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A feasibility study of electric cars powered by solar energy – The cases of The Netherlands, Norway and Brazil

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Abstract

Transportation is a large source of CO_2 emissions on the planet due to the required combustion of fossil fuels in vehicles with an internal combustion engine (ICE). Electric Vehicles (EVs), on the other hand, offer a low CO_2 emission alternative to ICE powered vehicles. However, EVs can become even more sustainable when charged by sustainable electricity. Motivated by this issue, this study evaluates three main questions: (1) how can the electricity production of a solar PV system be balanced with a passenger electric car demand?; (2) how much can EVs CO_2 emissions be reduced?; and (3) how economically feasible charging EVs by PV systems is?. The analysis was carried out by taking into consideration three different countries namely The Netherlands, Norway and Brazil within a time horizon of 10 years. A model was developed in order to calculate the energy produced and consumed every hour, during the entire analysis period. The model assumes a Nissan Leaf 2017 of 30 kWh battery capacity commuting to work 5 days a week and not being charged during the weekends. The charging system is assumed to be a solar mono-Si PV carport system installed in parking lots where the user parks and charges his car while he is at work. As input values, data from PVGIS was used in which The Netherlands, Norway and Brazil have an annual average solar irradiation of 1,294 kWh/m^2, 1,132 kWh/m^2 and 1,801 kWh/m^2 respectively. The results showed that local conditions highly influence the technical, environmental and economic outcomes of each case. In The Netherlands and Norway, where low and variable solar irradiations are present, big systems of 10.2 kWp and 79 kWp respectively are required in order to provide all the necessary electricity to the car. These conditions cause 81% and 96% of the energy produced respectively to be fed back to the grid. Under another proposed scenario in which 75% of the total electricity produced is actually used in the car, only 26 full charges are needed to fulfil the car demand over one year in The Netherlands. In comparison, in the same situation 31 and 35 charges are needed in Brazil and Norway respectively. Economically, the adoption of such systems (EV and solar PV) can achieve returns up to 25% (The Netherlands), 23% (Norway) and 21% (Brazil) per year and payback times up to 2, 2 and 3 years respectively. Environmentally, coupling solar PV and EV can reduce the carbon intensity to 13 and 5 gCO_2-equivalent/km in The Netherlands and Brazil respectively. In Norway, because of its very sustainable electricity mix, an EV entirely powered by the grid has a carbon intensity of 1.6 gCO_2-equivalent/km. Over 10 years, 18, 30 and 20 tonsCO_2-equivalent can be saved in The Netherlands, Norway and Brazil by using EVs coupled with a renewable energy source. While providing all the energy required by the car with solar PV is not economically viable yet, small/medium solar PVs, which use the grid to back up them, are perfectly feasible. In all three countries analyzed, using EV has the potential to decrease significantly transport CO_2 emissions, with and without a PV system. The developed model gave a broad overview of how all the variables can impact the systems' outcomes, but validation with experimental data is still necessary.

Keywords: Electric vehicles, Solar PV systems, CO_2 emissions, Renewable energy, Feasibility study.

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List of acronyms

ANEEL	Agência nacional de energia elétrica
BEV	Battery electric car
CAT	Climate action tracker
CCS	Combine charging system
CCS(2)	Carbon Capture System
COE	Cost of electricity
CBS	Centraal Bureau voor de Statistiek
DC	Direct current
DISI	Direct Injection Spark Ignition
DOD	Depth of discharge
EEA	European Environment Agency
EPA	Environmental Protection Agency
EPE	Empresa de Energia Elétrica
ESTI	European Solar Test Installation
EV	Electric vehicle
EVSE	Electric vehicle supply equipment
EU	European Union
GHG	Greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP	Global warming potential
HEV	Hybrid Electric Vehicles
ICCT	International Council on Clean Transportation
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
IEA	International energy agency
IEC	International electrotechnical commission
IRENA	International Renewable Energy Agency
LCA	Life cycle Analysis
LCCA	Life cycle cost analysis
LCI	Life cycle Inventory
LCOE	Levelized cost of electricity
LDV	Light duty vehicles
Li-Ion	Lithium Ion
MIRR	Mean internal return rate
MRI	Minimum rate of interest
NEDC	New European Driving Cycle
NPV	Net present value
NTS	National Travel Survey
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturers
PV	Photovoltaic
Remap	Renewable energy roadmap
PHEV	Plug-in Hybrid Electric Vehicles
PVGIS	Photovoltaic Geographical Information System
REEV	Range Extended Electric Vehicles
RES	Renewable energy system
SAE	Society of Automotive Engineers
SOC	State of Charge
SUBAT	Sustainable Batteries project
UK	United Kingdom
VUB	Vrije Universiteit Brussel
V2G	Vehicle to grid

Introduction

This project explores the feasibility of charging electric vehicles, in particular passenger cars, by solar photovoltaic power from an energetic perspective, an environmental perspective along with a financial scope. In this introduction, the project background and reasons are explained.

