barcelona, n.d.). [20]

- Private facilities

In the municipality of Barcelona, there are currently 1,144 private PV installations that have generated a total of 16.77 MW in 2022. Power installed surged after the derogation of the Spanish Sunlight Tax (the *Impuesto del Sol*), in 2018, according to the Institut Català d'Energia (Distribució per sectors, n.d.). [47]



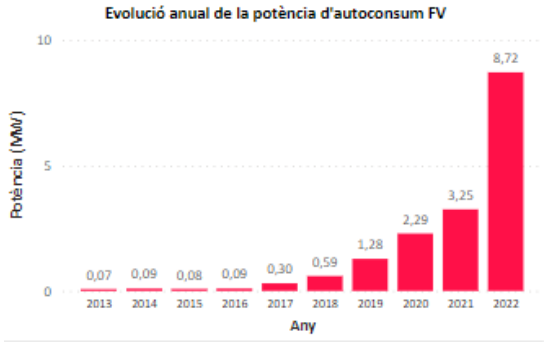


Figure 12: *Private PV installations per year in Barcelona, 2013-2022 (left).* ***Figure 13:*** *Solar energy power installed in Barcelona (right*) (Evolució de l'autoconsum, n.d.) [49]

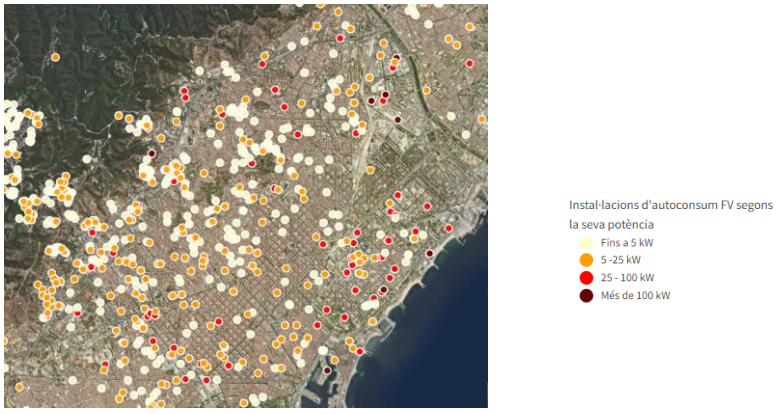


Figure 14: *Location of private PV panels in Barcelona by kW output. Data from the Institut Cartografic i Geològic de Catalunya* (Instal·lacions d'Autoconsum, 2022) [48]

- Public facilities

Barcelona's government has installed PV systems in public facilities to promote a clean energy local transition. There have been more than 100 PV systems installed in parks and city squares. There is a total of 3,658 kWp in function, which generates 4,358 MWh/year. This is enough to fully supply electrical energy to 2000 households a year.

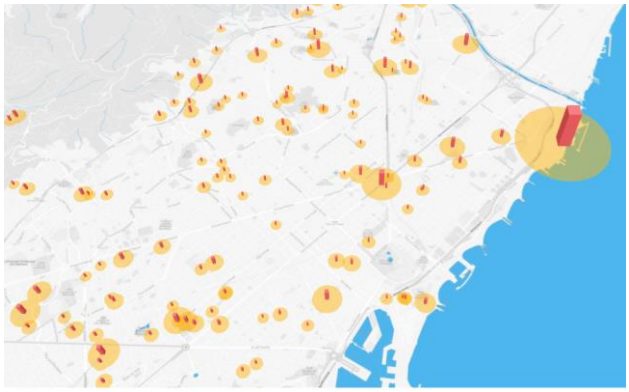


Figure 15: *Public facilities where PV systems are installed* (Mapa: quanta energia, n.d.) [11]

Solar panels can be installed in different formations, depending on rooftop conditions and inclination possibilities. Examples of PV panel systems installed in Barcelona:

Figure 16: *Private PV panels in "Delta-Wing" formation (East-West orientation)* (Rabada, 2019) [36]

Figure 17: *Private flat rooftop PV installation in Sant Martí's neighbourhood* (Guerrero, 2022) [41]

Figure 18: *Forum's PV formation at 35º inclination towards the south. It is equipped with 2,686 photovoltaic modules, covering a total area of 3,494 m² and has a nominal potential of 443 kilowatts. In 2007, the solar pergola produced almost 500,000 kilowatt hours of electricity* (Does the giant, n.d.) [144]

Figure 19: *PV panels in "Fàbrica del Sol" in a pergola. The building incorporates measures to promote sustainable energy systems* (Fàbrica del Sol, n.d.) [143]

Figure 20: *Vertical PV installation on a façade* (MacDonald, 2020) [142]

1.2.2.1 State-of-the-Art: Global Trends

On a global scale, new projects and innovative ideas are being advanced to promote solar energy.

By way of reference, three projects located in similar latitudes to Barcelona are mentioned here as examples:

- United States

The State of California passed a law in 2020 that required all new homes to have solar panels. The initiative was originally started by then-Governor Arnold Schwarzenegger in 2004. He proposed to have one million installed on roofs by 2017. Currently there are more than 1.3 million households with solar panel installations.

Las Vegas, Nevada, recently became the largest city government in America to be run entirely on renewable energy.

- Masadar, United Arab Emirates

Masadar city is a sustainable urban community in Abu Dhabi, UAE. It is an energy efficient hub that aims to prove cities can be sustainable even in desertic environments. These include projects ranging from solar photovoltaic throughout the city, battery storage, sustainable mobility, sustainable agriculture, recycling methods and the application of materials science (Masterplan, 2023) [164]

- Fujisawa, Japan

Fujisawa, located in the outskirts of Tokyo, is a large neighborhood that was created under the slogan “self-creation and self-consumption of energy”. The experimental smart city has solar panels, everywhere equipped with batteries. LEVs are abundant throughout the neighborhood. This has led to a decrease in CO_2 emissions by 70% (About Fujisawa, n.d.) [165].

Figure 21: *Masadar (left) and Fujisawa (right), cities represented using BIM* (Masterplan, 2023; About Fujisawa, n.d.) [164] [165]

1.2.3 Microgrids: The Way of the Future

In this section we detail the specific components comprising a microgrid, including their material parts and technologies, as relevant to the composition of the system.

1.2.3.1 Panel Manufacturing

- Solar PV cell

PV panels are made as a junction of adjacent vertical layers with different components, each providing a unique function. Solar panels are assembled in advance via manufacturing facilities, using automated robotic equipment and sensors to precisely position the components with extreme accuracy. It is essential that manufacturing plants are extremely clean and controlled to prevent any contamination during assembly. China accounts for 80% of the world's manufactured PV panels (How Are Solar, 2023; Svarc, 2021; Gudova, 2022; Svarc, 2020; Componentes, n.d.) [168, 169, 170, 171, 172].

1. Silica Sand

It all starts with raw material, in this case silica sand, originating from crushed quartz rock that contains large amounts of silicon dioxide (SiO_2). To purify silicon, it is heated to 1,410 ºC in an electric furnace. This achieves 99% purity, which is nonetheless not enough to be used for solar panels. Metallurgical silicon is mixed in a reactor with HCl at elevated temperatures, resulting in $SiHCl_3$ gas. The gas is then cooled and liquefied for distillation. Consequently, the next step is to purify this metallurgical silicon using the Siemens process. After, in another reactor, a mix with hydrogen gas dissolves the product, leaving approximately 99.9999% pure silicon behind.

Silicon has been used as the semiconductor material of a solar PV panel for most of the solar industry's history. Silicon (Si) presents multiple advantages. For one, silicon is recognized as having a long lifespan. Chemically and electronically, it is an easy material to optimize to produce the photovoltaic effect. Silicon is also an abundant and available product, making it worthwhile for large-scale systems, as it is the most abundant element in Earth after oxygen.

As of 2022, 95% of PV panels are made of crystalline silicon (c-Si) wafers. Only 5% of the total use experimental techniques or in-development technologies, like organic photovoltaic cells.

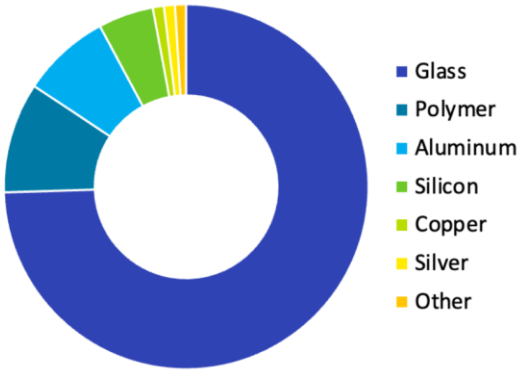


Figure 22: *Crystalline silicon by weight. Crystalline silicon is made from 76% glass, 10% plastic, 8% aluminum, 5% silicon and 1% copper, with less than 0.1% silver and other metals* (Hoffs, 2022) [73]

2. Ingots

In the process of melting, it is paramount to ensure all atoms are aligned in the desired structure and orientation. Solar manufacturers add boron to negatively charge the silicon, creating an N-type or phosphorus ions to silicon to give the solar cell a positive charge or P-type. All solar cells use a combination of N-type and P-type silicon to form a PN junction. Electrons pass between the two layers and, when struck by photons from the sunlight, are knocked free to create an electrical current. N-type cells have less impurities, higher temperature performance and lower LID. But N-type cells are more expensive to fabricate.

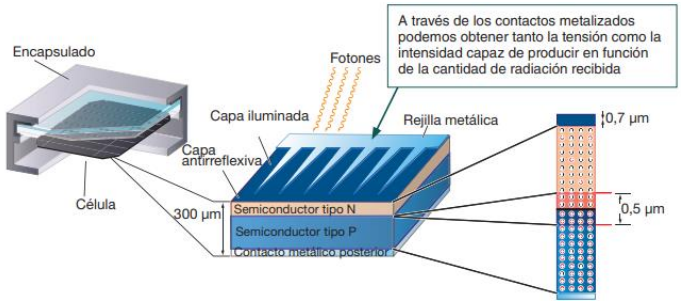


Figure 23: *P-type and N-type cell junctions layered* (Componentes, n.d.)

3.Wafers

Silicon ingots are sliced into thin disks of 1 mm, also called wafers. They are square with rounded edges. Because pure silicon is shiny, it can reflect the sunlight. To reduce the amount of sunlight lost, 35% of sunlight that hits it is reflected. An anti-reflective coating is put on the silicon wafer.

4. Producing a solar cell

Next, wafers are converted into solar cells capable of converting power into electricity. Each wafer is treated with metal conductors, giving the wafer grid-like matrix surface. The coating will facilitate the absorption of sunlight, rather than reflecting it.

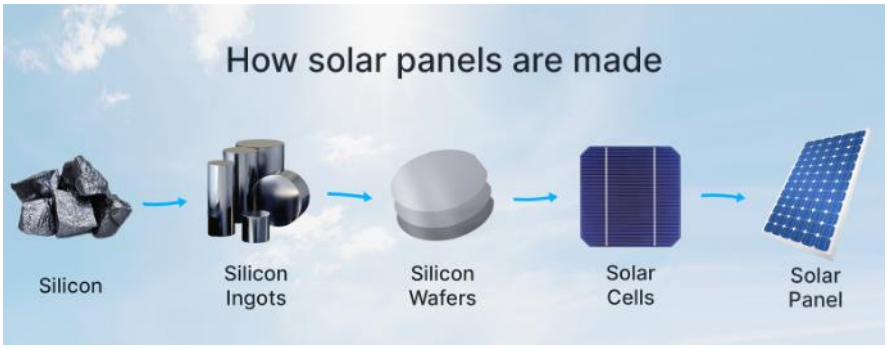


Figure 24: *Manufacturing process of a PV module* (Almerini, 2023)

- Reinforced glass

Reinforced glass sheet is usually 6-7 millimeters thick. Tempered glass is the perfect material for the job because it is much stronger and durable than regular glass, protecting it from damaging impacts. Since the silicon wafers and metal conductors are fragile, they need to be protected.

Without protection, electrical circuitry would not survive elements from the outside world. The system reinforced with tempered glass provides a protective layer that is anti-reflective, thus maximizing energy of the sun (How Do Solar Panels, n.d.) [14].

Glass can resist high pressures and heat changes. It is able to protect the solar cells from weather and airborne debris. To improve efficiency and performance it must have high transmissivity. This is achieved by having low quantities of iron content.

- Aluminum plastic frame

Solar cells are soldered together using metal connectors to link the cells. Aluminum frame plays a role by protecting the edge of the laminate section. Aluminum sections are designed to be lightweight and stiff.

It is essential that they are not corrosive nor a robust material. Solar panel metal frame is useful to protect against weather conditions and to help mount the system at the desired angle. Under the casing, the panel has insulation properties. Insulation is important because temperature overheating will lead to decreasing panel efficiency.

- Ethylene vinyl acetate (EVA) film layers

For increased longevity, PV cells are encapsulated in a plastic layer; EVA glue is used to bind everything together. This film is very durable and weather resistant, preventing moisture and dirt ingress from contaminating the cells. EVA provides a shock absorption that help protect cells from interconnected wires from vibrations.

- Polymer solar backsheet

A backsheet is made from highly durable, polymer-based material, usually Mylar or Tedlar. This prevents water, soil and other materials from entering inside. It acts as a moisture barrier, providing mechanical resistance, while also ensuring thermal stability and long-term UV resistance.

- PV junction box with diodes, cables and connectors

Wires are necessary to transfer energy to the inverter. Aluminum and copper cables are mostly used. The cables connect the solar cells and transmit the generated electricity. Subsequently, the junction box is added, to enable connections inside the module. Junction box is weatherproof as it is the central point where all cell sets are interconnected and must be protected from moisture and dirt. By-pass diodes help prevent efficiency losses in case of shade or dirt.

- Quality Control

Finally, tests are conducted to estimate the power output, efficiency, voltage, current and temperature tolerance of each panel. This is done under STC or NOCT conditions.

Visual inspections are done to detect any defects, such as cracks, scratches or blemishes on the solar cells or panel surface. Electrical tests are furthermore done to verify that they produce the expected amount of energy, and that there are no electrical connection problems.

Stability tests verify the resistance of the panel in extreme conditions, such as high temperatures or humidity changes.

Performance testing is done, verifying that the panel meets the specifications for efficiency and output power.

Finally, these panels are subjected to quality control throughout the supply chain, making sure that the materials used to manufacture the panels meet the required specifications and quality standards.

Solar panels just need packaging before they are ready to be shipped, to be made functional.

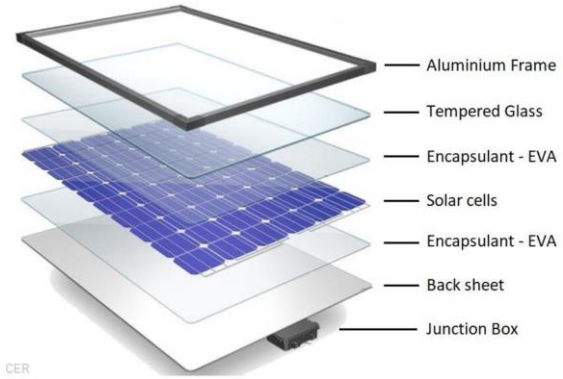


Figure 25: *Solar panel vertical layer components* (Svarc, 2020)

1.2.3.2 Photovoltaic Panel System

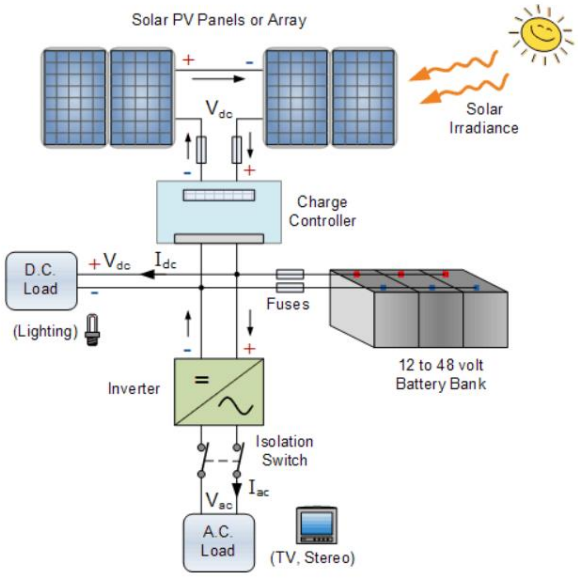


Figure 26: *Off-grid photovoltaic panel system components* (Stand Alone, n.d.). [191]

- Step 1: Sunlight

Light from the sun is made up from photons of energy. Solar panels let photons impact electrons and knock them away from the atoms. This charges the atoms and generates electrical flow. Photoelectric effect is the emission of atoms from metal when sunlight hits.

Energy from the photon is transferred to an atom of the semiconducting material in the p-n junction. When a semiconductor is exposed to light, it absorbs the light's energy and transfers it to negatively charged particles in the material called electrons. The corresponding extra energy allows electrons to flow through material in the form of electrical current. This is known as the photovoltaic effect (Stand Alone, n.d.) [191].

- Step 2: Solar Panels Arrays

A solar PV panel consists of many cells made from layers of semi-conducting material. Solar panels produce electricity from sunlight. They are made from crystal silicon slices, glass, polymer backing and aluminum framing.

Solar panels can be connected in series or in parallel. Connected in series allows a user to obtain a greater voltage output, but if just one panel reduces efficiency, the whole system is affected. Connecting panels in parallel allows a user to obtain less voltage overall, but panels work independently from each other.

- Step 3: Charge Control: DC-AC Controller

A charge controller regulates the amount of current that is fed back into the battery bank. Its main function is to prevent overcharging batteries. Charge controllers also block battery bank from leaking back into the photovoltaic array, draining the battery bank. The controller must have enough capacity to handle the total current of the system safely.

A charge controller is responsible for performance, durability and functions. Charge controllers regulate and coordinates the main components of any off-grid systems, such as the PV generator, batteries and loads. PWM (Pulse Width Modulated) is the most common type of controller, and the kind most used on smaller arrays.

- Step 4: Inverter

Inverters are used to convert direct current electricity running at 12, 24 or 48 V, generated by solar photovoltaic modules, into alternating current running at 220 or 230 V. Inverters elevate the volt battery capacity to the connected system, such that it is equivalent to 220V/50Hz.