Transport represents almost a quarter of Europe's greenhouse gas emissions and it is the main cause of air pollution in cities. The transport sector has not seen the same gradual decline in emissions as other sectors: emissions only started to decrease in 2007 and they still remain higher than in 1990. Within this sector, road transport is by far the biggest emitter accounting for more than 70% of all greenhouse gas (GHG) emissions from transport in 2014. Meanwhile, other sectors can already experience significant decreases in their carbon footprints[1]. This is the result of several polices that stimulate a greener future and which fit in the view of the European Commission’s Sustainable Goals (EEA, 2015).

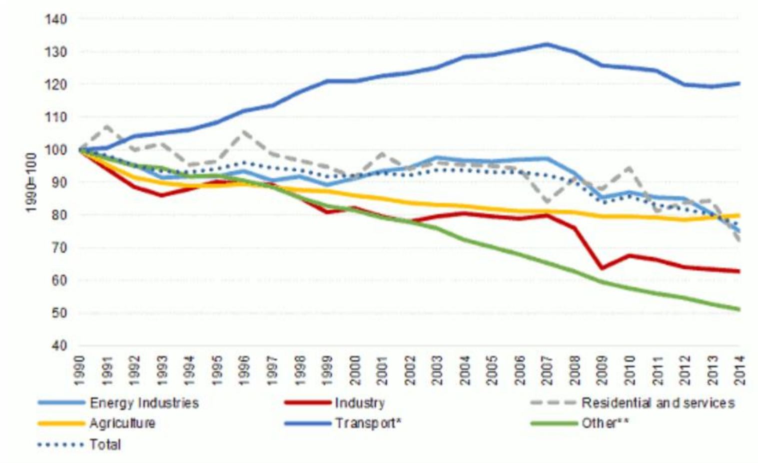


Figure 1 –European greenhouse gas emissions by sector, namely energy industries, industry, residential and services, agriculture and transport, where 1990 is indexed at 100.
Source: (EEA, 2015)

With the global shift towards a low-carbon and circular economy[2], the EC's low-emission mobility strategy (European Comission, 2016), adopted in July 2016, aims to ensure that Europe stays competitive and able to respond to the increasing mobility needs of people and goods. Europe's answer to the emission reduction challenge in the transport sector is an irreversible shift to low-emission mobility. By middle of the 21st century, greenhouse gas emissions from transport will need to be at least 60% lower than in 1990 as well as be firmly on the path towards zero. At present, the main strategy for achieving a low-carbon transportation is its electrification by mass adoption of electric cars.

An electric car is an alternative fuel automobile that uses electric motors and motor controllers for propulsion in place of more common propulsion means such as the internal combustion engine (ICE). Electricity can be used as a transportation fuel to power battery electric vehicles (EVs). EVs store electricity in an energy storage device, such as a battery. The electricity powers the vehicle's wheels via an electric motor. EVs have limited energy storage capacity, which must be replenished by plugging into an electrical source.

[1] A carbon footprint is historically defined as the total emissions caused by an individual, event, organization, or product, expressed as carbon dioxide equivalent.

[2] A circular economy is an economic system where products and services are traded in closed loops or ‘cycles’. A circular economy is characterized as an economy which is regenerative by design, with the aim to retain as much value as possible of products, parts and materials. This means that the aim should be to create a system that allows for the long life, optimal reuse, refurbishment, remanufacturing and recycling of products and materials.

Adding to features like immediate torque, silent ride and premium performance, EVs also have lower fuel and maintenance costs. Furthermore, consumers ultimately gather social pride and responsibility from helping to create a better, healthier planet. For all these reasons, EVs have caught the attention of car-lovers and commuters alike. Electric cars are commonly powered by on-board battery packs, and as such are battery electric vehicles (BEVs). Although electric cars often have a good acceleration and a generally acceptable top speed, the poorer energy capacity of batteries compared to fossil fuels, results in electric cars having a relatively poor drive range between charges. Moreover, recharging can take significant lengths of time. However, for everyday use, for instance commuting purposes, rather than day-long journeys, electric cars are very practical vehicles that can be inexpensively recharged. Other on-board energy storage means or energy generation methods that may extend the drive range or faster recharge batteries are being investigated at present, in order to improve EV's performance.

According to IRENA's global renewable energy roadmap (REmap) (IRENA, 2017), worldwide the total number of electric vehicles can potentially be increased to 160 million. This is a very challenging target, but if achieved, it would provide an important step towards raising the renewable-energy share of the transport sector. As a target, this total is split into 158 million passenger or Light Duty Vehicles (LDV), 1.4 million buses and 900,000 commercial vehicles.

With a geometric growth from the 500,000 units sold in 2015, sales of electric vehicles would need to rise to about 50 million units in 2030 to hit 160 million around the world. Growth in LDV sales could vary considerably, depending on the ownership rates at different income levels around the developing world. Additionally, new mobility systems, such as car and ride-sharing, could greatly reduce the number of vehicles needed to move passengers.

Figure 2 shows one possible scenario through which the 160 million electric vehicles target for 2030 could be reached, namely by 120 million EVs in "major markets" (OECD countries plus China), and 40 million EVs in the rest of the world. In this scenario, EV sales in major markets would need to grow by over 30% per year for the next 12 years; developing countries would not see a significant take-up of EVs for perhaps five to ten more years (probably providing more time for cost reductions as well as electricity grid and storage improvements), but from that point on, they would show a growth of over 60% per year through 2030 to "catch up" with the other regions (IRENA, 2017).

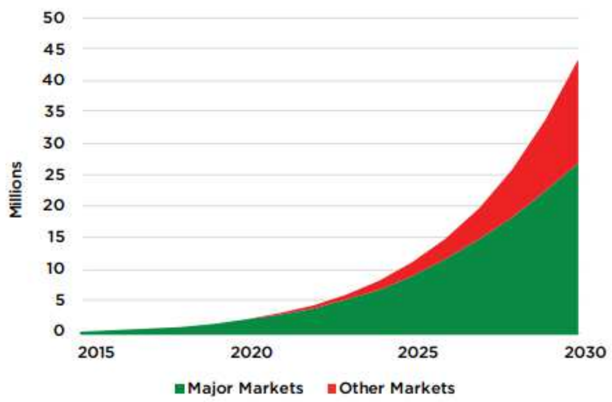


Figure 2 – A scenario for the sales of electric vehicles over time.
Source: (IRENA, 2017)

Electricity that powers an EV can come from many sources, from fossil fuel based electricity to low-emission sources like wind, solar, hydro, and nuclear power. The latter could enable EVs to dramatically reduce gaseous emissions. However, if this electricity comes from fossil based sources such as coal or natural gas, the electric car could change from an 'environmental hero' to an 'environmental fraud'. According to a research from the Mobility, Logistics and Automotive Technology Research Centre at the Free University of Brussels (VUB) (Holtl, et al., 2018), a battery-powered electric vehicle that uses electricity generated by fossil fuels will emit slightly more emissions over its lifetime than a diesel-powered car –

however still less than a gasoline car. Nevertheless, EVs that use electricity generated by renewable sources will produce up to six times less carbon emissions over their lifetimes than a gasoline car. This means that in order to the e-mobility switch to be most effective, countries will have to guarantee that sustainable energy is being used to power their EVs.

> At this point, an important research question still open ended emerges: how much CO_2 does a solar powered EV emit in different countries with different electricity grids?

Besides providing clean energy sources to power the fleet, another aspect which has an important role on the mass adoption of EVs is creating the necessary infrastructure to charge them. Nowadays, there is a great amount of gas stations everywhere and filling a tank can take just some minutes. Charging electric vehicles, as already mentioned, requires more time. Additionally, even in developed countries there is a lack of charging spots, for undeveloped countries this can be even inexistent. Nevertheless, improvements in the charging technology are pushing to faster more reliable ways to charge EVs (Egbue & Long, 2012).

The conditions described above create the biggest challenge for EVs, which is indeed to match its demand with the generation of electricity by renewables sources like solar photovoltaic (PV), for instance. The problem is that this technology, by its nature, is intermittent and faces the common criticism that when production is at its peak, householders are often unable to utilize all the energy. Extrapolated to a larger scale, intermittent renewables are a real concern for electricity networks; its supply unpredictable nature means that network operators need a stand-by generating capacity in the form of fossil-fueled generators.

> Therefore, another significant research question is: how can the electricity withdrawn from the grid or solar photovoltaic systems be optimally balanced with the energy needs of an EV?

The potential oversupply of electric vehicle battery packs, due to the increasing number of electric vehicles on the roads (Curry, 2017) and the intermittent nature of solar PV, creates the possibility of making use of this spare stock and prolong the use of the generated solar energy. The immediate solution is the development of decentralized charging stations with solar PV panel built in, which provides electricity to the cars connected to it. These solar charging stations, which can be carports or conventional rooftops systems could hold the key to acceptance of large-scale solar. Imagine shopping centers car parks or public and private parking lots covered with canopies holding megawatts of solar with designated charge points for electric vehicles. In that way, an ‘useless’ surface area can be used to generate the energy for urban transport, bringing together generation and consumption and avoiding use of big rural fields, one of the main criticisms of large scale solar generation (Pimm, et al., 2018).

Clearly, if either of these two technologies (electric cars and solar PV) reaches anywhere near their predicted potential they will have a key role to play in the move towards a low carbon economy. The marriage of both ones over the coming years seems to be a no-brainer and the solar industry should be actively promoting this symbiotic relationship. Despite short-term challenges, the future of EV and PV looks very bright indeed.

> Because the financial consequences of electric driving on solar power are not well known yet, the third relevant research question is: what are the cost of charging solar powered EVs?

The current study seeks to evaluate technically, economically and environmentally the possibility to use solar photovoltaic technology to power EVs. Nowadays, the electricity mix of most countries still contains a significant share of fossil based resources. Despite the growth of the renewables share around the world, the transition to a more sustainable way of transport continually represents a great challenge. Therefore, this study seeks to provide a method, based on a unique model, to assess the feasibility of using solar PV to charge EVs directly and/or indirectly.

Solar PV was the chosen technology because crystalline silicon PV cells are the most common solar cells used in commercially available solar panels, representing more than 95% of world solar cells total production in 2017. The remaining 5% is related to the thin film technology (Fraunhofer Institute for Solar Energy Systems, 2018).