Output capacity determines the maximum power to be installed in the system. A safety coefficient is applied as a safety factor. If amplifications of the system are decided in the future, it is necessary that the systems can sustain enough wattage power.

In case the system is frequently affected by shadows or debris accumulation, it is interesting to use a microinverter in each panel to monetize energy output individually.

Inverters are noisy apparatuses. It is recommended to install them away from daily lifestyle to avoid any inconvenience (Ojeda, 2022) [193].

- Step 5: Storage capacity: Batteries

Batteries manage to store energy for later use in the future. Batteries make it possible to draw energy for use in cases when there is no production from the panels: at night, during grid outages or during a streak of low energy production due to climate conditions.

Batteries have a cathode and an anode, which are opposite kinds of electrical terminals. Separated by an electrolyte, this facilitates electrical transference. The battery is attached to an exterior circuit. When electrons go through the circuit, ions move through the electrolyte. The ions move between the cathode and the anode and increase chemical potential energy, which results in the battery being charged. Batteries lose efficiency as they evolve and must be changed when their life cycle expires.

Batteries are a critical component of the clean energy future for one key reason: they can match variable energy supply to energy demand (Energy storage, n.d.) [33].

- Step 6: Grid system

Photovoltaic systems can be set up in off-grid or on-grid models. A comparison of both systems is done is the following table:

Grid System	Off-Grid	On-Grid
Battery	Yes	No
Bidirectional meter	No	Yes
Grid	Independent from grid	Dependent on grid
Installation Price	More expensive	Less expensive
Costs Saved	Less expensive electrical bills	More expensive electrical bills. Use energy from the grid
Compensation Tariff	No	Yes. Sell surplus to the grid
Electrical security	Supply based on climate conditions	Ensures supply year-round
Space	More space for the battery	Less space required

Table 1: *Off-grid versus on-grid comparison*

2. TECHNICAL-ECONOMICAL ANALYSIS

2.1 Characteristics

Before installing PV panels, certain characteristics have to be chosen that directly affect the cost and effectiveness of the system. This study defines a standard photovoltaic module and does the computations necessary to supply a LEV.

2.1.1 Cell Type

The two most common solar panel models are monocrystalline and polycrystalline cell types. Monocrystalline have better properties than polycrystalline solar panels, but in contrast they are more expensive.

CELL TYPE	Monocrystalline	Polycrystalline
Efficiency	15-23%	13-16%
Space-efficient	More power per square meter =>Space-efficient	Less power per square meter => Less space-efficient
Heat conditions	Performance suffers less under heat conditions	Performance suffers under heat conditions
Temperature coefficient	-0.3ºC to -0.45ºC	-0.5ºC
Lifespan	Better under heat conditions => longer lifespan 25-40 years	Less lifespan 15-35 years
Annual degradation	0.55%/year	0.7%/year
Recycling	90-95%	90-95% (easier to produce)
Low-light Conditions	Better under low-light conditions	Inferior under low-light conditions
Aesthetics	Uniform and black hue	Blueish hue with variegated pattern
Price per Watt	1-1.5 €/Watt	0.9-1 €/Watt

Table 2: *Monocrystalline versus polycrystalline solar cell comparison* (Polycrystalline, n.d.) [71]

Thin-film solar cell technology is excluded in this study, as it is a relatively new method that is still in development phase. Thin-filmed solar panels are less efficient and can degrade faster than conventional solar systems. They are less energy intensive to produce, but cheaper. A common type is amorphous silicon (a-Si).

2.1.2 Power

Domestic solar panel power production ranges from 250-450 W. It is the best amount to save in electricity bills. It is essential to do a preliminary study to not oversize or downsize the works.

The power rating of a solar panel is calculated under standard test conditions (STC). This is at a cell temperature of 25°C, an irradiance level of 1000 W/m^2 and air mass of 1.5 Air Mass.

Power output is a mathematical model that depends on the voltage [volts] and current intensity [Amperes] (Ghayad, 2022) [157]:

$$Power\ [W] = Volts\ [V] * Amperes[A]$$

For example, a 300 W panel with 23.7% losses in locations with a 230 V AC grid will produce an intensity of:

$$300\ [W] * 0.763 = 230\ [V] * Amperes[A]$$

$$Amperes[A] = 0.9952\ [A]$$

Intensity required for a 24 V battery bank:

$$300\ [W] * 0.763 = 24\ [V] * Amperes[A]$$

$$Amperes[A] = 9.537\ [A]$$

I-V curves based on solar irradiance and temperature:

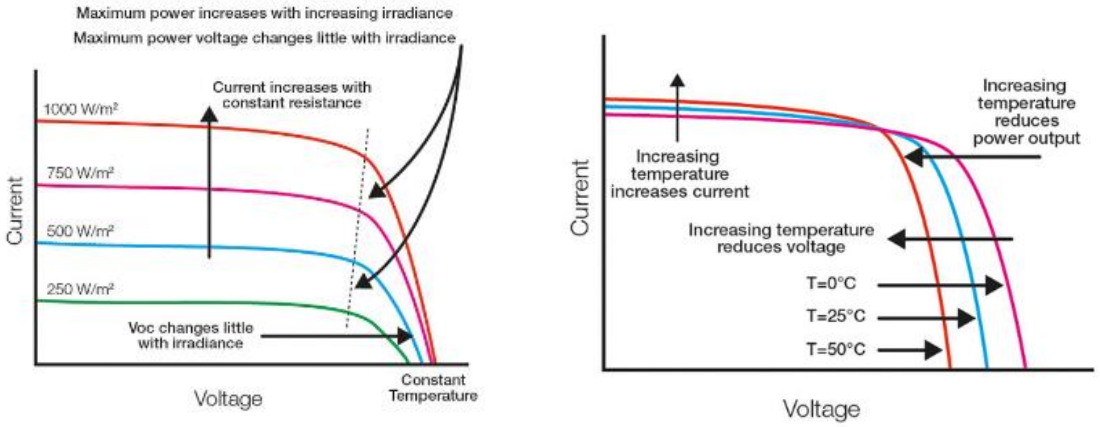


Figure 27: *I-V curve based on solar irradiance (left).* ***Figure 28:*** *I-V curve based on temperature (right)* (What is solar, 2023)

P-V curve:

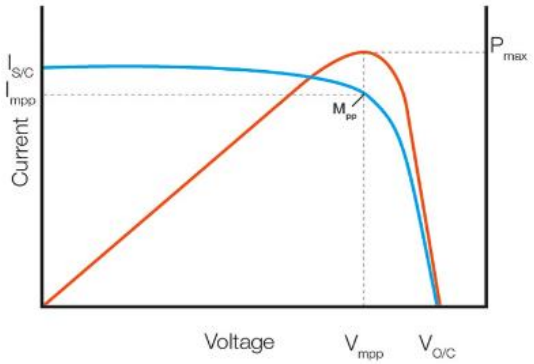


Figure 29: *P-V curves. I_{sc}: Short circuit current, V_{oc}: Open circuit current, V_{mpp}: Power at maximum, M_{pp}: Maximum power point on the I-V curve* (Ghayad, 2022) [157]

The ratio of the actual maximum obtainable power to the product of the short-circuit current I_{sc} and open circuit current voltage V_{oc} is defined as the fill factor (FF):

$$FF = \frac{Vmpp * Mpp}{Voc * Isc}$$

It is essentially a measure of the performance of a PV module. Deviations from the expected value or changes in FF indicate that a fault is present.

2.1.3 Dimensions

Solar panel dimensions are paramount to compute the energy gathered from the sun. Wattage output depends on the dimensions. As solar panels size increases, their capacity to generate electricity increases as well. Dimensions are an important aspect in Barcelona because not all rooftops have enough space to install the systems required to propel LEVs corresponding to residents or users in the corresponding building. Space must be optimized efficiently to reach maximum output (Cuánto pesa, n.d.) [75]

Panels are composed of cells, generally assembled in a module of 60 or 72 cells each. Typically, a cell is a 156 x 156 mm square. 60-cells are composed of 6x10 array cells with dimensions of 992 x 1640 millimeters or 1.626 m^2. 72-cell modules are composed of 6x12 array cells with dimensions of 992 x 1956 millimeters, or 1.94 m^2. Panel width is constant, ranging from 32 to 40 mm.

The system used in the study is composed of 8 panels of 60 cells each, so that the necessary space for one system is:

$$System\ Surface = 1.626\ [m^2] * 8\ [panels] = 13[m^2]$$

If we consider the average rooftop has 105 m^2 available space to install solar panels, a building in Barcelona can hold:

$$Systems\ per\ building = \frac{105\ [m^2]}{13[m^2]} = 8\left[\frac{systems}{building\ block}\right]$$

Even considering that not everyone in Barcelona owns a vehicle, most building blocks in Barcelona will not be able to hold enough solar panel systems on their rooftops. An alternative is to install systems in the interior of city blocks, or on balconies.[3]

2.1.4 Weight

An advantage of solar panels is their low structural loads as applied on rooftop surfaces. Most of the weight comes from materials that protect the PV panel, such as glass. The weight of the panel itself is approximately 10-15 kg/m^2 applied as gravitational force. If a 60-cell panel is on average 1.626 m^2, the load applied per panel is:

$$Panel\ Weight = 15\left[\frac{\mathrm{kg}}{\mathrm{m}^2}\right] * 1.626\ [\mathrm{m}^2] = 24.39\ \left[\frac{\mathrm{kg}}{\mathrm{panel}}\right]$$

This weight does not account for the mounting structure that supports the panel. Further evaluation on rooftop structural bearing load is necessary.

Nowadays, virtually all rooftops in Barcelona are capable of supporting a PV panel system installation.

2.1.5 Warranty and Lifespan

Solar panel failures are not common whatsoever. In fact, a study by the National Renewable Energy Laboratory (NREL) found that just 5 in 10,000 modern solar panels fail, which represents a rate of 0.05% of total panels installed. A solar panel's performance warranty will typically guarantee 90% production at 10 years and 80% at 25 years.

A solar PV system represents a multi-decade investment. Monocrystalline solar panels have longer lifespans ranging, from 25-40 years. Polycrystalline solar panel lifespans range from 15-35 years (What to know, 2023) [78]

[3] Refer to the Solideo calculator in Appendix 5.1 to estimate rooftop dimensions and output capacity of each building.

Figure 30: *Hand on a solar panel as the sun wanes* (Why Do Solar, n.d.) [76]

- Performance Warranty

Also known as power output warranty; ensures that the solar panel still produces a minimum amount of power output after the expected 25-year cycle of a panel.

- Product Warranty

Warranty that protects customers against defects, such as imperfections in the frame, glass loose junction boxes, faulty connectors, bad cells, damaged cell connections, defective backsheet, quality issues and material failures. A product warranty will typically guarantee 10-12 years without failing.

- Inverter Warranty

Inverter warranties are usually around 5 years.

- Installation Warranty

Typically, 1 or 2 years after installation.

It should be noted that warranties do not guarantee of a specific amount of solar production from your system, in the case that weather conditions are not ideal.

The warranty will not typically cover damage to solar panels due to power failure, fire, flood, lightning strikes, incidents caused by accidental breakage, explosions, vandalism, acts of war or other events beyond the manufacturer's control (How to Understand, n.d.) [80].

2.1.6 Aesthetics

Solar panels are one of the most visible signs of a transition towards renewable energy sources. As their presence grows across our rooftops and other surfaces, it is important that they blend in with or enhance the aesthetics of their surroundings.

Solar panels have existed for many decades. New improvements have occurred since their invention, but their aesthetics are still left old-fashioned without relatively improving much.

It is important to provide technical solutions that also blend in with the environment. It is often noted that solar panels are an eyesore, which scares off new customers, making potential buyers reluctant to install them on their rooftops. To keep the photovoltaic panel industry booming, potential customers will need solar panels that look appealing.

Several projects are in place to make solar panels thinner, more flexible, more transparent, and available in different colors (Solar Panels and the Importance, 2020) [59]

Figure 31: *Colored solar panels provided by SwissINSO* (Facade, n.d.) [183]

New models are being developed that mimic architectural design and aim to imitate surfaces of buildings. The panels, which can be produced in any color or size, reproduce the building's surface appearance, going unnoticed.

Figure 32: *Sistine Solar creates custom solar panels designed to mimic home facades and other environments* (Matheson, 2017) [60]

Rooftop surface is another aspect to consider when installing a PV panel. Barcelona rooftops are mostly tiles (clay, ceramic, metal, synthetic, slate or concrete), tar and gravel. These do not pose a problem for installation in Barcelona. Other options are rooftop shingles, slates or in-roof mounted systems, that could be evaluated.

2.2 Efficiency and Performance

Solar panel efficiency is a measure of the amount of sunlight that is absorbed by the surface of the solar panels and is converted into electricity. Efficiency is based on cell structure, silicon type, cell layout configuration and panel size.

Efficiency is calculated using the following formula under STC:

$$Efficiency\ [\%] = \frac{Pmax.}{(Area * 1000)} * 100 = \frac{300\ [W]}{\left(1.626\ [m^2] * 1000\left[\frac{W}{m^2}\right]\right)} * 100 = 18.45\ [\%]$$

Performance ratio:

$$PR\ [\%] = \frac{Net\ Production}{TSI * Area * Eff.} = \frac{1{,}350\left[\frac{W}{m^2}\right]}{5{,}600\left[\frac{W}{m^2}\right] * 1{,}626\ [m^2] * 0.1845} * 100 = 80\ [\%]$$

In real-world use, solar panel operating efficiency and performance are dependent on many external factors. Depending on the local environmental conditions, these various factors can reduce panel efficiency and overall system performance (Vashishtha, 2012) [175].

2.2.1 Solar Irradiance

Barcelona presents around 2,500 hours of sunlight a year. That is enough hours to make the installation of a PV system installation worthwhile. Solar irradiation is the power of electromagnetic radiation received from the sun per unit area in watts per meter square W/m^2.

To measure sunlight hours, it is necessary to know the Peak Sun Hour (PSH). Peak Sun Hour (Hora de Pico Solar, in Spanish) is the amount of solar energy that radiates over a surface of 1,000 W/m^2 in an hour. This means that even if there are 13-15 hours of sunlight a day, not all rays radiate at 1000 W/m^2. In Barcelona, the average solar irradiation equates to 5.61 hours at 1000 W/m^2 (Ibrahim, et al., 2019) [100].[4]

[4] The design of a photovoltaic system relies on solar radiation at a particular site. Irradiance is the measure of the power density of sunlight or the total power from a radiant source falling on a unit area. The solar constant for Earth is the irradiance received by Earth from the sun through the atmosphere. S = E/ (4πR2) = 1370 W/m2. Where: E=is the Sun total power = 3.9x1026W, R= is the average earth/sun distance = 1.5 x1011m.

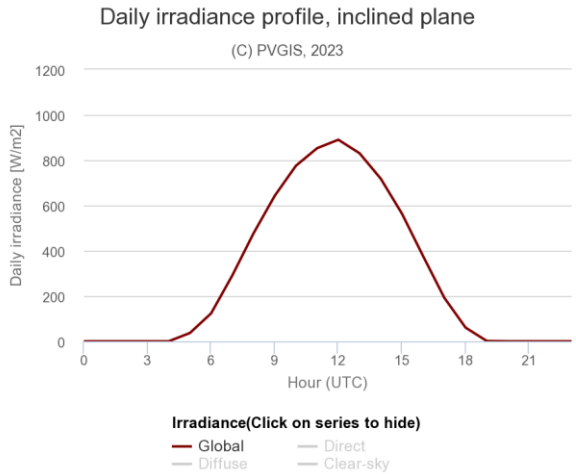


Figure 33: *Typical solar irradiance in Barcelona, PVGIS* (Performance of Off-Grid, 2022) [184]

$$TSI = \int_{4h}^{19h} Irradiance\ dh = 5{,}610\ \left[\frac{W}{m^2}\right]$$

Not all months have the same amount of sunlight hours or solar irradiation. This should be considered when computing energy output.

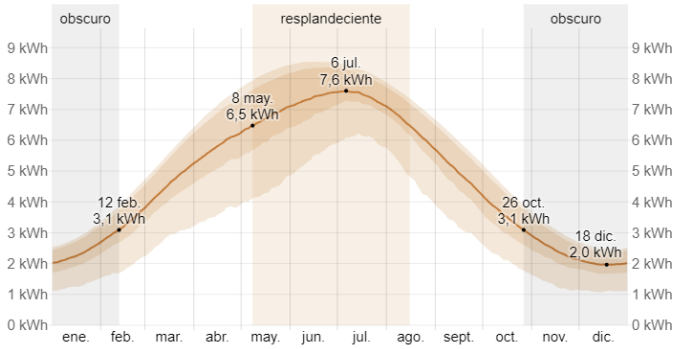


Figure 34: *Average solar irradiance in Barcelona per month. Lower-bands represents the 25th and upper-band the 75th percentile* (Clima, n.d.) [173].

The amount of solar irradiance varies, depending on how far the object is from the sun, the angle of the sun and the solar cycle (Quasching and Hanitsch, 1995).

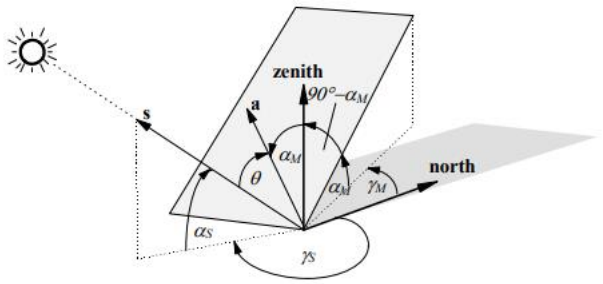


Figure 35: *Solar ray's incidence angles* (Quasching and Hanitsch, 1995) [154]

- Total Solar Irradiance (TSI)

Solar irradiance is the output of energy from the Sun that reaches the Earth. It is a measure of all wavelength's incidence on the Earth. It varies depending on the time of the year because the distance (and angles) to the Sun change.

$$TSI = Direct + Diffused + Refracted$$

- Direct Normal Irradiance (DNI)

DNI is what we receive directly from the sun, minus atmospheric losses due to absorption and scattering of particles. It varies depending on the cloudiness of the moment and also the season of the year in which is measured. It is measured perpendicular to incoming sunlight.

DNI is not constant as it depends on the time of year and solar ray incidence angles. It can be computed using the following formula:

$$DNI = Irradiance * \frac{cos(\theta)}{sin(\alpha s)}$$

- θ: Angle of incidence

- α_s: Solar Altitude

- Diffused Horizontal Irradiance (DHI)

Irradiation received from light that is scattered from the atmosphere. It can represent up to 15% of the total irradiation received.

- Refracted Horizontal Irradiance (RHI)

Refracted irradiation emitted by the terrestrial surface. Refraction depends on the albedo coefficient (A), which measures the fraction of global incident irradiation reflected by the ground in front of a tilted plane.

- *A*: Albedo coefficient taken as 0.2 if not specified.

- α_m : Solar generator altitude

$$RHI = TSI * A * 0.5 * (1 - \cos(\alpha m))$$

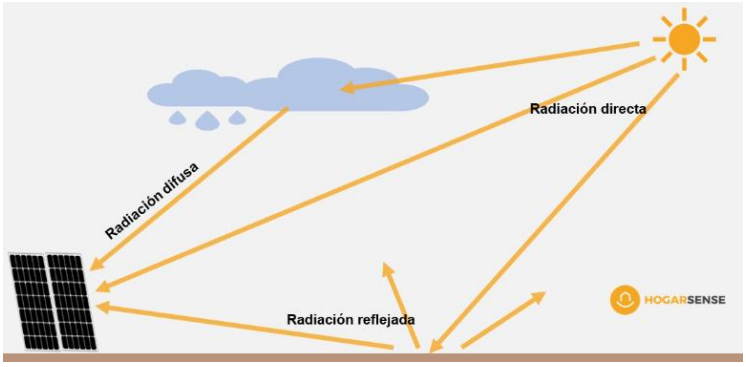


Figure 36: *Solar irradiance components; direct, diffused, and refracted irradiance* (Carbonell, 2023) [99]

2.2.2 Temperature Effects

- Temperature Effect

A common misconception about solar panels is that they are best suited if temperatures are as high as possible. The optimal temperature for PV panels is between 20-25ºC, which is the optimal temperature tested in STC. When temperature increases above 25ºC, panels start to become counterproductive.

Solar panels use photons to excite electrons within the semiconductor, if a solar panel overheats, electrons within the semiconductor are overexcited, thus lowering the overall voltage output of the panel.

Effect of temperature is based on a temperature coefficient ranging between 0.2-0.5%/ºC, depending on the type of solar panel module. The temperature coefficient represents the rate at which a solar panel will underperform with respect to each Celsius degree increase above the optimal temperature. As the temperature coefficient decreases, the less a solar module is affected by increases in temperature (Mike, 2021) [27].

For example, let us consider a summer day in Barcelona at 32ºC. A solar panel in NOCT conditions has a temperature of 53.33ºC and a temperature coefficient of 0.4 %/ºC. To calculate how much efficiency output will decrease:

$$Efficiency\ loss = (NOCT\ temperature[ºC] - 25[ºC]) * Temp.\ Coefficient\left[\frac{\%}{ºC}\right]$$

$$Efficiency\ loss = 28.33\ [ºC] * 0{,}4\ \left[\frac{\%}{ºC}\right] = \ 11.332\ \%$$

- Panel Overheat

Consider a summer day in Barcelona at 32ºC and irradiation of 745 W/m^2. To calculate the estimated solar panel temperature increase (Marsh, 2020) [90]:

$$At^{ºC} = 0.034 * Irradiance - 4$$

$$At^{ºC} = 0.034 * 745 - 4 = 21.33\ ºC$$

$$PV\ cell\ Temp.[ºC] = 21.33 + 32 = 53.33\ [ºC]$$

- Heat mitigation measures

To limit solar panels from overheating, several measures can be taken to prevent loss of performance. The most common method is to use a thermally conductive substrate, which helps vent heat away from the glass layers of the module (Wai Zhe et al., 2019) [92].

Moreover, to reduce the effect of heat on solar panels, a space can be left between the rooftop and solar panel to allow for circulation of air. Another option could be to install a cooling system or ventilation system.

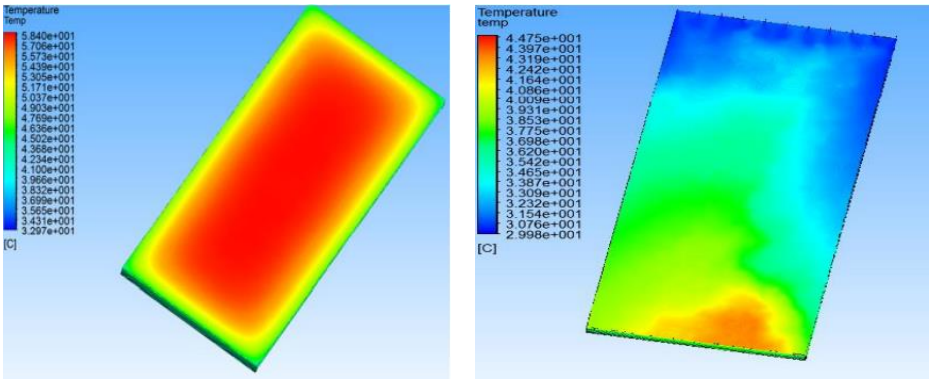


Figure 37: *Temperature distribution of a solar panel without cooling system using computational fluid dynamics (left).* ***Figure 38:*** *Temperature distribution of PV panel at inlet water temperature of 30 °C (right)* (Wai Zhe et al., 2019) [92]

- Cold Conditions

Cold temperatures do not affect overall panel performance as long as there are sunlight rays. Even in below freezing levels, solar panels turn sunlight into electricity. This is because solar panels absorb energy from the sun's abundant light, not the sun's heat. As long as sunlight is hitting the panel, it will produce electricity.

Summer days produce more energy because there are more hours of sunlight. However, the best conditions for optimal solar production are cold, sunny days, which usually occur in winter.

2.2.3 Annual Degradation

Solar panels undergo degradation over the years. The following is a list of possible occurrences that degrade a solar panel. A performance coefficient accounts for degradation effects.

- Age-related Degradation

As solar panels age they lose on average 0.5% efficiency for every passing year. The life cycle is around 25 years before performance has decreased to 80-90% and a new system would be better (Stenhouse, 2021) [77]. Typically, 3% is lost in the first year, while the annual loss over the remaining 24 years is much less, at around 0.3% to 0.7% per year depending on panel type (Solar Panel Energy, n.d.) [79].

- Light Induced Degradation (LID)

There are various forms of degradation to solar panels related to light.

- Ultra Violet Induced Degradation (UVID): Once installed outside and exposed to sunlight, UV radiation causes the crystalline silicon oxide on the surface of the panel to form a layer of boron dioxide (BH_2O_2) that reduces efficiency.

- Light and Elevated Temperature-Induced Degradation (LeTID): High temperatures affect all solar panels reducing power output over time.

-Direct Light-Induced Degradation (DLID): Affects the conditions during the initial setup period and cause the electronics within the photovoltaic cells to warp or buckle from heat.

- Potential-Induced-Degradation (PID)

PID refers to degradation induced by high voltages. It takes place when different components in the solar panel operate at different voltages. Voltage leaks reduce the amount of electricity sent to the inverter.

Moreover, reactions in the semiconductor materials used in the cells can create shadowing that reduces the amount of light that the panel can send to the inverter and convert it into power.

- Microcracks

Microcracks occur in the silicon of the solar cells. In hot weather, materials expand and in cold weather materials contract, due to the thermal expansion coefficient. The constant expansion and contraction put cells under strain and causes crack formation. Electrical connections weaken as a result of these little fractures, resulting in fewer pathways for the electrons from the sun to take, and therefore less energy reaching the inverter (What is the degradation, 2022) [95]. Solar cells generate electrical current that flow through interconnected cells; if there is an internal fault, the zone creates resistance further creating hot spots.

The thermal expansion coefficient for solar panels is as follows (Akshay, 2022) [150]:

$$\delta = (\alpha g * C - \alpha c * D) * \Delta T$$

- δ: Cell spacing in [mm] due to difference in temperature ΔT [ºC]

- α_g: Thermal expansion coefficient of glass: $9x10^{-6}$ [$ºC^{-1}$]

- α_c: Thermal expansion coefficient of cell: $21x10^{-6}$ [$ºC^{-1}$]

- C: Cell center to the center distance: 200 [mm]

- D: Width of the photovoltaic cell: 156 [mm]

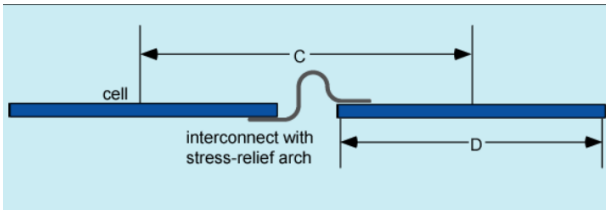


Figure 39: *Cells interconnected with a stress-relief arch*

$$\delta = (9x10^{-6} * 200 - 21x10^{-6} * 156) * \Delta T$$

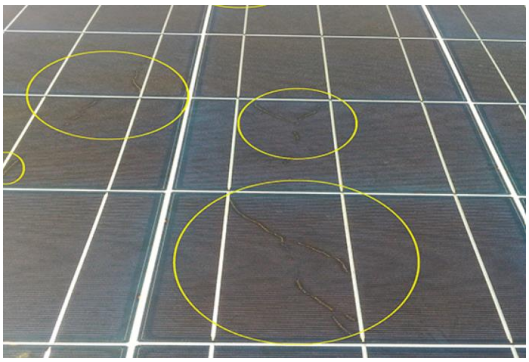
$$\delta = -0.0015 * \Delta T$$

- Decolorization

Solar panel decolorization occurs as result of an uncontrollable chemical reaction from materials within the panel. This process occurs when several additives begin to disappear after losing strength against UV rays.

Decolorization is related to transmittance reduction, affecting the cell's output power by 10-13% in the case of total decolorization and 8% if partially affected.

This usually occurs because of poor storage and handling conditions, causing bleaching of the EVA film and the backsheet, which sets off corrosion in the cell. Brown and yellow pigment is due to Ethyl Vinyl Acetate (EVA).



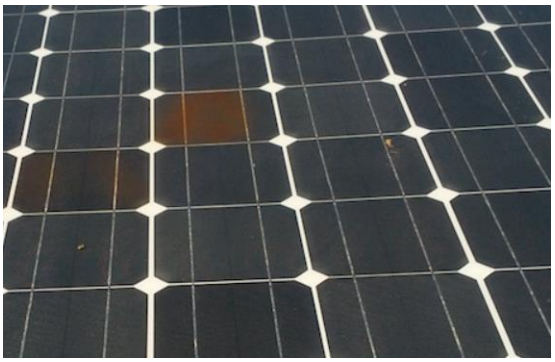


Figure 40: *Panels affected by microcracks (left).* ***Figure 41:*** *Panel affected by decolorization hotspots (right)* (Understanding the Degradation, 2020) [96]

- Weather Conditions

Heavy rainfalls cause cell corrosion and contamination. Moisture penetration in the PV module leads to corrosion, affecting metallic connections between the cells and damaging adhesion with the metallic frame (Understanding the Degradation, 2020) [96].

2.2.4 Debris and Weather Accumulation

It is important that materials do not accumulate on the surface of a PV panel as this can affect the ability to capture sunlight. Occasional maintenance procedures are necessary to prevent debris from accumulating. Monitorization systems exist that warn users when elements accumulate on top of the solar panels.

- Dust

Dust accumulation can hinder PV panel performance. The greatest factors that contribute to dust build-up are geographical location and the surrounding elements that might pollute a system. This can affect effectiveness by up to 5%.

- Rainfall

In the case of dirty rain, rain carrying airborne particles, it is likely to bring high-pollutant contaminants. Inclined panels are not as affected since water flows downward and off without accumulating. Rainfall can often clear panel debris accumulation.

- Weather Conditions: hail, snow, and wind

Extreme weather conditions are a major concern for PV panel owners. In the case of hailstones there is greater risk of damaging the PV panels, as impact can damage the protecting glass. Installing a protective cover (layer of plexiglass) might suffice. Adding a layer of methacrylate forms a durable, hard surface overtop of the panels, that offers additional protection, with a corresponding cost factor.

When a solar panel is coated with snow it is unable to absorb light to generate power. This is not common in Barcelona, so it is not a hazard to consider.

Light wind tends to have a positive effect since it tends to cool the panel and remove debris accumulated over top.

- Leaves

Especially relevant if located near trees or nature. Also, households near trees have wildlife that is prone to bird droppings. If the wildlife conditions were truly unfavorable a wire mesh can be installed over top.

2.2.5 Shading

Solar panels are very sensitive to shade. Even if one panel is affected by shade it will affect the whole system if it is connected in series. Partial shading can reduce output by 50% (What is the degradation, 2022) [95].

Preventive measures include bypass diodes that isolate shaded cells, rerouting the currents of underperforming cells.

Other measures to prevent shading include adding microinverters or optimizers that are attached to the panel. Moreover, following Lenardic, parallel connected systems are also a possibility as the system reduces efficiency by 90%. They work because they have bypass diodes (Lenardic, 2018) [151].

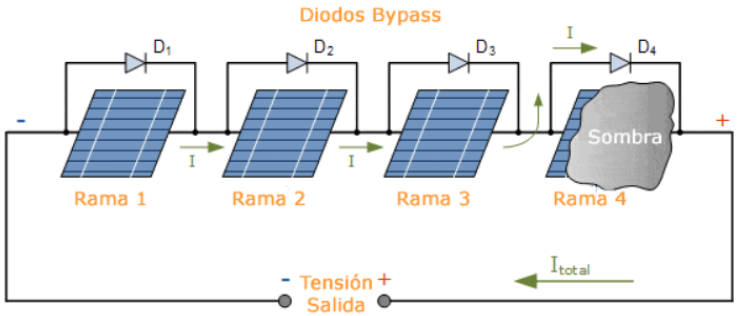


Figure 42: *System in series affected by shade is saved by rerouting the current with a bypass diode* (Alonso Lorenzo, n.d. -a) [178]

Panels can be affected by different types of shades:

- Temporary shading

Typically includes clouds, bird droppings, dust or fallen leaves.

- Shading resulting from built structures

Direct shadows from the building itself, usually due to chimneys, lighting conductors, satellite dishes, antennae, roofs, façade protrusions, offset building structures or roof superstructures.

- Shading from nearby location

Shades coming from the building surrounding that could originate from trees, bushes, antennas, cables running over the buildings, neighboring buildings or distant buildings.

- Self-shading

Mounting structure and photovoltaic panels that are tilted can cause self-shading when the sun impacts on an angle. It is necessary to optimize tilt and separation between module rows.

To avoid self-shading, a minimum distance between panels is necessary. Considering the minimum angle of incidence during the year that occurs in the winter solstice (December 22), when the sun is at its zenith over the Tropic of Capricorn. Therefore, the angle can be calculated (How To Calculate, n.d.) [156] from an inclination of α=66º:

$$\beta = 90 - (\alpha + 23.27)$$

$$\beta = 90 - (66 + 23.27) = 0.73º$$

To determine the distance between successive rows of photovoltaic panels to avoid self-shadows:

$$z = \frac{h * \sin(180º - (\alpha + \beta))}{\sin(\beta)} = \frac{1.64 * \sin(180 - (66 + 0.73))}{\sin(0.73)} = 2.05\ [m]$$

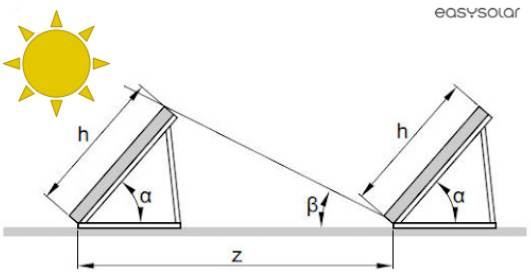


Figure 43: *Minimum required distance Z between panels to avoid self-shading given certain parameters* (How To Calculate, n.d.) [156]

To account for solar shading, a specific analysis is developed in each case. There exist some equations to calculate solar shading and provide an accurate estimation for the client in each condition.

Shading analysis must be developed in each case specifically during the site survey to provide accurate measures of shading potential computations are made (The Effects of Solar, n.d.) [94].

- h: Height of panel
- D: Diameter of panel
- α_s: Solar Altitude
- Φ: Solar Azimuth
- Ψ: Panel Azimuth
- w: Width of panel
- y: Vertical shadow angle (VSA)

$$h = \left(\frac{(D * \tan\alpha)}{(\cos(\Phi - \Psi))}\right)$$

$$w = D^{*}\tan\big((\Phi\text{-}\Psi)\big)$$

$$y = \arctan\left(\frac{\tan(\alpha)}{(\cos(\Phi - \Psi))}\right)$$

Shading can be quantified based on solar access value (SAV). This metric expresses the available energy as a percentage of what would be available in ideal (i.e., shade-free) conditions. It is a measure of how much sunlight reaches a solar PV system after accounting for direct and indirect irradiance and the impact of shade. This metric allows identification of how significant shade is affecting output power as a percentage (Key Solar, n.d.; Erika, 2023) [101] [102].

$$\text{Solar Acess Value} = \frac{\text{E. Shade}}{\text{E. No Shade}}$$

2.2.6 Azimuth and Zenith Orientation

2.2.6.1 Azimuth Direction

In the northern hemisphere the general rule is that panels should face the south (and in the southern hemisphere, true north). This is the best direction because panels will receive direct sunlight perpendicularly. An important distinction is that solar panels must face solar or geographic south instead of magnetic south.

In Barcelona, solar panels generate more energy when they are located facing towards the south. This is especially important in winter when the sun is lower. A personalized study for each household must be done given rooftop capabilities (see also Appendix 5.1).