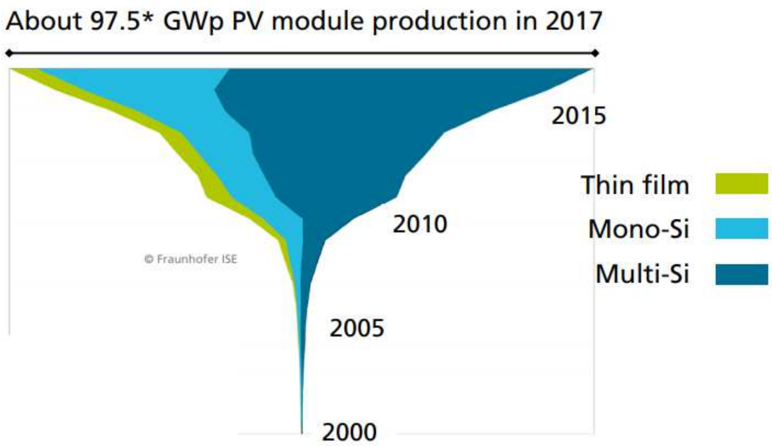


Figure 3 - Annual production of PV modules by technology worldwide.
Source: (Fraunhofer Institute for Solar Energy Systems, 2018)

This market dominance is explained by its benefits, according to Fraunhofer Institute for Solar Energy Systems, 2018, which include:

- Maturity: There is a considerable amount of information on evaluating the reliability and robustness of the design, which is crucial to obtaining capital for deployment projects.
- Performance: A standard industrially produced silicon cell offers higher efficiencies than any other mass-produced single-junction device. Higher efficiencies reduce the cost of the final installation because fewer solar cells need to be manufactured and installed for a given output.
- Reliability: Crystalline silicon cells reach module lifetimes of 25+ years and exhibit little long-term degradation.
- Abundance: Silicon is the second most abundant element in Earth's crust (after oxygen).

Additionally, silicon cells are widely used on decentralized systems because of its easiness to install and modularization, making it a good choice for households or buildings owners to install their own small-scale power plant. Those features also match with rooftop and carport systems, the type of charging stations envisaged by this study. As it will be better explained in the next chapters, it is assumed an average daily routine situation in which the car owners charge their car in the afternoon during the working hours. Consequently, the charging stations have to be installed at or close to their work places and those systems seem to provide the most suitable design for that kind of situation.

Figure 4 - Typical carport system (left) and a rooftop system scheme (right).

Everyday private and public companies install charging stations around cities and some of them are already coupled with solar PV systems like in Figure 4. The present study will assess how those systems behave from a technical, economic and environmental perspective.

Therefore, a model was developed in order to estimate the main parameters regarding these solar stations and electric cars, as the state of charge (SOC) of the car battery, PV electricity production, the amount of energy that the car consumes, the amount of electricity that is being fed back to the grid, the amount of electricity from the grid that is being used and the necessity of local storage. In such systems, due to the yearly and daily production intermittence of solar systems, it is very important to quantify when the electricity is being produced, when it is being used and when it can be exchanged (by charging the car). A daily or monthly analysis can lead to wrong estimations and big simplifications. For that reason, the developed model has an hourly approach that calculates all variables on an hourly basis in a timeframe of 10 years.

This study's model allows a wide range of possible analyses and therefore many different results can be obtained from it. However, this study's goal is to evaluate the possibility of using PV technology to charge EVs as well as to analyze the most important aspects impacting the system. In order to do that, several scenarios that simulate different system's configurations in which the relative amount of electricity produced by the PV system varies accordingly were considered, besides an extra scenario assuming a conventional car, running on gasoline, which was used as the base case and for comparisons. Finally, one last scenario envisages built-in solar panels on the car. The idea was to analyze if the panels on the car are able to generate enough energy and how much the current technology has to be improved in order to make it possible.

Additionally, four scenarios have been modelled for three different locations: namely Brazil, The Netherlands and Norway. The first one - Brazil - is a tropical country with a relatively high share of renewables. The second one - The Netherlands - is an European country with low share of renewables and thirdly, Norway, an European country with an almost 100% renewable mix, where electric cars already represent a significant share of its fleet. The goal was to explore what were the main differences between these three locations in terms of the technical, environmental and economic aspects.

It is important to mention that this study focuses only on aspects related to the vehicles' "fuel" which is, in the case of electric cars, the electricity used and its generation. Therefore, vehicle production, its acquisition, construction of charging stations (besides aspects closely related to the PV panels), disposal of the car or any equipment are not considered. In a comparison with a Life Cycle Analysis (LCA), the present study is just focusing on the "use" phase. All costs and emissions, which are not related to the electricity generation, are neglected, so all results should be treated with awareness about these assumptions.