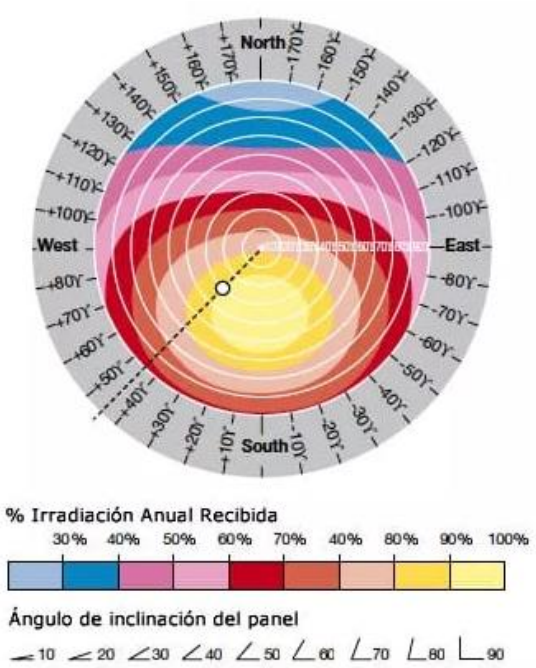


Figure 44: *Optimal Azimuth and Zenith orientation for a latitude of 41º* (Solar Panel Orientation, n.d.; Alonso Lorenzo, n.d. -d) [104][107]

If south orientation is not possible due to rooftop inclination, south-east or south-west orientation are also valid as they only lose between 1-4 % efficiency. In the case of east or west orientation, efficiency loss is substantial, at around 20-30%, although this serves to optimize space.

Northern orientation is the least favorable and should be avoided at all cost, as a special study will have to be conducted to analyze if it is worth an investment into the system (Com puc calcular, 2021) [88].

East-west orientation is also possible if the rooftop or conditions do not allow the solar panels to orient itself towards the south. An advantage of this orientation is that peak production coincides with the hours of peak consumption when in the morning and in the evening after work. South orientation generates more energy in peak hours, but east-west orientation distributes energy throughout the day.

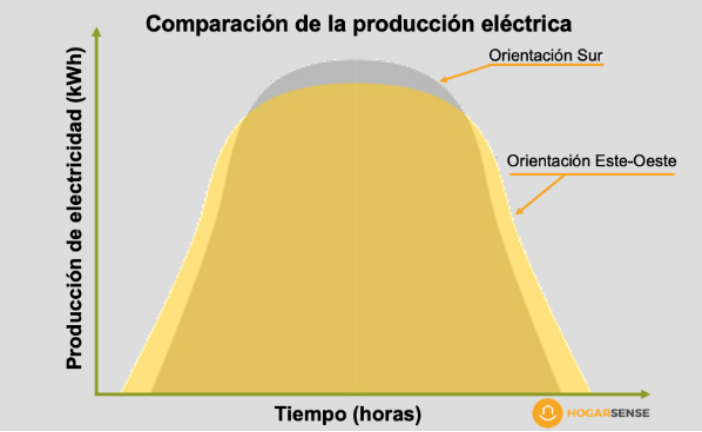


Figure 45: *Production based on southern or east-west orientation. Southern orientation produces more during peak hours but east-west orientation has greater production in the morning and at night* (Cómo orientar, n.d.) [103]

East-west orientation is placed in "Delta-Wing" formation. It is especially beneficial since it optimizes space, and no self-shadows are created (Insa, n.d.) [105]. It is an option on smaller rooftops were Delta-Wing formation allows for better space optimization. It is considered that this system allows 30% more space production per square meter.

Ideal inclination for this orientation is 15º, as this optimizes both panels. It is also favorable since it reduces impact on wind currents.

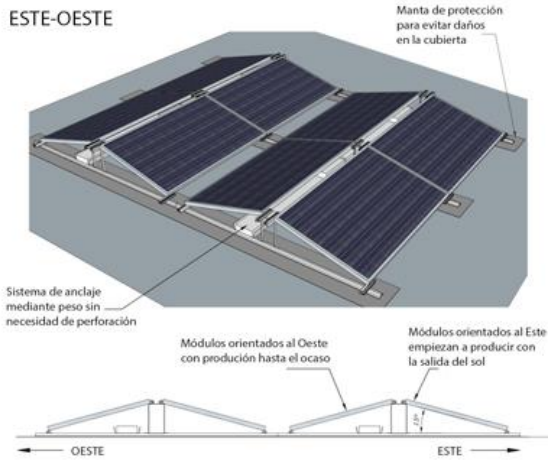


Figure 46: *Delta-Wing formation schema*

2.2.6.2 Angle Tilt Zenith

A solar panel will harness the most power when the sun's rays hit its surface perpendicularly. Ensuring panels have optimum orientation and tilt angle is crucial to optimize energy output. Being exposed to appropriate tilt conditions ensures intensity of sunlight for the greatest period.

To perform at their best, solar panels should face south and be installed at an angle between 30 and 45 degrees (depending on how far you are from the equator). General rule states that panels should be tilted at an angle equal to the latitude. For example, in Barcelona the latitude is 41.38º. So, tilt should be around 41º. However, tilt angle changes depending on the season of the year. Each case should be studied individually as rooftop configurations vary between different buildings and households.

The Tilt and Orientation Factor (TOF) considers the slope and direction of a given surface. TOF expresses actual conditions compared to optimal conditions in a percentage. Three methods are proposed to choose an inclination angle.

Panels facing east or west at a pitch angle of five degrees or more will still work well, but will produce 10 to 20% less electricity than those installed under ideal conditions (Solar 101, 2023) 32]

Three methods are proposed to decide the best angle tilt based on given criteria:

- Method 1: Constant changes with a monitorization system

There exist tracking systems that monetize the panel in non-fixed positions to optimize energy efficiency. These systems are more expensive but can provide higher energy output, since the panel inclination changes every day. There are tabulated inclination values for each day of the year.

Location and latitude are also adjusted for. The angle that a solar panel should be set at to produce the most energy each year is determined by the geographical latitude (Cómo orientar, n.d.) [103].

Season	**Inclination computation (β)**	**Optimal inclination (β)**
Winter	$29 + \Phi * 0.9$	66º
Autumn and Spring	$\Phi - 2.5$	38.5º
Summer	$(\Phi * 0.9) - 23.5$	13.4º

Table 3: *Optimal inclination β based on latitude in Barcelona of* $\Phi = 41^{o}$

- Method 2: Three changes a year

Changing the panel inclination three to four times a year based on the season of the year, according to IDAE manuals.

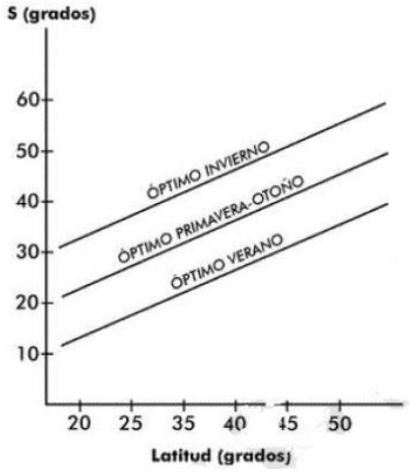


Figure 47: *Production interpolation based on latitude and year season. Basically, the closer the panel is located to the equator the more the panel should be placed facing straight up* (Cómo orientar, n.d.; Com puc calcular, 2001) [103][88]

- Method 3: Fixed Inclination

Fixed inclination is the most popular method for on-grid systems, since it aims to maximize production thought the year. A fixed angle β is maintained through the year to capture the most amount of sunlight:

$$\beta = 3.7 + 0.69 * \Phi$$

$$\beta = 3.7 + 0.69 * 41 = 32º$$

2.3 Electrical Production

An estimation of all electricity produced by solar panels is calculated for Barcelona. The amount of energy produced will help estimate the LEV fleet to be propelled in 2050. Electricity produced is obtained considering the city as a whole. The estimate considers multiple variables, such as surface available, panel quantity, percentage of users who pursue the installation, solar irradiance, wattage power or performance of solar panels.

Specifications exist for each building block that can alter the results, since variables change for each individual case.

2.3.1 Surface area

Barcelona's government established that there are 7,899,532 m^2 of available space in the municipality to capture PV solar energy output (Mapa: quanta energia, n.d.) [11]. This accounts for private rooftops and indoor terraces in city blocks. If built space increases, more solar panels can be installed, and more energy can be obtained. The following map shows in red the most accessible spots to gather solar energy in Barcelona.

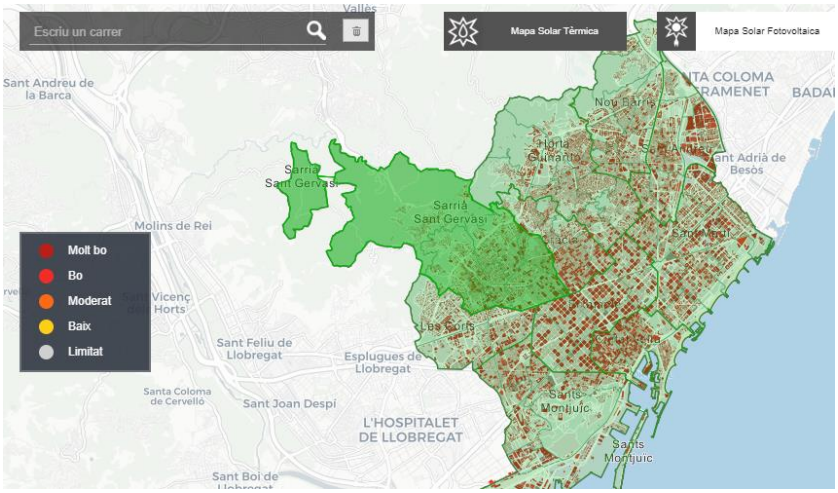


Figure 48: *Available space for PV installations in Barcelona corresponding with its output potential, showing the possibility of highlighting by district* (Mapa: quanta energia, n.d.) [11]

It does not take into consideration other spaces such as esplanades or parks that could also be used to optimize panel systems. Therefore, a 15% surface increase is established to account for all possible space in city:

$$Surface\ Area = \ 7{,}899{,}532\ [m^2] * 1{,}15\ \approx 9{,}000{,}000\ [m^2]$$

The study will evaluate necessary output energy to run LEVs in 2050 in Barcelona as a whole. However, each building has different conditions that generate differing output potential. Via the map on figure 48, each building block can estimate data on sunlight quality (very good, good, moderate, low, limited), available surface m^2, available power kW, possible energy generated

kW/year, CO_2 emissions saved $kgCO_2eq./year$, initial investment €/year, maintenance costs €/year and economic benefit €/year.

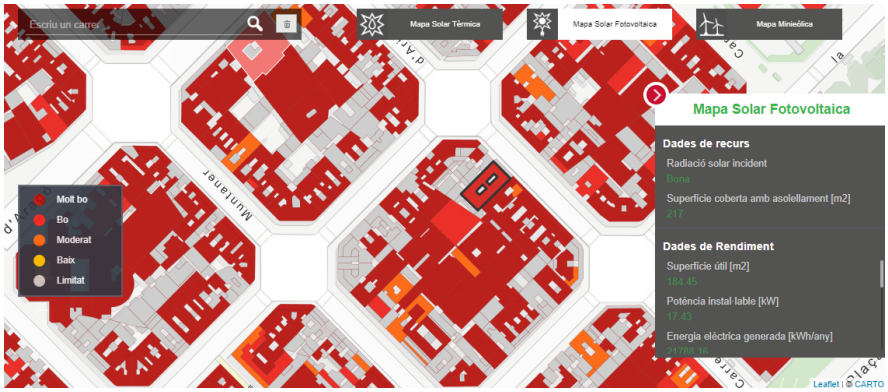


Figure 49: *Zoom of Figure 48 showcasing an Eixample block where installations can be carried out* (Mapa: quanta energia, n.d.) [11]

2.3.2 Panel Quantity

- Panels in Barcelona

Let us suppose there are 9,000,000 m^2 of available space to retain solar energy in Barcelona and the average panel dimension is 1.626 m^2. Number of solar panels installed in Barcelona could be:

$$9{,}000{,}000\ [m^2] \div 1.626\ [m^2] = \ 5{,}535{,}055\ \left[\frac{panels}{BCN}\right]$$

If all available space was accounted for in energy generation, it would not be accurate, since such a scenario would only occur if all customers decided to opt for a PV panel system installation, which is unlikely to happen.

Following we consider a case where 75% of all customers pursue a PV installation. Personally, I believe 75% it is an overestimation, since many citizens are against solar panels due to their cost and aesthetics. However, percentage installations could increase if the government obliged customers to pursue a PV panel system to reduce CO_2 emissions in the city or if the economic benefit output would outweigh any negatives. For example, if electricity from the central grid or gas prices skyrocketed, a PV system might become more viable. Also, if the PV panel systems installation became cheaper in the future, it would make them more accessible to the average citizen.

$$5{,}535{,}055\ \left[\frac{panels}{BCN}\right] * 0.75 = \ 4{,}151{,}292\ \left[\frac{panels}{BCN}\right]$$

- Systems in Barcelona

The necessary the number of 8-panel systems in Barcelona necessary to propel a LEV every year is:

$$4{,}151{,}292\left[\frac{panels}{BCN}\right] \div 8\left[\frac{systems}{panel}\right] = 518{,}911\ \left[\frac{systems}{BCN}\right]$$

2.3.3 Electrical Production

Electrical production depends on solar irradiance, that is based on peak sun hour (PSH). It depends on the season of the year and the geographical location. Let us consider an average value of 5.61 PSH that corresponds to average values of peak sun hours in Barcelona. In Barcelona, from October to March the peak sun hour is less than 5.61. Perhaps, on-grid systems are necessary to supply electricity in that time of year, while better batteries would be needed that allow to store more energy.

Furthermore, production also depends on panel wattage power. Let us use a standard 300 W panel. Higher wattage capacity improves electrical production but also increases investment price.

Moreover, a performance coefficient is applied since panels do not perform at full capacity. Temperature effects that occur during summer, when temperature increases over 25ºC, affect solar panel output. Annual degradation impacts performance of panels over time as they are used. There is a 3% decrease the first year and 0.55% loss of performance the following years for monocrystalline panels. Finally, it is assumed that the optimal orientation (angle tilt and inclination) cannot be always achieved. A factor is applied to account for possible mispositions. The performance coefficient is thus considered as 0.8, accounting for all possible losses.

It is considered that panels are not subjected to shade or debris effects (Solar panels: How much, n.d.; What is the output, n.d.).[67] [68]

Electrical production per panel a day is:

$$Electrical\ Production = 5.61\ [HPS] * 300\ [W] * 0.8 = 1.35\ \left[\frac{kWh}{panel * day}\right]$$

Electrical production per panel a year:

$$Electrical\ Production = 1.35\left[\frac{kWh}{panel * day}\right] * 365\ [days] = \ 491.45\left[\frac{kWh}{panel * year}\right]$$

Electrical production of all panels installed in Barcelona per year:

$$Electrical\ Production = 491.45\left[\frac{kWh}{panel * year}\right] *\ 4{,}151{,}292\left[\frac{panels}{BCN}\right]$$

$$= \mathbf{2{,}040.1}\ \left[\frac{GWh}{BCN * year}\right]$$

2.4 Vehicle Comparison

In this section, three LEV models are evaluated: an average model LEV, which is the case considered in the standard report, a high-end LEV, like a Tesla model, and a lower-end LEV, like the Nissan LEAF.

It is especially important to consider their consumption rate, autonomous distance and charging time. Further to this, vehicle prices are taken into considered in the economic report, found in section 2.8.

When the project discusses vehicles, it refers to cars, motorcycles or larger vehicles like vans. Vehicle types have different average consumption rates. Generally, the report focuses explicitly on cars.

For simplicity, hydrogen vehicles are excluded in this project, as only 4 units were sold in Spain in 2022. It is still a very new technology that needs more development (De Aragon, 2023) [85].

2.4.1 Consumption

The production of energy required to power a LEV is based on the consumption capacity of the vehicle and the number of kilometers travelled a year.

Three models that have different consumption rates are evaluated since by 2050 not all LEV will have the same characteristics.

Consider a milage of 20,000 kilometers a year. Perhaps this milage rate is an overestimation for drivers based in Barcelona, since distances are not as extended as they are in the countryside. On the contrary, Barcelona residents may have second residences, in part to address the unfavorable environmental conditions of a major city, raising milage.

To compute kilowatts hour necessary in Barcelona per vehicle we use:

$$LEV\ Consumption = \frac{Kilometers}{Year} * \frac{Consumption\ in\ kWh}{100\ Kilometers}$$

- Average LEV

The study considers a standard model where average values are assessed. This is a consumption rate of 17 kWh/100km and a vehicle milage of 20,000 kilometers a year.

$$LEV\ Charge\ Consumption = \frac{20{,}000 * 17}{100} = 3{,}400\ \left[\frac{kWh}{year}\right]$$

- Tesla Model S

If a high-end model such as a Tesla S is assessed, the consumption rate increases; thus, consumption requires 19 kWh/100km.

$$LEV\ Charge\ Consumption = \frac{20{,}000 * 19}{100} = 3{,}800\ \left[\frac{kWh}{LEV * year}\right]$$

- Nissan LEAF

Analogously, a lower-end model requires on average a consumption of 14 kWh/100km.

$$LEV\ Charge\ Consumption = \frac{20{,}000 * 14}{100} = 2{,}800\ \left[\frac{kWh}{LEV * year}\right]$$

Furthermore, not all vehicles in Barcelona are cars. Motorcycles represent a large amount of the vehicle fleet in Barcelona. In general, electrical motorcycles require less consumption. Therefore, if there is a growth in two-wheel electric transport, replacing movement in four-wheel vehicles, the electrical production required might be less than estimated.

However, this study evaluates the city as a whole or pack. Each individual case is different, so that households who use motorcycles will require less energy output. The study will focus primarily on cars, but it must be stated that many users will not require as many panels as calculated. In any given building with various households, these variations could occur.

Transport Mode LEV	Percentage fleet	Consumption
Cars (Private + Taxis)	65%	17 [kWh/100km]
Motorcycles + Moped	30%	9 [kWh/100km]
Other (Vans + Buses)	5%	25 [kWh/100km]

Table 4 : *LEV transport mode distribution* (Fleet, 2022) [174]

2.4.2 Autonomous Distance and Charging Time

A major disadvantage of LEVs are their long charging time rates and their limited autonomous distance. An extended charging infrastructure is necessary to function properly.