The remainder of this study is organized as follows. In Chapter 2 a literature review is given about electric cars, charging stations with PV applications and experiences as well as estimations of solar cars (solar panels built in on cars). The methodology used to construct the model for analysis is explained, along with all equations, in Chapter 3. Explanations about all the input data needed regarding electricity rates, gasoline prices, driving pattern, etc. are also given in the same chapter. Then, in Chapter 4, the results are presented separately by country and scenario, but in this section there is no discussion yet because this is part of Chapter 6. In fact, Chapter 6 is preceded by Chapter 5, which is meant for the sensitivity analysis that comprises an impact evaluation of several variables on the results such as fuel prices (gasoline and electricity), PV costs and total distance travelled. Chapter 7 presents an hypothetical scenario where solar panels are built in on the car and the technical feasibility of such a system is analyzed. Lastly, in Chapter 8, the conclusions of this study are shown together with recommendations with the aim to improve and expand the current knowledge and debate about the subject.

Literature Review

2.1. Electric cars

A basic definition about electric cars was already given in the introduction of this report. However, this topic will be explained in more detail in this section. First of all the main types of EVs are categorized by the degree to which electricity is used as their energy source.

Hybrid Electric Vehicles (HEVs)

HEVs are powered by both petrol and electricity. The electric energy is generated by the car's own braking system to recharge the battery or by the conventional engine. Some sub-types can enable charging the battery in external outlets; these are called Plug-in Hybrid Vehicles (PHEV).

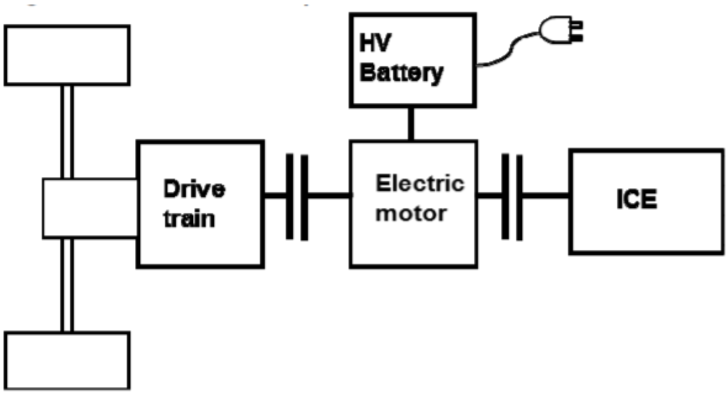


Figure 5 - BEV powertrain scheme.
Source: (Edwards, et al., 2014)

HEVs start off using the electric motor then the petrol engine cuts in as load or speed rises. The two motors are controlled by an internal computer which ensures the best economy for the driving conditions. The Honda Civic Hybrid and Toyota Camry Hybrid are both examples of HEVs in the market.

Range Extended Electric Vehicles (REEVs)

This type of EV is also powered by both petrol and electricity. Extended-range electric vehicles have a plug-in battery pack and an electric motor as well as an internal combustion engine. What differentiates them from a plug-in hybrid is that the electric motor always drives the wheels with the internal combustion engine acting as a generator to recharge the battery when it is depleted. An example of a REEV in the market is the Chevrolet Volt.

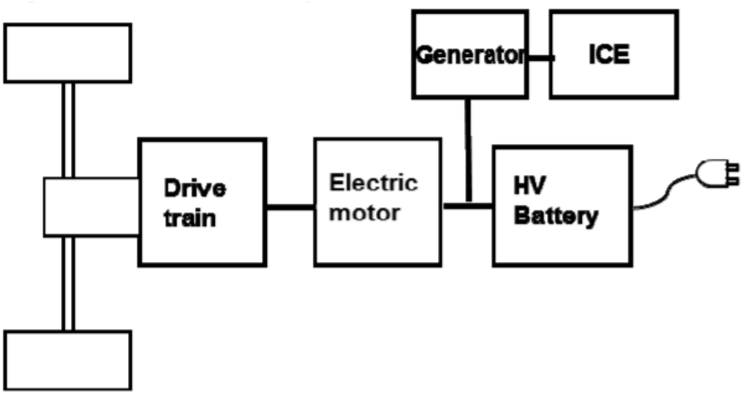


Figure 6 - REEV powertrain scheme.
Source: (Edwards, et al., 2014)

Battery Electric Vehicles (BEVs)

BEVs are fully electric vehicles, meaning they are only powered by electricity and do not have a petrol engine, fuel tank or exhaust pipe. BEVs are also known as 'plug-in' EVs as they use an external electrical charging outlet to charge the battery. BEVs can also recharge their batteries through regenerative braking. Examples of BEVs are Tesla Model S and Nissan Leaf.

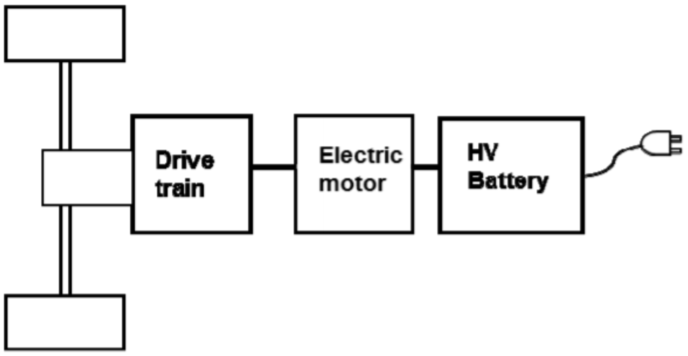


Figure 7 - BEVs powertrain scheme.
Source: (Edwards, et al., 2014)