In metropolitan Barcelona, however, distances necessary to commute to work or other requirements are not as long as when moving between towns in the countryside. Therefore, a charging infrastructure would likely be more developed than in other parts of the country. Urban areas potentially optimize charging infrastructure.

Charging time and autonomous distance is computed for each LEV model. Charging time required to load a battery from zero to full capacity is computed as:

$$Charging\ Time = \frac{Battery\ Capacity}{Charging\ Power}$$

Autonomous distance in kilometers from a full battery to a vehicle halt:

$$Autonomous\ distance = \frac{Battery\ Capacity}{Consumption}$$

- Average LEV

A typical battery of a LEV is around 40 kWh. A 3.5 kWh charger is used to charge the vehicle. High charging time is due to a low kilowatt hour charging device.

$$Charging\ time = \frac{40\ [kWh]}{3.5\ [kWh]} = 11\ hours\ 26\ minutes$$

Most LEVs have around 100 km autonomous distance capacity for every 17-kWh battery available. Therefore, a 40-kWh battery has an autonomous distance of:

$$Autonomous\ distance = \frac{40\ [kWh] * 100[km]}{17\ [kWh]} = 235.29\ [km]$$

- Tesla Model S

Analogous procedure as for the average LEV is computed. Battery of a Tesla Model S is 100 kWh.

$$Charging\ Time = \frac{100[kWh]}{3.5\ [kWh]} = 28\ hours\ 34\ minutes$$

$$Autonomous\ distance = \frac{100\ [kWh] * 100[km]}{19\ [kWh]} = 526.32\ [km]$$

- Nissan LEAF

Analogous procedure as for the average LEV is computed. Battery of Nissan LEAF is around 20 kWh.

$$Charging\ Time = \frac{20\ [kWh]}{3.5\ [kWh]} = 5\ hours\ 41\ minutes$$

$$Autonomous\ distance = \frac{20\ [kWh] * 100\ [km]}{14\ [kWh]} = 142.86\ [km]$$

Figure 50: *Recent models of the Nissan LEAF (left) and Tesla Model S (right*) (García, 2018) [132]

2.5 2050 LEV Estimation

Three scenarios are posed in Barcelona, where the sum of vehicles in the registered fleet would increase, decrease or stay the same by 2050. Afterwards, given standard variables assumed of solar irradiance, performance, or vehicle type, an estimated energy production is computed.

2.5.1 2050 LEV Estimation: Hypotheses

A transition from fueled vehicles to LEVs will occur in the following decades, so it is difficult to estimate how many LEVs there will be in Barcelona by 2050. Different suppositions are compared to analyze possible scenarios. The analysis focuses on vehicles registered in Barcelona city, excluding vehicles that enter from the suburbs every day.

- Hypothesis 1: Same vehicles in 2050

Barcelona has had approximately 950,000 registered vehicles for over two decades, never surpassing 1,000,000 vehicles, nor decreasing bellow 900,000.

In 2007, when the economy was booming and before the financial crisis, there were 991,151 vehicles registered in the city. Vehicles assigned decreased to 914,511 in 2013 after the effects of the crisis had hit. Barcelona had around 962,111 vehicles in 2017 (Subirana, 2018) [81]. These values have had a downward trend but are currently still in the range of 900,000 vehicles. Perhaps, vehicle demand will continue this trend, so that in 2050 there will be around **950,000** vehicles registered in the city.

- Hypothesis 2: Less vehicles in 2050

According to City of Barcelona data, there were more vehicles in the year 2000 than there are now in 2023. Vehicle ownership has had a downward trend. There are multiple causes that could cause a vehicle decrease in Barcelona by 2050.

Governmental intervention is incentivizing other methods of transport, especially public transport or bicycles that might shift the necessity of the private vehicles. New urbanization measures in Barcelona, known as the “Superilles” or Superblocks, are shifting space priority in the city from private vehicles. This causes less available space in the city for vehicles and a decrease in total available parking spots.

Railway options continue to be developed to cover medium and long-distance mobility throughout the country. This could cause less demand of private vehicles, and could especially reduce users travelling into Barcelona on long-distance journeys.

If fuel vehicles undergo too many restricting measures, such as the ZBE (the Barcelona low-emission zone) filtering which vehicles can circulate throughout the city based on vehicle emissions, vehicle numbers could decrease. There is also the 2035 EU plan to ban selling combustion cars, while a further plan projects 2050 as the year to stop them from circulating altogether. All these restricting measures can generate a negative response from fuel vehicle customers that will opt for other transport methods that do not undergo restrictions.

Car-sharing options might also be more prevalent. Apps such as “BlaBlaCar” allow customers to share vehicle trips. Further, the expected expansion of ride-hailing services such as Uber and

Cabify, complementing the traditional taxi, could lead to a reduction of vehicle ownership. The city features street-level services in short-distance electric motorcycle rentals, facilitated through company apps. If these technologies are further developed, users that previously used private vehicles upon occasion might opt for sharing with others, renting two or four-wheel vehicles short-term or relying on ride-hailing and taxi-type services instead.

Remote work options also make vehicles less necessary. If citizens could work from home, there would be less need to purchase a private vehicle to commute, or commuting frequency could decrease.

Finally, although Barcelona is one of the European cities with most motorcyclists, representing 30% of the total vehicle fleet, almost 50% of motorcyclists in Barcelona consider it a dangerous transport method. This could decrease the amount of those riding motorcycles, who might opt for other, safer options instead. Energy consumption data by sector and territory is drawn from the Institut Català d'Energia (Distribució per sectors, n.d.) [147].

Due to all these implications, lets us suppose a case where the number of vehicles decreases by one third to **600,000** by 2050.

Even if the number of vehicles decreases, this does not mean Barcelona will become less congested, as the study does not evaluate vehicles coming from the suburbs. According to estimates, there are 1,368,804 vehicles that enter the city every day (Coche eléctrico, 2019) [56].

- Hypothesis 3: More vehicles in 2050

Even if alternatives to the private vehicle are being developed, Barcelona is still mostly designed for cars, stemming from an urban planning model of the 19th and 20th centuries. Let us suppose that the population in Barcelona slightly increases in the lead-up to 2050. This could be justified by estimates that people will choose to live in larger cities as they present better and more opportunities. An increase in demographics could cause more vehicles in cities.

Another factor could be rising family income, which could correlate with an increase in vehicles per household. If salaries increase in Spain, people will have more purchasing power and could opt for more private vehicles per household instead of alternatives.

Municipality of Barcelona had 6,201 LEV in 2019. Although numbers are increasing every year, they only represent 1.47% of total vehicles in the market. Other countries such as Norway have 20% of the fleet as low-emission vehicles. This is due to strong governmental incentives that caused that 79% of vehicles sold in 2022 were LEVs. If the Spanish government applied more incentives, this could generate more customers who are drawn to LEVs due to external benefits.

Suppose the number of vehicles registered in Barcelona reaches **1,000,000** by 2050.

The following section 2.5.2 addresses the above scenarios.

2.5.2 2050 LEV Estimation: Supply

To estimate LEV supply via solar energy, possible scenarios are envisioned. A standard model is considered where average conditions are evaluated. More production could be achieved, affecting the amortization period and economical benefit.

Energy output is treated in Barcelona as a global amount. Obviously, each case should be studied separately since user output potential can vary depending on individual parameters.

Variables that affect output production depend on panel characteristics, such as photovoltaic panel type, wattage power or panel dimensions. Plus, performance and efficiency parameters come into play: solar irradiance based on season of year, annual degradation, temperature effects or orientation (angle tilt and direction). The analysis also depends on vehicle type and model: consumption, milage and number of vehicles in the city. Finally, output capacity is based on surface available to capture energy and the percentage of installations done in the Barcelona.[5]

$$Electrical\ Production = \mathbf{2,046,469,390}\ \left[\frac{kWh}{BCN * year}\right]$$

$$Energy\ Required\left[\frac{kWh}{BCN * year}\right] = EVs\ (nº\ units\ 2050) * LEV\ Charge\left[\frac{kWh}{year}\right]$$

To ensure the city has enough energy it must satisfy:

$$\begin{cases} if\ Electrical\ Production \geq Energy\ Required, & OK \\ \\ if\ Electrical\ Production < Energy\ Required, & NO \end{cases}$$

- Hypothesis 1: Same vehicles in 2050: 950,000 vehicles

$$Energy\ Required\left[\frac{kWh}{BCN * year}\right] = 950{,}000\ [vehciles] * 3{,}400\left[\frac{kWh}{year}\right]$$

$$= \mathbf{3,230,000,000}\left[\frac{kWh}{BCN * year}\right]$$

Considering a standard model, if the number of vehicles stayed the same at 950,000 vehicles in 2050, the system would not generate enough energy to supply all the fleet.

[5] It is possible to establish different scenarios by changing these variables, as seen in the accompanying Excel sheet.

- Hypothesis 2: Less vehicles in 2050: 600,000 vehicles

$$Energy\ Required\left[\frac{kWh}{BCN * year}\right] = 600{,}000\ [vehicles] * 3{,}400\left[\frac{kWh}{year}\right]$$

$$= \mathbf{2{,}040{,}000{,}000}\left[\frac{kWh}{BCN * year}\right]$$

If the number of vehicles decreased to 600,000 by 2050, a standard PV panel system model would suffice to propel 600,000 vehicles given the variables stated above.

2.6 CO_2 Emissions

Installing PV panels and transitioning towards a LEV economy is not only an economic incentive. It also generates positive externalities on climate conditions by reducing greenhouse gas emissions in the atmosphere.

The following chapter analyzes the reduction of CO_2 emissions that are due to obtaining energy from PV panels. Afterwards, a comparison between internal gas vehicles opposed to electric-powered vehicle emissions is evaluated.

2.6.1 Panel CO_2

For every 1 kWp installed of solar energy, it is possible to reduce 908 kg/kWp in CO_2. This considers life cycle emissions, mining, manufacturing, installation, and disposal. The calculation is based on CO_2 not emitted per system during a 25-year lifespan (Beneficios, 2019) [137]:

$$908\ \left[kg\,\frac{CO2}{kWp}\right] * 25[years] * 2.4\left[\frac{kWp}{system}\right] = 54{,}480\ \left[kg\,\frac{CO2\ in\ 25\ years}{system}\right]$$

CO_2 not emitted in Barcelona during a 25-year period is:

$$54{,}480\ \left[kg\,\frac{CO2\ in\ 25\ years}{system}\right] * 518{,}911\ [systems] * 10^{-3}\left[\frac{T}{kg}\right]$$

$$= 28{,}270{,}271.28\ [T\ of\ CO2]$$

2.6.2 LEVs CO_2

Road transport accounts for around 20% of CO_2 emissions worldwide. Transitioning to LEVs will drastically reduce pollution (Tiseo, 2023) [160].

- Fuel vehicles

Fuel vehicles emit other types of gases apart from CO_2. They are excluded in the study.

- Fuel cycle

Average CO_2 emission of fuel vehicles of 121 g of CO_2/km [153]. To calculate emissions related to fuel gases in Barcelona over a 25-year period, consider a lower-bound hypothesis of 600,000 vehicles and 20,000-kilometer milage per year for each vehicle:

$$121\left[g\,\frac{CO2}{km}\right] * 20{,}000\left[\frac{km}{year}\right] * 600{,}000\ [vehicles] * 25\ [years] =$$

$$= 36{,}300{,}000\ [T\ of\ CO2]$$

- Vehicle Manufacturing

Vehicle manufacturing emits 6 $[T\ of\ CO2]$ per vehicle. Accounting for 600,000 vehicles in Barcelona:

$$CO2\ Manufacturing = 600{,}000\ [veh] * 6\ [T\ of\ CO2] = 3{,}600{,}000\ [T\ CO2]$$

Therefore, the sum of all emissions of fuel vehicles is 39,900,000 $[T\ of\ CO2]$ during the 25 year-period in Barcelona.

- LEVs

-Electricity

Although electric vehicles do not emit gases when they run, CO_2 can be emitted during the generation of electricity that is drawn from the central grid and stored in batteries (Market, 2018) [162]. Average CO_2 emissions are 0.309 kg/kWh [189]:

$$CO2\ electricity\ generated = \frac{0.309[\ kg\ CO2]}{[kWh]} * \frac{17\ [kWh]}{100\ [km]} * 20{,}000\ [km]$$

$$* 600{,}000\ [vehicles] * 25\ [years] = 15{,}759{,}000\ [T\ of\ CO2]$$

-Battery production (minerals and assembly)

LEV lithium battery production generates emissions when it they are produced. Battery production on average accounts for 5,8 $[T\ of\ CO2]$ per vehicle. Total amount of CO_2 emissions due to battery production in Barcelona are:

$$CO2\ Batteries = 600{,}000\ [veh] * 5.8\ [T\ of\ CO2] = 3{,}480{,}000\ [T\ of\ CO2]$$

-Vehicle Manufacturing

Vehicle manufacturing accounts for 5,4 $[T\ of\ CO2]$. Note that it is a similar value to fuel vehicles. CO_2 emissions generated due to vehicle manufacturing in Barcelona is:

$$CO2\ Manufacturing = 600{,}000[veh] * 5.4[T\ of\ CO2] = 3{,}240{,}000\ [T\ of\ CO2]$$

Accounting for all processes, LEVs emit 22,479,000 $[T\ of\ CO2]$ during their lifetime in Barcelona.

CO_2 emission distribution based on source is represented in the following chart:

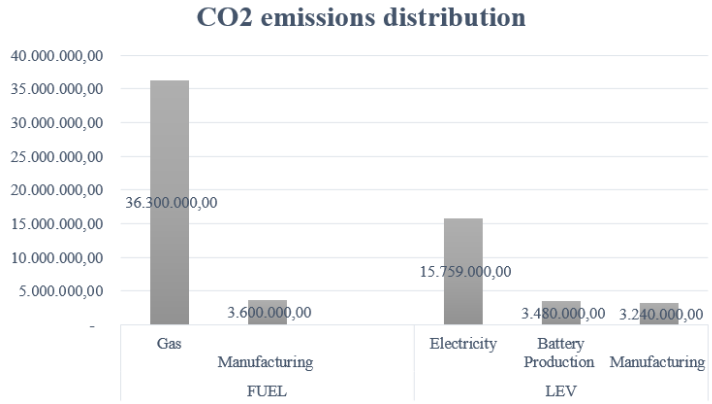


Chart 1: *CO_2 emission distribution, internal combustion engines vs LEVs in a 25-year period. Excel generated.* (Comparative, 2021) [161]

Clearly, the highest polluters by far are gas emissions generated from fuel vehicles. Moreover, a common misconception is that low emission vehicles are not completely emission-free, since they also produce CO_2 emissions.

If all vehicles transitioned to LEVs in the next 25 years, in Barcelona a total could be saved as follows:

$$CO2\ saved\ LEVs = 39{,}900{,}000 - 22{,}479{,}000 = \mathbf{17{,}421{,}000}\ [\boldsymbol{T\ of\ CO2}]$$

2.6.3 Monetary CO_2 Value

Total CO_2 emissions not emitted if society would transition to PV panel systems and LEVs in Barcelona over a 25-year period:

$$CO2\ not\ emitted = 32{,}076{,}679.92 + 17{,}421{,}000 =$$

$$= 49{,}497{,}679.92\ [T\ of\ CO2]$$

The cost society pays for situations such as damage to crops, health care costs from heat waves, droughts, loss of property from flooding and sea level rise; ties them to their sources through a price, usually in the form of a monetary value on the carbon dioxide emitted. Nowadays, monetary value of carbon dioxide is established at 86 €/T. This value could potentially fluctuate if CO_2 emitted is considered more valuable. An increase of monetary CO_2 price has been the trend over the past decades (Carbon Pricing, 2023) [167].

Placing an adequate cost signals emitters to lower CO_2 emissions. Placing an adequate price on greenhouse gas emissions is of fundamental relevance to internalize the external cost of climate change in the broadest possible range of economic decision-making, and in setting economic incentives for clean development. A consensus is established by governments on the fundamental role of pricing to help transition towards a decarbonized economy.

$$Monetary\ value\ CO2 = 49{,}497{,}679.92\ [T\ CO2] * 86\left[\frac{€}{T}\right] =$$

$$= 4{,}256{,}800{,}473.12\ [€]$$

2.7 Pricing and Costs

Pricing of the PV panel system is based on an 8-panel system. The cost is composed of an initial investment price where all elements of the systems are assembled together. It also includes installation costs, insurance, structural verifications and taxes. There are furthermore operational costs to run the system effectively, while government incentives to help purchase the system also come into play.

Currently a PV installation PPW is around 0.8-1.2 €/kWh, including incentives. An estimated price for the system is carried out by obtaining materials from different companies.

Figure 10: Past modules prices and projection to 2035 based on learning curve

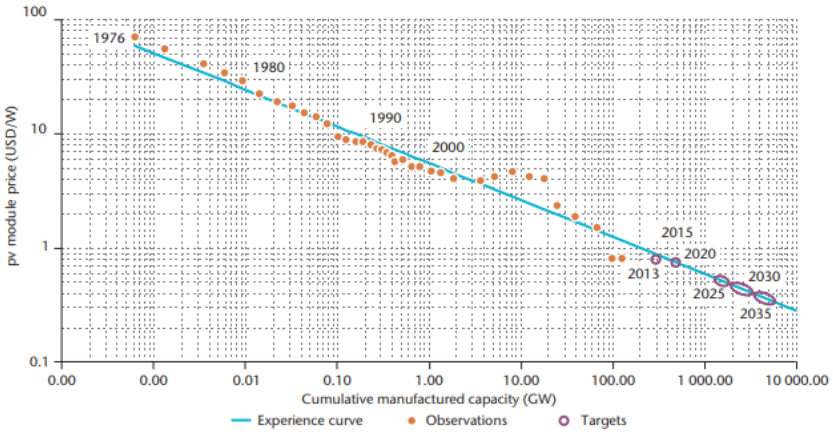


Figure 51: *PPW based on manufactured capacity. The graph shows that the price of PV panels is decreasing every year. In estimates by the International Energy Agency, by 2035 a PV panel would cost around 0.25 €/W* (Technology Roadmap, 2014) [44]

2.7.1 Investment

In this section we apply a scenario where each part is bought separately and assembled into a single system. It could be more convenient for users, however, for a system to be bought as a kit, because it is easier to match volt capacity and power range.

2.7.1.1 Panels

Let us consider a 300 W panel. Considering average conditions, the price is approximately 165 € per panel. Let us choose a 60-cell monocrystalline panel from LG. LG is cataloged as a Tier-1 premium brand (Qué es el Tier 1, 2020) [149].

Figure 52: *LG MonocrystallineX Plus LG295S1C-A5* (LG MonoX, n.d.) [121]

For a PV system of 8 panels the investment required is:

$$Panel\ price(system) = 165\left[\frac{€}{panel}\right] * 8[panels] = \mathbf{1,320}\ \left[\frac{€}{\boldsymbol{system}}\right]$$

Panel fill factor:

$$FF = \frac{Vmpp * Mpp}{Voc * Isc} = \frac{31.3 * 9.43}{38.6 * 10.02} = 0.763$$

2.7.1.2 Mounting structures

To obtain the correct position for the solar panels, it is essential to use mounting racks that stabilize and give appropriate inclination and durability to the structure. A strong support is mandatory to achieve maximum efficiency for our solar panels. To avoid external loads, no movement is permitted. Structure has to be strong enough to resist wind loads, snow precipitations or even small earthquakes. In Barcelona only wind loads are a critical possibility.

Figure 53: *I-beams, screws and junctions, and a structure capable to withstanding a 30º inclination for a system of 8 panels.* (Suporte Triangular, n.d.) [108]

Pieces comply with aluminum standards with respect to its chemical composition S / EN573-3 and with respect to the mechanics S / EN755-2 and tolerances. Pieces withstand corrosion effect with proper coating galvanization.

An average price for the mounting structure, considering quality and cost effectiveness, is approximately 60€ per piece. This leads to a total of 420€ for a group of 8 panels.

2.7.1.3 DC-AC Protector

DC-AC protector shields the installation network in case of tension surges, but also protects the installation and all its wiring in case of outage. The whole kit costs **286€**.

Figure 54: *ECO-DC-INV-AC 1 STRING / 1 MPPT 1P+NX16A – TOSCANO* (Cuadro de protección, 2023) [185]

2.7.1.4 Battery

Batteries store energy of PV panels, and are only required for off-grid systems. They allow energy to be used any time of the day, providing stability to the grid. They allow energy usage at night when the PV panels do not produce energy, during a blackout or during days with little solar production.

An average battery lifespan is around 10 years after enough cycles have been executed; therefore, they must be replaced twice throughout the lifespan of a PV panel.

Figure 55: *2.8 kWh Pylontech Lithium battery 24V. Lifespan 6000 cycles* (2.8 kWh Pylontech, n.d.) [113]

Batteries are the most expensive elements of a PV panel system. the Pylontech Lithium costs 1,147€ per battery. Considering they must be replaced twice during a life cycle of PV panel system:

$$Batteries = 1{,}147[€] * 2 = \mathbf{2{,}294}\ [€]$$

2.7.1.5 Inverter

An inverter's main function is changing electricity from direct to alternating current. An inverter ensures the power generated is compatible with the grid. In case of power outage, solar inverters can disconnect from the grid (Thoubboron, 2018) [152].

Considering we decide to use 300 W panels in a system containing 8-panels each, the system runs at:

$$System\ Power = 300\ [W] * 8\ [panels] = 2{,}400\ \left[\frac{W}{system}\right]$$

To avoid inverter scalping, energy output lost due to undersizing an inverter, it is recommended to have a margin of security in case the energy output exceeds capacity. Most sources recommend around a 40% variance margin of error from the maximum DC power. A string inverter supplying the whole system will require at least:

$$Inverter\ power = 2{,}400\ [W] * 1.4 = 3{,}360\ [W]$$

Thus, let us consider an inverter of 3.5 kW.

Figure 56: *Monophasic 3.5kW 24V* inverter (Inversor híbrido, n.d.) [109]

An estimated price is around **750€** per inverter. Inverter prices have a large variance. These are just estimated values per systems of 8 panels. For example, if many households in the same building block decided to install inverters it would be a better option to buy a high quality one for the whole building block. Inverters have to be kept safe from heat, since they lose efficiency if subjected to high temperatures.

2.7.1. Monitorization System

A monitorization system is an essential apparatus used to track a PV panel system. It allows to notify the user in case of failure anomalies so changes can be made to guarantee system efficiency (Guijarro, 2022) [123].

Let us choose the model *Victron GX Touch.* This model allows to adjust to certain parameters during the day, such as predicting necessary demand and output potential, adjusting to climate conditions or delivering monthly reports on economic aspects and CO_2 emissions saved. It is priced at **352€**.

More advanced models allow to remotely adjust the panels to optimize angle tilt and orientation in real time. They are not considered in this project because they are more expensive, and a special mounting structure is required.

Figure 57 : *GX Touch 70 de Victron* (Guijarro, 2022) [122]

2.7.1.7 Cables

A PV system requires the right cables to perform well. Each country has specific laws regarding cable installation. In Spain it is based on "El Reglamento Electrotécnico para Baja Tensión (REBT)", which dictates how cables should be placed.

First, the norm establishes a necessary cross section to avoid tension losses. Secondly, it establishes maximum temperature intensity of an installation to avoid short-circuit problems (Santana, 2020) [127].

1. Cross-section *S* necessary

$$S = \frac{2 * L * I}{\Delta V * U * k}$$

- Length of cable *L*: The longer the cable, the greater chance tension losses occur. That is why the cable cross-section necessary increases when the length of the cables increases. Let us suppose there are 12.5 meters distance from the panels to the DC-AC protector.

- Maximum current that flows through cable *I*: Considering power and voltage conditions of a solar panel let us use I = 9.5375 A.

- Tension loss *V*: In the case of tension loss, voltage decreases due to overheating the conductor because it allows to convey more energy than it can support. Suppose that the system allows for a tension loss of 2%, thus ΔV=0.02.

- Nominal tension *U*: Parameter that relates necessary voltage of the AC system. Let us suppose a nominal tension of 24 V, which is in line with a 300 W power panel chosen.

- Electrical cable conduction *k*: Type of material that incorporates the cable can affect its conductivity. Let us use copper cables and suppose they function at 20ºC most of the time. Cable conduction coefficient is tabulated as k = 56.

The cross-section necessary to avoid tension losses is:

$$S = \frac{2 * 12.5 * 9.537}{0.02 * 24 * 56} = 8.87\ [mm^2]$$

It is necessary at least an 8.87 mm^2 cross section to sustain the power voltage system in case of an outage. A 12-meter cable of 10 mm^2 is used to connect the panels to the system. The price ranges around **95€** per pack. Cables make sure the panels are connected from the rooftop to the batteries (Santana, 2020) [127].

Figure 58: *12-meter copper cable with 10 mm^2 cross section* (12m/roll, n.d.) [126]

2. Short-circuit conductivity temperature

The short-circuit conductivity temperature is as follows (Alonso Lorenzo, n.d. -b) [128]:

$$Tc = To + (Tmax. - To) * \left(\frac{I}{V\ max.}\right)$$

- Ambiance temperature of conductor T_o: 20ºC

- Maximum temperature as established by the REBT T_{max}.: 90ºC

- Maximum intensity I_{max}: 9.5375 A

- Maximum volt capacity V_{max}.: 48 V as established in the voltage drop. 2%*24 V = 48 V

$$Tc = 20 + (90\ - 20) * \left(\frac{9.5375}{48}\right) = 33.91\ [ºC]$$

If the temperatures exceeded 33.91ºC the system could be prone to short-circuit conductivity failure. It is relevant in Barcelona since during summer it is possible to surpass 33.91ºC. It might be necessary to add insulation around the cables in case heat waves ensue.

2.7.1.8 LEV Charger

It is intended that no gas-powered vehicles will be allowed on the streets in 2050. Charging LEV devices are necessary to power an electric-run fleet. The main disadvantage of LEVs is the insufficiency of charging stations throughout the city. Although urban centers such as Barcelona are most equipped, there are currently 1,381 charging spots, between public and private stations. This is not enough to sustain a LEV transition; new solutions have to be proposed to increase EVSE (Electrical Vehicle Supply Estimation) (Gil, 2023) [163].

Figure 59: *Public LEV charging on Diagonal Street in Barcelona, 2017* (McGee, 2017) [58]

This project purposes LEV chargers installed essentially in private parking spots, found in private parking garages of individual buildings, or in buildings dedicated exclusively to parking. Each household would then have access to a charging station at the location of its permanent parking spot, without queue times, deciding when to charge or the possibility to charge without extra fees. To deal with this energy surge, PV panel systems are installed.

The possibility to charge vehicles in public, short-term parking spots throughout the city is not evaluated in this study, but perhaps could have some potential. Another possibility not considered here is where a private micro-grid makes a charging station available to third parties from the building in question, selling stored surplus for economic benefit. Further variables would each require an independent study and analysis.

For our purposes here, let us choose a ANDAIIC EV Charger, which mounts on the wall and connects to the battery. LEV chargers are connected to the battery to supply energy. It is a portable charger, so it could potentially charge at any station that has energy stored in a battery.

Figure 60: *ANDAIIC EV Charger Electric Car Portable Charger Type 2 IEC62196 Mode 2 8A/10A/13A/16A Current Adjustable 10m Cable. Output Power: Max 3.6KW* (iHunt, n.d.) [130]

It only has a maximum charging capacity of 3.6 kW, which is a low wattage output that affects charging time of LEVs. However, it should be enough time to charge a vehicle during the afternoon, after work or during nighttime. It is priced at **170€**.

With this LEV charger, the profile of the system and its components is complete.

2.7.1.9 Legal Aspects

2.7.1.9.1 Legalization

It is necessary to legalize a panel system before installation. The procedure depends on the kilowatts output installed. In the case of installation systems of less than 10 kW in an urban environment in the region of Catalonia, the process is as follows (Legalización, n.d.) [133]:

1. Memoria Técnica de Diseño (MTD), the technical design report, carried out by the installation company.

2. Reglamento Electrotécnico de Baja Tensión (REBT): The low tension electro-technical regulation, requiring the installation to be in good conditions.

3. Registre d'Instal·lacions Tècniques de Seguretat Industrial de Catalunya (RITSIC), of the Government of Catalonia, the Generalitat: Registry of geographical location and power output.

4. Registro en el Registre d'Autoconsum a Catalunya (RAC), of the Government of Catalonia, the Generalitat: Registration is only mandatory in the case of an on-grid system. A special license is given (CAU).

5. Change of contract: Once the installation is done the company will change service from the central grid to self-consumption

The price to verify all these documents is **450€**, if contracting a company specialized to do all the paperwork and legalize the procedure. In Catalonia, the price to legalize the procedure is reduced with ICIO incentives at 95% (Autoconsumo fotovoltaico (n.d.) [134]

2.7.1.9.2 Structural Verification

Structural verification is carried out to guarantee system stability. A study on action loads applied on PV panels and rooftop surfaces is evaluated. Solar panels can be subjected to wind loads that generate turbulences. Further to this, wind fluctuations can accumulate under the panel and generate suction loads.

An ultimate limit state (ULS) design is studied to guarantee safety requirements and failure conditions. For example, to verify the ULS design of the structure, a case of a turbulent wind load of 125 km/h in northerly direction is the most unfavorable condition. It would be the most dangerous, since panels are inclined towards the south, thus creating suction loads. The pressure that this wind applies on a perpendicular surface is 75 kg/m^2. However, part of wind pressure is lost as it flows though the panels.

Wind force can be decomposed in two components, as seen in data from bid for tenders offered by the Spanish Ministerio de Hacienda y Administraciones Públicas (Plataforma de Contratación, n.d.) [145]:

- F1: Parallel to panel surface (does not apply force)

- F2: Perpendicular force on the panel surface

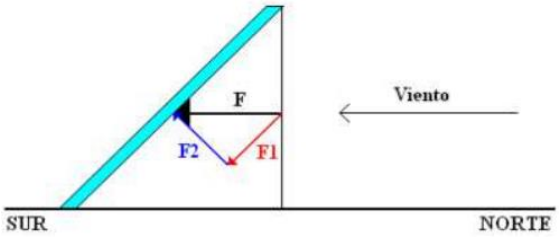


Figure 61: *Schema representing northernly wind loads on a panel*

ULS design and verification must ensure:

$$Loads\ Applied\ < Resistance$$

$$Loads\ Applied = \sum Permanent + Varaible$$

Permanent loads depend on the panel and mounting structure weight. It is previously studied that permanent loads do not cause failure in the majority of cases as rooftops are capable of supporting enough weight. Variable loads are generally wind or snow. In Barcelona, wind can be especially problematic.

$$F2 = F * \sin(\alpha) = 75\left[\frac{\text{kg}}{\text{m}^2}\right] * \sin(41º) = 49.21\left[\frac{\text{kg}}{\text{m}^2}\right]$$

$$S = Area\ panel * \sin(\alpha) = 1.626\ [m^2] * \sin(41º) = 1.066\ [m^2]$$

Therefore, the force applied on the panel surface is:

$$F = F2 * S = 49.2 \left[\frac{\text{kg}}{\text{m}^2}\right] * 1.066\ [m^2] = 52.45\ \left[\frac{kg}{panel}\right]$$

Resistance of the panel is based on the self-weight of the panel and the strength of the supporting structure junctions. At least 52.45 kg of self-weight is required to counter a wind load of 120 km/h.

This involves a non-mandatory procedure carried out by a specialized engineering company ("Certificado Final de Obra Visado por Colegio de Ingenieros"), according to NBE-AE-88. Service cost ranges around **200€**.

2.7.1.10 Labor Installation

Specialized labor is necessary to carry out a PV installation. A site assessment is done to estimate an installation price based on building conditions and installation procedure. Mainly, important parameters are height of the structure, accessibility to the rooftop and risk level. Typical rates charge around 20-35€/hour for qualified technicians. This includes panel disposition but also pole mount, supporting structures, wirings, and safety measures among other procedures.

External costs are site assessment, system design (site plans), permit management or ordering equipment.

Generally, this accounts to a price of 1,000€-1,200€ of labor cost overall per system installed. Installation procedure of solar panels costs 21% tax rate (VAT). It is one of the only taxes left as they have eliminated many taxes to incentivize solar panel installation. This tax only applies during the installation procedure. In the case of new buildings this tax rate is reduced to 10%. (Fiscalidad, n.d.) [129]

2.7.1.11 Bidirectional Meter (On-Grid)

A bidirectional meter is only required for on-grid systems. It is not considered in the Excel computation for this scenario as it is an off-grid model. However, it is mentioned to account for the possibility of on-grid systems, if connecting to them is of interest in the future.

It measures the amount of energy an electrical system produces and uses. It allows to manage surplus energy waste by selling it back into a central grid. But, if the solar panels do not generate enough energy, the bidirectional meter will compensate your system by obtaining energy from the central grid. This is especially useful when solar panels have been under a streak of low solar irradiance or have not been performing well.

Figure 62: *Bidirectional Single-Three-Phase Direct Analyzer-Meter for Zero Discharge 100A MAXGE* (Funcionamiento, 2023) [125]

The bidirectional meter costs **180€**.

2.7.1.12 Investment Analysis Cost Distribution

The battery is the most expensive element of a PV system. It accounts for 30% of the total investment cost, although it is distributed in two payments separated by a decade. It is an element that is worth investing money on in an off-grid model since it affects system efficiency.

Labour costs and solar panels are the next most expensive element of a system at 17% of the total cost each.

Product	€/system	%
Battery	2,294	30
Manpower	1,331	17
Panels	1,320	17
Inverter	750	10
Legalization	450	6
Mounting Structure	420	5
Monitorization system	350	5
DC-AC Protector	286	4
Structural Verification	200	3
LEV Charger	170	2
Cables	95	1

Table 5: *Investment analysis cost distribution, figures rounded. Author's data.*

2.7.2 Operational

Operational costs refer to costs that occur throughout the lifespan of the solar panels. This includes maintenance costs or an insurance that guards the panels in case of a catastrophe.

2.7.2.1 Maintenance Costs

An advantage of solar panels is that they are not high-maintenance. Common concerns are periodic cleaning and keeping them from obstacles such as debris or possible shadows.

Regular inspections should be carried out to detect faults and potential issues. Repairing and maintaining solar panels can often help avoid minor issues from becoming more serious and costly.

PV panels need to be cleaned 2 to 4 times a year. Checks are usually self-service; it is not required to have a specialist to maintain them.

A typical cost is 10€ per panel. Consider they are cleaned three times a year and we have an 8-panel system:

$$Regular\ Checks = 10 * 3 * 8 = 240 \left[\frac{€}{year}\right]$$

A common recommendation is to install a monitoring system that lets you track exactly how much energy your solar panels produce over the course of time. A monitoring system will let you know when a solar panel malfunctions. It is important to regularly check panels, especially in the case that the monitoring system indicates there are some problems (How to Protect, 2022) [98].

If we hire a maintenance service that monitorizes the system (solar panels, inverter, cables, efficiency checks etc.) with a software it can cost:

$$Maintenance\ Monitoring = 100 \left[\frac{€}{year}\right]$$

Total maintenance costs for an 8-panel system considering regular checks and a software monitoring system:

$$Total\ Maintenance = 240 + 100 = 340 \left[\frac{€}{year}\right]$$

2.7.2.2 Insurance

To avoid possible problems, it might be worth investing in an insurance policy to cover hidden costs. Insurance covers electrical damages, material damages (due to cracks, fire, explosions, or lightning strikes), loose wiring or an inverter not communicating. It can also cover damage caused to third parties, unexpected loss of efficiency or machinery malfunction due to design errors (Seguro Para Placas, n.d.) [110].

Many customers express the fear of their panels being stolen or vandalized. It is better to install panels on a rooftop where the installation is less accessible, and they are more visible to neighbors.