Other important aspect to be assessed is the electric cars range and their average use per day in urban areas. The average kilometers driven by a car in one year in the Netherlands is 20,000km (for cars>1,500kg weight which is typical for EV) (Cent. Bur. Stat., 2012). This corresponds to a daily distance of 55km/day. With approximately 260 working days a year, 14,300km are driven on days going to the workplace. A major component of this is daily commuting to work which comprises 45km/day or ~80% of the daily distance driven. (Harikumaran, et al., 2012) (Mouli, et al., 2016)

With record-high new electric car registrations in 2016 (over 750,000 thousand sales worldwide) the transition to electric road transport technologies that began only a decade ago is gaining momentum and holds promise for a low-emission future. In the next 10 to 20 years the electric car market will likely transition from early deployment to mass market adoption. Assessments of country targets, original equipment manufacturers (OEM) announcements and scenarios on electric car deployment seem to confirm these positive signals indicating that the electric car stock may range between 9 million and 20 million by 2020 and between 40 million and 70 million by 2025 (IEA - International Energy Agency, 2017). Norway had the highest electric car market share globally (29%) in 2016. The current forecast is that in the Netherlands there will be 200,000 EVs in 2020 (Chandra, et al., 2016).

Environmental aspects of EVs

The rising demand for electric cars is very clear however what about their environmental impact? Some studies have been trying to estimate it and compare with the environmental burden of conventional cars.

A few studies consider battery and/or EV production explicitly at varied levels of detail and transparency. Samaras & Meisterling, 2008 focus on energy and global warming potential (GWP), providing an inventory based primarily on energy consumption within lifecycle stages. The article concluded that PHEVs reduce GHG emissions by 32% compared to conventional vehicles, but have small reductions compared to traditional hybrids. In addition, batteries are an important component of PHEVs, and GHGs associated with lithium-ion battery materials and production account for 2–5% of life cycle emissions from PHEVs.

Burnham, et al., 2006 provides a stylized representation of vehicle production relying on material content to estimate GWP criteria, air pollution and energy use to give a basis for comparing EVs with other technologies within the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. Van den Bossche, et al., 2006 and

Matheys, et al., 2008 perform a more complete assessment of traction batteries within the EU-sponsored Sustainable Batteries (SUBAT) project. Their results are generally presented as Eco Indicator points (a combination of several environments impacts) and in general terms, globally three battery technologies (lead–acid, nickel–cadmium and nickel-metal hydride) appear to have very comparable impacts on the environment. These technologies have a significant higher environmental impact than the lithium-ion and the sodium–nickel chloride technology.

Daimler AG, 2009 presents results from a comparative study of a hybrid and a conventional version of the same car from a full LCA perspective. This is likely the most complete life cycle inventory (LCI) of an EV. According to the author the CO_2 emissions of the S 400 HYBRID have been cut to 147gCO_2/km. However, it is for a hybrid rather than a full-battery EV. Hawkins, et al., 2012 developed an open inventory for a life cycle assessment of electric vehicles and conventional ones. Their results show a benefit in the use of electric cars using the European electricity mix to power them; if renewables were used these benefits would be even higher. EVs powered by the present European electricity mix offer a 10% to 24% decrease in GWP relative to conventional diesel or gasoline vehicles assuming lifetimes of 150,000 km.

Lastly, according to Mouli, et al., 2016, regarding CO_2, comparing conventional with grid powered, CO_2 emissions are reduced on an average by 38.5g/km. Nevertheless, the author considered PV systems to have 0 emissions, which is a big simplification since during production solar panels have an environmental burden.

2.2. Charging Stations

Guarantee the necessary infrastructure to charge electric cars is very important in order to foster their adoption. Guaranteeing a vast network of charging stations is indispensable to the transition from conventional to electric cars. In addition, most of the countries still have an electricity production heavily based on fossil fuels, which makes electric cars not much better than conventional cars, environmentally speaking.

An electric vehicle charging station is an equipment that connects an EV to a source of electricity to recharge plug-in electric cars. Some charging stations have advanced features such as smart metering, cellular capability and network connectivity, while others are more basic. Charging stations are also called electric vehicle supply equipment (EVSE) and are provided in municipal parking locations by electric utility companies or by private companies. These stations provide special connectors that conform to the variety of electric charging connector standards. Currently, there are three levels of charging and the availability of these levels depends on the car and on the grid conditions being used.

Level 1—Home Charging: Level 1 charging cords are standard equipment on a new EV. Level 1 charging only requires a grounded (three-prong) 120V outlet and can add about 40 miles of range in an eight-hour overnight charge. Overnight Level 1 charging is suitable for low- and medium-range plug-in hybrids and for BEV drivers with low daily driving usage.

Level 2—Home and Public Charging: Level 2 charging typically requires a charging unit on a 240V circuit, like the circuit used to power a common electric clothes dryer. The charging rate depends on the vehicle's acceptance rate and the maximum current available. With a typical 30 amp circuit, about 180 miles can be added during an eight-hour charge. Level 2 chargers are the most common public chargers, and you can find them at places like offices, grocery stores and parking garages. Public Level 2 chargers have a standard EV connection plug that fits all current vehicles, except for Teslas, which require an adapter (Yilmaz & Philip, 2013).