Figure 63: *PV panel system collapse on roadway after a wind-shock (*Seguro para placas, 2023) [112]

Often, insurance for solar panel installations are included with home insurance. For example, rates are around 20€ bonus for every 3000€ invested. Let us consider an extra item associated with home insurance of 68€/year (Seguro RC, n.d.) [111].

2.7.2.3 Investment + Operational Analysis Cost Distribution

Regarding investment prices, the battery was the most expensive component of the system. If operational costs are included in the study, maintenance of the solar panels is the most expensive aspect of owning PV panels, almost accounting for 50% of expenses throughout the 25-year span.

Product	€/system	%
Maintenance	8,500	48
Battery	2,294	13
Insurance	1,700	9
Manpower	1,331	7
Panels	1,320	7
Inverter	750	4
Legalization	450	3
Mounting Structure	420	2
Monitorization system	350	2
DC-AC Protector	286	2
Structural Verification	200	1
LEV Charger	170	1
Cables	95	1

Table 6: *Investment + Operational costs of a PV panel system over 25-year period*

2.7.3 Legislation and Incentives

Solar panels are a new technology that is expensive because it is still in development. New customers are often discouraged from purchasing a PV system due to long amortization periods. The Spanish government has established policies to promote and incentivize renewable energies, including solar.

2.7.3.1 Government Incentives

- IBI

Property tax reductions for companies or particulars are reimbursed at 50%. There is an IBI (Impuesto sobre Bienes Inmuebles) reduction for the first 3 years. The average IBI in Barcelona is around 600€ a year. For the next 3 years after the installation, there is a 50% discount of IBI for all affected owners. (IBI en Barcelona, 2022) [135].

$$IBI = 600\ [€] * 3\ [years] = 1800\ [€\ in\ 3\ years]$$

$$Discounted\ IBI = 900\ [€\ in\ 3\ years]$$

- ICIO

A work permit tax deduction on ICIO (Impuesto sobre Construcciones, Instalaciones y Obras), which is reduced to 95% in Barcelona. Given the legalization procedure considered for a standard system savings are as follows:

$$Discounted\ ICIO = 450\ [€] * 0.95 = 427.5€$$

- IRPF

IRPF deductions incentivize renewable energy sources. This law is part of "Plan de Recuperación, Transformación y Resilencia" of MITECO, a plan for recovery, transformation and resilience of the Ministry for the Ecological Transition and the Demographic Challenge. It is possible to apply tax deductions based on the investment of the system and a reduction of energy consumption:

A. A 20% tax deduction if 7% reduction in heating or cooling is achieved in a household. Maximum 5,000€.

B. A 40% tax deduction if 30% reduction in energy consumption in achieved in a household. Maximum 10,000€.

C. A 60% tax deduction if 30% reduction in energy consumption is achieved in a building block. Maximum 15,000€.

The most common case is that not all incentives are granted. It is also not realistic that there will be a 30% reduction of energy consumption, since buying a LEV will indeed consume more electricity. Therefore, IRPF deductions will not be included in the study.

- European Funds Next Generation

Next Generation funds are used to finance government incentives in the plan "Plan de Recuperación, Transformación y Resiliencia (PRTR)". NG funds are used to supply all projects that have energy efficiency as a goal. Based on the type of customer (business, service company, individual, etc.), a different amount is awarded. For example, for a single household, a total of 1,110€ is awarded per kWp installed, and 490€ per kWp installed for the battery, thus:

$$1{,}110\ \left[\frac{€}{kWp}\right] * 2.4\ [kWp] = 2{,}664€$$

$$490\ \left[\frac{€}{kWp}\right] * 2.4\ [kWp] = 1{,}176€$$

$$Discounted\ NG\ funds\ = 3{,}840€$$

Other tax benefits include a 50% tax deduction of the "Impuesto sobre Actividades Económicas "(IAE), which only applies to some businesses or self-employed people. Here we will not consider it, although it could be a factor.

Total incentives granted to finance a PV panel system are thus:

$$\sum Incentive\ benefits = IBI + ICIO + NG = 5{,}167.5€$$

2.7.3.2 Permits

If the building's community or association of owners seeks to install a PV system on the rooftop, the "17.1 Ley de Propiedad Horiontal" regulates the permits in Spain, while the "Llibre V del Codi Civil (CC)" is applied in Catalonia.

The favorable vote of most of the owners, i.e., a simple majority, is required to carry out the works or actions to install renewable energy sources on buildings. Accreditation through the building's energy efficiency certificate or the implementation of renewable energy sources for common use, as well as the application for aid and subsidies, loans, or any type of financing by the community of owners to public or private entities, can be executed if a favorable vote is achieved (553.25 del Codi Civil).

2.7.3.3 Sunlight Tax (Impuesto del Sol)

The Spanish "Sunlight Tax", approved October 9 2015 (Real Decreto 900/2015), legislated that customers had to pay equivalent electricity taxes when selling energy. It affected on-grid customers that sold surplus energy from solar panel installations to private companies. It intended to protect traditional electricity companies from losing business. Furthermore, it prohibited communities from sharing energy in the same building, thus limiting the possibility of taking full advantage of economies of scale. The tax was exempt for off-grid customers of systems of less than 10 kW (Impuesto al sol, 2023) [136].

Spain was one of the only countries in the world with a sunlight tax. This disincentivized development of PV systems thought the country and hampered a renewable energy transition (as established by the EU, 30% of energy obtained in 2030 must come from renewable sources).

The EU stated that a sunlight tax was an illegal procedure. After October 5 2018, the government had abolished the Sunlight Tax for PV users. Once this tax was derogated, it incentivized customers to purchase PV systems; from then on, an increase in demand throughout the country was apparent and development in the sector boomed.

2.7.4 Solar Panel System ROI

A PV panel investment calculation is done considering a typical lifespan of a system. Consider a standard installation given the parameters previously exposed. It is installed in 2024 and an evaluation is done by 2050. The investment is evaluated, considering if Next Generation funds are received and if they are not awarded. A comparison of these two scenarios is done comparing different parameters (IRENA, 2022b) [177].

2.7.4.1 With Next Generation Funds

Consult table spreadsheet in Excel format.

- Price per Watt

PPW is the price that solar homeowners will pay for every watt of solar power installed. PPW allows to compare one system against another comparing the price paid per solar energy output received:

$$PPW = \frac{NET\ system\ cost}{System\ wattage} = \frac{2{,}498.5\ [€]}{2{,}400\ [W]} = 1.04\left[\frac{€}{W}\right]$$

- Weighted Average Cost of Capital

WACC or discount rate is the minimum rate of return companies expect to receive by leveraging debt. It is composed of the risk-free rate and a risk premium.

$$WACC = Riskfree\ Rate + Risk\ Premium$$

Risk-free rate is the minimum return an investor expects for an investment without accounting for a risk factor. To establish a risk-free rate, the lowest risk bonds are considered, public debt bonds at three years. A recent reference appearing in the BOE, the official state bulletin, on 4 May 2023, is 2.856%.

Risk premium is a measure of excess return measured by an increased level of risk. It is a measure of the extra return demanded by market participants for the increased risk. According to the law 2/2015 ("Ley de desindexación de la economía española") the minimum risk premium is established at an additional 2%.

$$WACC = 2.856 + 2 = 4.856\%$$

- Net Present Value

Net present value is how much an investment is worth throughout its lifetime adjusted to the present value of money. A standard case yields a positive NPV, therefore it is interesting to pursue the investment opportunity.

$$NPV = -\ Initial\ Investment + \sum_{1}^{n} \frac{Cashflow, n}{(1 + WACC)^n}$$

$$NPV = -\ 2.666.5 + 6.862.31$$

$$NPV = 4{,}195.81€$$

- Internal Rate of Return

Internal rate of return yields the return rate an investment would stop being profitable. A standard case yields an investment return of 19% of the money invested. It is an investment worth pursuing since 19% IRR is far higher than the established WACC.

$$NPV = -\ Initial\ Investment + \sum_{1}^{n} \frac{Cashflow, n}{(1 + IRR)^n} = 0$$

$$IRR = 19\%$$

- Pay-back Period

Pay-back refers to the time an investment starts to generate a positive cumulative cashflow. Generally, a PV installation takes around 8 years to amortize. Given a pay-back period of 5.78 years, this corresponds to a shorter amortization period than average. The investment is worth pursuing since it has a shorter amortization period than average.

Amortization period can be calculated as:

$$Payback\ period = Negative\ cummulative\ years + \frac{Last\ negative\ Value}{Cashflow}$$

$$Payback\ period = 5 + \frac{338.5}{432} = 5.78\ [years]$$

Coefficient	Result
PPW	1.04 [€/W]
WACC	4.856 %
NPV	4,195.81 €
IRR	19 %
Pay-Back Period	5.78 years

Table 7: *PV panel system economical coefficients with NG funds. Author's data.*

2.7.4.2 Without Next Generation Funds

Furthermore, and in contrast, let us consider a scenario where Next Generation funds are not awarded. Would the investment still be profitable?

Coefficient	Result
PPW	2.64 [€/W]
WACC	4.856 %
NPV	355.81 €
IRR	5 %
Pay-Back Period	14.67 years

Table 9: *PV panel system economical coefficients without NG funds. Author's data.*

Without Next Generation subsidies, the NPV is still positive, but it only yields 355.81€ over a 25-year period. Moreover, the IRR becomes 5%, just barely above the WACC coefficient.

The investment will almost not generate cashflow but in theory funds will not be lost. Considering that the pay-back period raised to almost 15 years means the investment is deemed high risk, it would not be worth pursuing forward if NG funds are nor received.

2.8 Costs Saved

To calculate costs saved, a distinction is made between opting for a PV panel system, a LEV or both simultaneously. A cost benefit analysis is evaluated considering the cost of opportunity of opting for a system instead of another.

Furthermore, a computation of costs saved is done hypothesizing that the systems is installed in 2024 and evaluation occurs 25-years later in 2050, after solar panels lose efficiency.

Results gather information on the distribution of costs. The study seeks to evaluate where costs can be optimized or if it is worth investing in the system at all, hypothesizing different scenarios.

2.8.1 PV Panel

Two scenarios are considered. The first is the case where it is decided to not pursue a PV panel system. This would mean electricity is obtained from the central grid, and each month the electricity invoice is paid.

The second case features a PV installation that would make it possible to save all electricity bills related to charging a LEV or to supply all household expenses every year. This recognizes that an initial investment is required to install the PV panel system.

2.8.1.1 No PV System

Electricity bill per household in Spain is 70 €/month on average (Cuánto cuesta la luz, 2023) [186]. Accounting for a 25-year expenditure it is paid:

$$Electricity\ bill\ household = 70\left[\frac{€}{month}\right] * 12\ [months] * 25\ [years]$$

$$= 21{,}000€\ in\ 25\ years$$

Moreover, the average price of charging a LEV is 0.2572 €/kWh (Coste de cargar, 2022) [65]. To power a LEV, it is necessary 3,400 kWh/year based on a standard vehicle model. This accounts for electricity costs of:

$$Electriciy\ bill\ LEV = 0.2572\ \left[\frac{€}{kWh}\right] * 3{,}400\ [kWh] * 25[years] = 21{,}862€\ in\ 25\ years$$

2.8.1.2 PV Panel System:

If a PV panel system was installed, it would require an initial investment cost, mainly the kit appliances and installation procedure. It also requires operational costs throughout the lifespan of the system. Government incentives are awarded to help purchase the system.

Panel expenses	Costs [€/LS]
INVESTMENT	7,666 [€/LS]
OPERATIONAL	408 [€/year]
INCENTIVES	-5,167.5 [€/LS]

Table 10: *PV panel system costs distribution. Author's data.*

However, an 8-panel system with conditions established in previous chapters, allows to save electricity bills equivalent to an average LEV or household expenditure. Further analysis can be found in section 2.7.4.

$$Total\ PV\ system\ cost = 7{,}666 - 5{,}167.5 + 408 * 25 = 12{,}698.5€\ in\ 25\ years$$

2.8.2 LEVs

An analysis of opting for a LEV versus a fuel vehicle is studied. A scenario is evaluated where two new vehicles are purchased during a 25-year period. Each vehicle is sold after their lifespan expires.

Furthermore, since owning a vehicle also requires external costs such as fuel, maintenance and circulation expenses, these are compared for each vehicle type.

2.8.2.1 Fuel Vehicle

Let us suppose that a new fuel vehicle is purchased in 2024 at an average cost of 25,000€. After 11 years it is sold accounting for a 75% depreciation at a cost of 6,250€.

Once the first vehicle is sold in 2035, a new vehicle is bought at a price of 20,000€ in the same year. A 20% reduction in price is applied because fuel vehicles will be subjected to more restrictions in future years, such as low-emissions zones in city centers, increasing taxes or the prohibition to buy fuel vehicles by 2035.

To conclude, the second vehicle is sold at the end of the process in 2050 after an 85% depreciation at a price of 3,000€, which is basically the value of the vehicle if sent to wreckage.

Transaction Fuel	Vehicle Price [€/LS]
BUY 1st 2024	25,000 [€]
SELL 1st 2035	-6,250 [€]
BUY 2nd 2035	20,000 [€]
SELL 2nd 2050	-3,000 [€]

Table 11: *Fuel vehicle price transaction in a 25-year period. Author's data.*

Owning a vehicle requires external costs associated with maintenance and road transactions. The following table is a list of average external costs for a fuel vehicle: [187]

EXTERNAL COSTS FUEL	Annual Price [€/year]	Annual Price [€/25-years]
Fuel gas	1,900 [€]	47,500 [€/25-years]
Maintenance	500 [€]	12,500 [€/25-years]
Street Parking	192 [€]	4,800 [€/25-years]
Insurance	650 [€]	3,750 [€/25-years]
Tools	80 [€]	2,000 [€/25-years]
Taxes (IVTM)	150 [€]	3,750 [€/25-years]
TOTAL	3,472 [€]	86,800 [€/25-years]

Table 12: *External costs to owning a fuel vehicle. Author's data.*

Notice that the most expensive aspect of owning a vehicle is fuel gas replenishment. If we consider a fuel price of 9.5€/100km and that an average vehicle milage is 20,000 kilometers a year, this adds to yearly costs of:

$$Fuel\ gas = \frac{9.5}{100}\left[\frac{€}{km}\right] * 20{,}000\ \left[\frac{km}{year}\right] = 1{,}900\ \left[\frac{€}{year}\right]$$

Gas replenishment for a fuel vehicle is more than double all other external costs. Costs such as parking options and road tools have large variances, as they depend on the habits of each driver, whereas maintenance, insurance and taxes are a cost that is less deviant.

A 25-year period expense is contemplated such that all external costs remain constant throughout the years. This is unlikely to occur because prices tend to fluctuate as time evolves. For simplicity, they will remain constant in the study.

2.8.2.2 LEVs

The main drawback of transitioning towards LEVs are current high vehicle purchase prices. Even if LEVs have many benefits, such as lower external costs, government incentives and climate-friendly emissions, their purchase often does not compensate, due to high initial investment.

To deal with the initial vehicle cost, the Spanish government incentivizes the purchase of LEVs with grants. Incentives to purchase a vehicle are granted in the Plan MOVES III. A sum of 4,500 euros is granted per car purchase. Greater deductions can be claimed under certain conditions, such as company vehicles.

Plan MOVES III is granted twice, once for each of the two vehicles purchased during the cycle of the study. Perhaps more incentives will arise in the future (in a potential Plan MOVES IV and subsequent plans), but this is not evaluated in this case.

Let us purchase an average new LEV in 2024 for 53,038€. After 11 years it is sold considering a 75% depreciation at 13,259.5€. A new LEV is bought in 2035 for 42,430.4€. A 20% price reduction is considered from 11 years ago, since it is hypothesized that LEVs will become cheaper and more affordable to the public in the future. In fact, according to most sources, the cost of electric cars will already be similar to petrol equivalents by 2027. Finally, to end the cycle, the vehicle is sold in 2050 for 6,364.56€ (Cuánto se desprecia, 2021) [188].

Transaction LEV	Vehicle Price [€/LS]
BUY 1st 2024	53,038 [€]
SELL 1st 2035	-13,259.5 [€]
BUY 2nd 2035	42,430.4 [€]
SELL 2nd 2050	-6,364.56 [€]
PLAN MOVES III (x2)	-9,000 [€]

Table 13: *LEV price transactions in a 25-year period. Author's data.*

Over the long run, external costs related to owning a LEV are cheaper.

If vehicles have a low-emissions tag they are granted free parking spaces in city centers in blue area zones in Barcelona, circulation taxes are 100% reimbursed and road tools are credited at 75%. Generally, LEVs require less maintenance costs.

EXTERNAL COSTS LEV	Annual Price [€/year]	Annual Price [€/25-year]
Electricity bill	874.48 [€]	21,862 [€/25-years]
Maintenance	100 [€]	2,500 [€/25-years]
Street Parking	FREE	FREE
Insurance	650 [€]	3,750 [€/25-years]
Tools	20 [€]	500 [€/25-years]
Taxes (IVTM)	FREE	FREE
TOTAL	**1,644.48 [€]**	**41,112 [€/25-years]**

Table 14: *External costs to owning a LEV. Author's data.*

2.8.3 Total Saved per Person

- Saved on PV panel system

Income is not earned through a PV panel system, rather it is money not spent on electricity bills for 25 years that generates a positive net benefit. This account to a positive cumulative cashflow of:

$$PV\ panel\ difference = \ 21{,}000 - 12{,}698.5 = +\mathbf{8{,}301.5}€$$

- Saved on vehicle purchase costs: Fuel vs LEV

A comparison of vehicle price (excluding external costs) for a LEV and a fuel vehicle is compared.

Transaction	LEV vs Fuel [€/year]	Cashflow [€/LS]
BUY 1st	53,083 – 4,500 – 25,000	23,538 [€]
SAVED SELL 1st	13,259.5 – 6,250	-7,009.5 [€]
BUY 2nd	42,430.4 – 4,500 – 20,000	17,930.4 [€]
SAVED SELL 2nd	6,364.56 – 3,000	-3,364.56 [€]
TOTAL	-	**31,094.34 [€/25-years]**

Table 15: *Fuel vs. LEV vehicle price comparison*

Clearly, the cost of purchasing a LEV is not a beneficial transaction. Car purchase accounts to 31.094.34€ in negative cashflow.