DC Fast Charging—Public Charging: Direct current (DC) fast charging is the fastest currently available recharging method. It can typically add 50 to 90 miles in 30 minutes, depending on the station's power capacity and the EV type. Tesla's Superchargers are even faster, adding up to 170 miles of range in a half hour. DC fast chargers are most useful for longer trips, cars in use most of the day (like taxis), and drivers who have limited access to home recharging. DC fast chargers use three different plug types and are not interchangeable. Japanese automakers typically use the CHAdeMO standard; most European and American makers use the Combined Charging System (CCS). Tesla's Supercharging stations use a proprietary connector specific to their vehicles.

Figure 8 - Type of charging plugs.
Source: http://www.powerenergetic.com

EV charging in Europe is defined by the standards in (SAE Standard J1772, 2010) (Standard IEC 62196, 2014). The charging plug type widely used in Europe for AC charging is the Type 2 Mennekes plug. It supports both single and three phase AC charging at Level 2 charging power level. However, in the future, DC charging using CHAdeMO and the Combined Charging Standard (CCS) will be most preferred charging standard for charging EV from PV at workplace due to the following reasons: Both EV and PV are inherently DC by nature. Dynamic charging of EV is possible, where the EV charging power can be varied with time. And DC charging facilitates vehicle-to-grid (V2G) protocol (Yilmaz & Philip, 2013).

The first parameter to be assessed in a charging station is to foresee the total electricity necessary to size the system sufficiently to attend the required demand. In Chandra, et al., 2016, charging profiles delivering 30 kWh/day to the EV battery were designed. If a daily commuting distance of 50 km/day is considered, based on Harikumaran, et al., 2012, 10 kWh/day charging energy is required by a Nissan Leaf (121 km range as per EPA driving cycle) assuming 95% charging efficiency. Thus, 30 kWh/day thus corresponds to the commuting energy needs of three EVs.

The next parameter is predicting the driving patterns and estimating when the electric cars will be connected to these charging stations. As this study focus on charging stations in commercial buildings, there are two possible patterns – one considering that EV is present on the whole week (7 days) and the second considering that EV is present only on weekdays i.e. 5 days/week. The first case is applicable for shopping malls, theatres etc. while the second case is suitable for offices, universities and factories.

Economic aspects of using solar energy systems

Many studies tried to assess the economic feasibility of solar powered charging stations. Mouli, et al., 2016 says that tracking systems are economically unfeasible as the 160€ or 208€ gain in energy cost/year cannot offset the 4,750€ or 8,177€ cost of installing a single or dual axis tracking system respectively. Based on Drury, et al., 2013, 0.57$/W and 0.98 $/W is the cost for 1-axis and 2-axis tracking system. Additionally, a common approach is used to evaluate every system: the annualized cost of electricity production is divided by the total useful electric energy produced in order to find the cost of electricity (COE). Then, this charging station COE is compared with the peak COE of electricity from the grid and with the feed in tariffs COE. Lastly, according to Mouli, et al., 2016 the yearly cost of fuel amounts to €2,013 on average in conventional cars. In electric cars powered by the grid it is €493/year, and in the cars powered by PV rooftop systems it is €215/year.

2.3. Solar car

A solar car is a solar vehicle used for land transport that run only or partly on power from the sun. Although some models can supplement that power using a battery, solar cars use solar panels either to recharge batteries or to run auxiliary. Solar cars depend on a solar array that uses photovoltaic cells (PV cells) to convert sunlight into electricity.

There are a few existing studies which discuss the use of PV roofs in passenger cars. Pisanti, 2015 compared a movable PV roof with solar tracking functions with a fixed horizontal PV for hybrid electric vehicles. The energetic analysis is limited to the maximum energy produced by the systems on monthly basis for a city in southern Italy considering the available solar irradiance. A solar energy gain in the range of 30–47% is found for the movable PV roof when compared with the fixed one, but no absolute values are reported. Giannouli & Yianoulis, 2012 determined the energy production potential of a horizontal PV roof installed on a hybrid electric vehicle. Also in this study, the solar energy production was based on solar irradiance availability for one location, in this case Greece. For a 1.2 m^2 solar PV roof, solar cells efficiency of 20% and 15,000 km of annual mileage, an annual saving in the range of 100 L gasoline was found. Birnie III, 2016 studied the competition for battery capacity of plug-in hybrid and electric vehicles when charged from vehicle-roof-integrated PV array and a work-place plug-in connection. The study is based on an optimistic assumption in which full exposure during driving and parking can be maintained. The author assumes a 300Wp horizontally mounted vehicle PV roof in New Jersey, 90% efficiency for the inverter/battery interface and an annual mileage of 12,000 miles. The study estimates that 12% of the annual vehicles mileage is covered by solar energy.

In addition, according to Lodi, et al., 2018, on average, the vehicle photovoltaic roof receives 58% of the available solar radiation in real-world conditions. The resulting average yearly irradiance value is 83.5 W/m^2 in the European Union (EU), thus resulting in an average share of usage of the available solar radiation of 58%. Average irradiance among the member states and the average EU-28 value is 143 W/m^2.