It is an expense that has a great margin of error since it depends on the model of the vehicle. However, LEV price is the missing part of the equation to make a transition towards a LEV fleet by 2050 possible. If society seeks to transition towards LEVs, it is mandatory to first focus on reducing LEV purchase prices, which will make them a more viable option.

- External costs: Fuel vs LEV

The following example considers all external costs remain constant through the years. The major cost saved is on fuel expenses.

EXTERNAL COSTS Fuel vs. LEV	Fuel vs LEV [€/year]	External costs price [€/25-year]
Fuel - Electricity bill	47,500 – 21,862	25,638 [€/25-years]
Maintenance	12,500-2,500	10,000 [€/25-years]
Parking	192	4,800 [€/25-years]
Insurance	4,050 – 4,050	0
Tools	2,000 – 500	1,500 [€/25-years]
Taxes (circulation permit)	3,750	3,750 [€/25-years]
TOTAL		**45,688 [€]**

Table 16: *Fuel vs. LEV external costs comparison*

Major external costs saved when opting for a LEV versus a fuel vehicle are the expenses saved on gas bills. This accounts to 56% of money saved on fuel when opting for a LEV. Also, maintenance accounts for 22% of costs saved. Overall, the sum saved is 45,688€ over a 25-year period.

However, this benefit is compensated with higher purchase LEV prices. According to computations, a sum of 14,593.66€ is saved on a LEV purchase over a 25-year period given the above hypothesis.

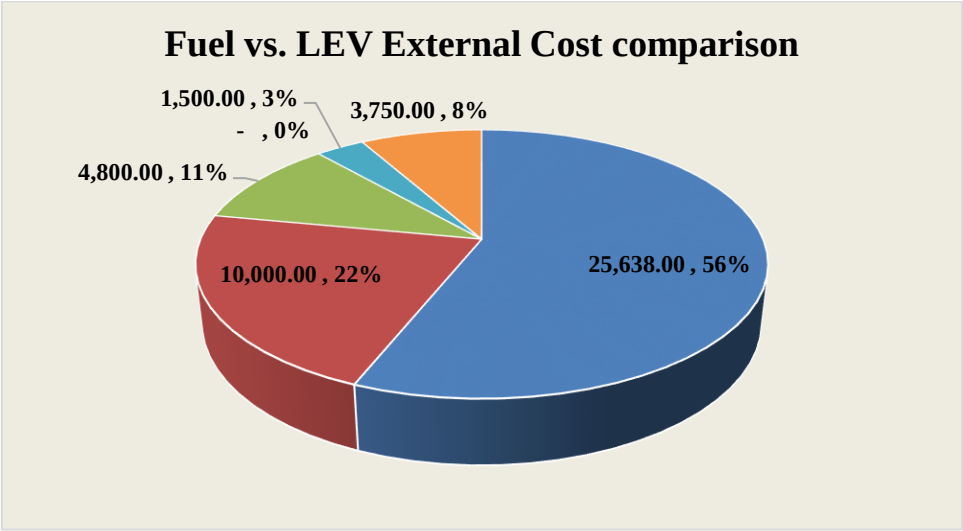


Chart 2: *Distribution of external costs comparison. Author's data, Excel generated.*

Furthermore, comparing two scenarios; a general case where a user does not use PV panels and uses a fuel vehicle, with the case of a user that uses both a PV panel system and a LEV, are compared to obtain the total benefit after 25 years.

Note that 22,895.16€ refers to potential expenditures not spent, rather than income earned.

Unit	Saved Cost 25-year period
PV Panel system	8,301.5 [€]
Car Price LEV	-31,094.34 [€]
External Costs LEV	45,688 [€]
TOTAL SAVED	**22,895.16 [€]**

Table 17: *Estimated costs saved for a user with PV panels and LEV during a 25-year period, as opposed to having NO PV panel system and a fuel vehicle. Author's data.*

2.8.4 Total Saved in Barcelona

Monetary value saved in the city of Barcelona during a 25-year period is the sum of money saved from three components. Saving on electricity bills due to PV panels, the sum of transitioning towards a LEV fleet by 2050, and the CO_2 emissions not emitted monetary cost.

Unit	Saved Cost in BCN per year	Saved Cost 25-year period in BCN
CO_2 emissions	195,509,954.74	4,887,748,868.5 [€]
PV Panel system	170,272,018.92	4,256,800,473.12 [€]
Car Price LEV	343,697,621,.65	8,592,440,541.14 [€]
TOTAL SAVED BCN	**709,479,595.31**	**17,736,989,882.76 [€]**

Table 18: *Total costs saved in Barcelona in 25 years. PV systems + LEVs. Author's data.*

Distribution of costs saved by source in Barcelona over a year:

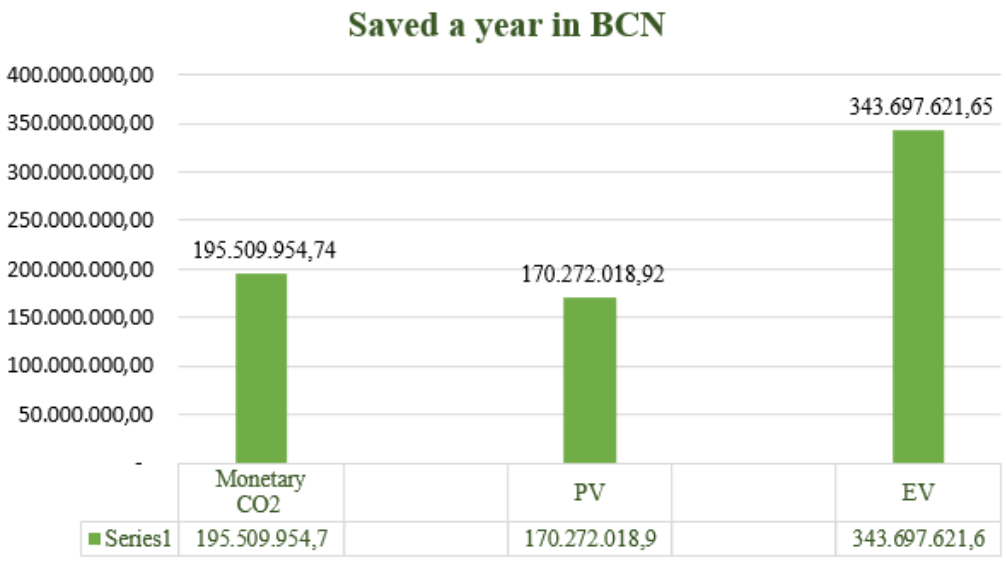


Chart 3: *Distribution by source of money saved in Barcelona per year in euros. Author's data. Excel generated.*

3. CONCLUSIONS

As seen in the project, solar power is one of the most accepted ways of obtaining energy. This is not only because solar systems allow to reduce costs, but also because of their environmental implications and availability throughout the world. Off-grid PV panels make it possible to be self-reliant from other sources of energy. In this way, the are a possible solution to future uncertainties that could potentially cause fluctuations in energy or gasoline prices.

This analysis of photovoltaic panel systems return on investment has given rise to many hypotheses. For example, a standard case where NG funds are awarded yields a positive cashflow in the system over the years. Without NG funds, the system would not be beneficial, since it barely earns any income. In fact, given that the discounted rate is almost equal to the IRR and that the amortization period increase to almost 15 years, this deemed the investment a risky alternative. If more incentives were awarded in the future, as it occurs in other countries, the system would yield a lower amortization period and be more suitable.

The study demonstrates that obtaining solar energy is a possibility in Barcelona. A major disadvantage is that it is not an accessible way of obtaining energy year-round, since it depends on climate conditions. Solar irradiance from October to March is less than the average value used in the calculations. In winter months, less energy can be used and stored. Perhaps off-grid systems are not viable in Barcelona and on-grid systems are necessary to supply the energy during winter months. Better batteries that allow to store more energy and have more cycles is an alternative, although this would mean a more expensive model.

Another concern is that there is not enough space in Barcelona to install the necessary systems to be independent. If a completely LEV fleet would exist in 2050, there would not be enough space in the city to install the necessary solar panels. Optimizing city space is necessary, so that panels might also be installed in public facilities, as it is currently happening.

The computations of the project are done mostly with reference to 4-wheel vehicles or cars, with the conclusion that around 600,000 cars can be propelled with solar panels. This correspond to the hypothesis that there will be less cars by 2050. Nevertheless, it does not consider other type of vehicles. In Barcelona there is a high percentage of motorcyclists. Around 30% of vehicle owners are two-wheel vehicles. These vehicles require less energy to charge and run. Even if the computations do not guarantee complete supply for all cars by 2050, it is possible to supply more vehicles than expected if individual cases are studied.

Moreover, an average LEV consumption rate is computed in the project. However, if customers decided to purchase lower-end models, such as the Nissan LEAF, PV panel supply will not require so much energy to propel these vehicles. If new LEV were released to the market with better consumption rates, the PV panels would be able to generate less energy. Therefore, less space is required to generate energy necessary and more vehicles can be propelled.

Given that in Barcelona there are relatively few charging stations, installing private charging stations can serve as an option to supply enough electricity to the incoming LEV fleet. There are a multitude of options that could improve the system proposed. For example, one would be sharing energy between the same building block community when there is a surplus of energy. Another option would be to increase supply of energy in public parking spots by paying an extra fee.

However, if society aims to transition towards a LEV fleet, it is mandatory to first focus on reducing vehicle purchase cost. As seen in the computations, it is the missing aspect of making LEVs a widespread reality.

Energy produced with solar can be used to propel LEVs or household expenses. If gasoline costs were to spike in future years, as it has happened due to the war in Ukraine, a transition towards LEV would be more beneficial, since more money would be saved. Likewise, if electricity bills surged in the future, PV panel supply would also be more effective. Basically, this system is an independent way of obtaining and managing energy without relying on public institutions and private investment to provide the necessary energy resources. Furthermore, it can serve as a hedge against worldwide uncertainties that cause fluctuations in prices.

Finally, and from a personal analysis as derived from this study, I suspect the reason why solar panels are not more prevalent in the world is because, as with many new technologies, they follow a learning curve. When more PV panels are produced and installed, it will make it possible to better understand the conditions and better optimize the system: a case of learning-by doing. This production then improves the product, which in turn increases demand once again. The production cycle follows a virtuous sequence of increasing demand and falling prices. At these lower prices, the technology becomes cost-effective and thus, demand increases once again. This positive feedback loop allows solar technology to evolve throughout the years, and it would ideally come into place to raise the viability of an off-grid PV panel supply for a LEV fleet in Barcelona in the year 2050.

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Reference and citation system: APA 7th Edition, 2019

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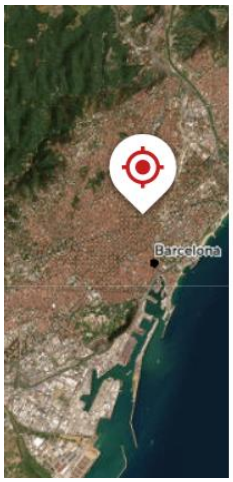
5. APPENDIX

5.1 Solar Panel Viability Analysis, Barcelona

New technologies allow in-depth information on photovoltaic parameters based on geographical location. Three examples are stated:

- Global Solar Atlas

The Global Solar Atlas gives specific data on solar irradiation (DNI, GHI, DIF), optimum angle tilt or power output, given a certain specific location or position (Global Solar Atlas, 2023) [155].

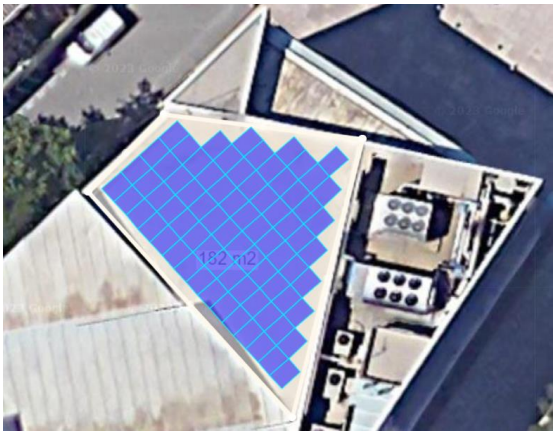


Map data			Per year
Specific photovoltaic power output	PVOUT specific	1574.2	kWh/kWp
Direct normal irradiation	DNI	1726.7	kWh/m²
Global horizontal irradiation	GHI	1613.5	kWh/m²
Diffuse horizontal irradiation	DIF	624.6	kWh/m²
Global tilted irradiation at optimum angle	GTI opta	1917.3	kWh/m²
Optimum tilt of PV modules	OPTA	36 / 180	°
Air temperature	TEMP	16.3	°C
Terrain elevation	ELE	39	m

Example of photovoltaic parameters in Barcelona, provided by GSA

- Solideo Calculator

Solideo allows to calculate square meters available in any rooftop giving an estimate on wattage power and money saved.



Example of a PV panel installation on Gabriel Ferreter library rooftop (Solideo, 2023) [37]

- PVGIS

- On-grid

PVGIS simulates production and solar irradiation based on geographical location, kilowatts installed, system losses, mounting options, slope or azimuth direction.

PVGIS-5 estimates of solar electricity generation:

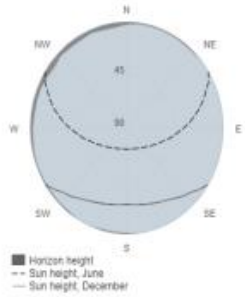
Provided inputs:

Latitude/Longitude:	41.398,2.169
Horizon:	Calculated
Database used:	PVGIS-SARAH2
PV technology:	Crystalline silicon
PV installed:	3.5 kWp
System loss:	20 %

Simulation outputs

Slope angle:	38 (opt) °
Azimuth angle:	4 (opt) °
Yearly PV energy production:	4849.79 kWh
Yearly in-plane irradiation:	1979.29 kWh/m²
Year-to-year variability:	130.53 kWh
Changes in output due to:	
Angle of incidence:	-2.53 %
Spectral effects:	0.73 %
Temperature and low irradiance:	-10.87 %
Total loss:	-29.99 %
PV electricity cost [per kWh]:	0.135 per kWh

Outline of horizon at chosen location:



Monthly energy output from fix-angle PV system:

Monthly in-plane irradiation for fixed-angle:

Monthly PV energy and solar irradiation

Month	E_m	H(i)_m	SD_m
January	329.6	127.7	43.4
February	340.1	133.8	39.6
March	435.0	173.4	35.6
April	434.5	176.0	36.7
May	477.8	197.2	34.2
June	480.7	201.9	16.2
July	496.3	211.1	19.1
August	474.8	201.7	19.3
September	409.9	171.9	21.7
October	355.7	145.3	42.7
November	304.8	120.9	38.3
December	310.7	118.4	31.3

E_m: Average monthly electricity production from the defined system [kWh].

H(i)_m: Average monthly sum of global irradiation per square meter received by the modules of the given system [kWh/m²].

SD_m: Standard deviation of the monthly electricity production due to year-to-year variation [kWh].

Simulation parameters for an on-grid model based in Barcelona

- Off-grid

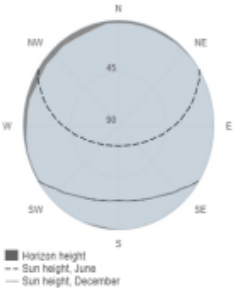
For an off-grid model, PVGIS provides information on battery performance and charging capacity.

PVGIS-5 estimates of solar electricity generation

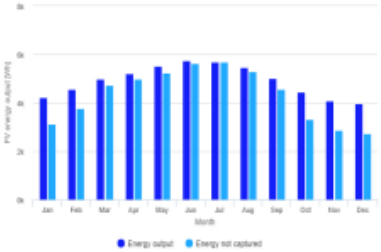
Provided inputs

Latitude/Longitude:	41.404,2.174	Slope angle:	40 °
Horizon:	Calculated	Azimuth angle	0 °
Database used:	PVGIS-SARAH2	**Simulation outputs**	
PV installed:	2500 Wp	Percentage days with full battery:	87.18 %
Battery capacity:	3500 Wh	Percentage days with empty battery:	100 %
Cutoff limit:	40 %	Average energy not captured:	4972.42 Wh
Consumption per day:	10000 Wh	Average energy missing:	5088.87 Wh

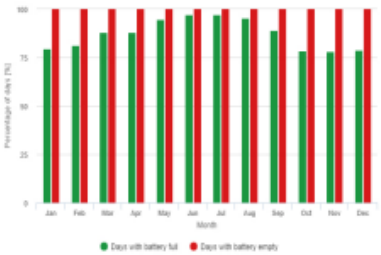
Outline of horizon at chosen location:



Power production estimate for off-grid PV:



Battery performance for off-grid PV system:



Monthly average performance

Month	E_d	E_l	f_f	f_e
January	4227.3	3131.8	79.4	100.0
February	4568.2	3765.2	81.3	100.0
March	4975.2	4724.0	88.1	100.0
April	5206.8	4996.3	87.9	100.0
May	5518.1	5241.9	94.6	100.0
June	5741.7	5639.1	97.3	100.0
July	5681.3	5701.9	97.2	100.0
August	5470.6	5284.1	95.4	100.0
September	5005.7	4570.2	89.0	100.0
October	4443.1	3337.6	78.4	100.0
November	4094.2	2859.8	78.1	100.0
December	3967.6	2719.9	79.0	100.0

E_d: Average energy production per day [Wh/day].
E_l: Average energy not captured per day [Wh/day].
f_f: Percentage of days when battery became full [%].
f_e: Percentage of days when battery became empty [%].

Probability of battery charge state at the end of the day:

Cs	Cb
40-46	51.0
46-52	3.0
52-58	2.0
58-64	3.0
64-70	3.0
70-76	2.0
76-82	3.0
82-88	4.0
88-94	3.0
94-100	26.0

Cs: Charge state at the end of each day [%].
Cb: Percentage of days with this charge state [%].

Simulation parameters for an off-grid model based in Barcelona

5.2 Excel Sheet

Excel sheet attached separately.