Some car manufacturers and start-ups are already working on this idea. For example, the Japanese automaker, Toyota, brought a new feature in the new 2017 Prius Plug-In. They say that the solar panel could increase car's efficiency by up to 10%. In good conditions, the panel would likely add about 2.2 miles of electric range to the vehicle throughout the day. Even though that can seem extremely optimistic, over the lifetime of the car it might make a small dent in the energy usage. Theoretically, Toyota's Prius Prime model could fill itself up with only the sun at the airport parking lot on a 10 day trip.

Figure 9 - Toyota Prius Prime.
Source: New Atlas, 2018

The German start-up Sono Motors, founded in 2016, is developing the Sion, a fully-electric vehicle that has solar cells integrated into its bodywork. It can be charged via solar power or from conventional power outlets. Sion will have 330 solar cells attached to the vehicle's roof, bonnet and sides and its battery system will offer a range of around 250 km (155 miles) before it needs recharging.

Figure 10 - Sion Solar Car.
Source: Sono Motors, 2018

In addition, a Dutch start-up called Lightyear is also developing a solar car. There is not much revealed about its project called, Lightyear One, but the company claims that the car can drive for months without charging. They say that the improvements, on aerodynamics, weight reduction, battery capacity along with solar panels will give Lightyear One a range of 400 to 800 km, depending on the configuration.

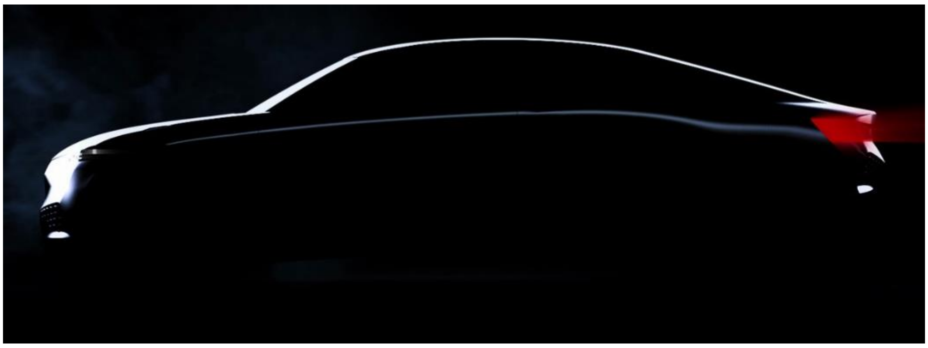


Figure 11 - Lightyear One.
Source: Lightyear, 2018

Methodology

In order to reach this study's objective, a model was developed either to calculate or estimate all parameters necessary to analyze the technical, economic and environmental feasibility of using solar energy to power electric vehicles. In this chapter, the methodological steps used, along with the model's conception and its references, will be fully explained.

Despite the fact that the technical, economic and environmental feasibility of a system are closely related, the developed model was divided in three sub-models: the technical, economic and environmental ones. In that way, the identification of the parameters, which are impacting the most each sub-model becomes clearer, facilitating the analysis of the whole model. The technical model determines the system’s energy balance, which is calculating and “tracking” where the energy is going in the system. Through that, it is possible to estimate the necessary parameters to evaluate the system and provide the required information to the other two sub-models. The economic sub-model is responsible to calculate the costs and savings of each possible system configuration and to evaluate them through financial indicators in order to assess its economic feasibility. Lastly, the environmental sub-model calculates the CO_2 emissions in order to evaluate the environmental feasibility of each configuration.

Following this methodology it was possible to build a general model whose most important task was analyzing how variables affect the system, but the results should always get close to real world situations. With that on view, the model was supported on three main premises or pillars:

1. **Real geographical places and situations of life**, where it could be applied. In this condition, the model allows the author to change important input values, such as hourly solar irradiation, driving patterns and total daily distance travelled. Additionally, parameters regarding the electric car assumed also can be adjusted according to the author objectives.
2. **Relevant aspects of reality**. By these assumptions, the model foresees electricity schemes, places where electricity can be fed back to the grid and the user rewarded by the utility company accordingly. In addition, the model can estimate a decay on the PV system performance as well as a change on electricity and gasoline prices throughout the years. Influences of inflation and currency devaluation can also be taken into account.
3. **Capacity of providing real tools to analyze results**. As a result of the previous two premises (pillars) through which many variables can be changed and adjusted, the model is able to calculate important indicators, such as: share of electricity being delivered by the grid, share of electricity produced by the PV system, total and relative CO_2 emissions, payback time, investment return rates, etc.

In summary, the technical sub-model calculates the performance of the system and provides the information regarding the amount of energy being used, fed to the grid or lost by system. The economic sub-model, based on the data provided by the technical one, assesses the economic feasibility. And, similarly, the environmental sub-model assesses the CO_2 emissions of the system.

As briefly explained in the introduction, the study assumes carport or rooftop systems as its envisaged PV structures. However, two other ways of powering a car are also included in the model in order to compare (and better analyze) the effectiveness of using a PV system. These three options are showed in the Figure 12.

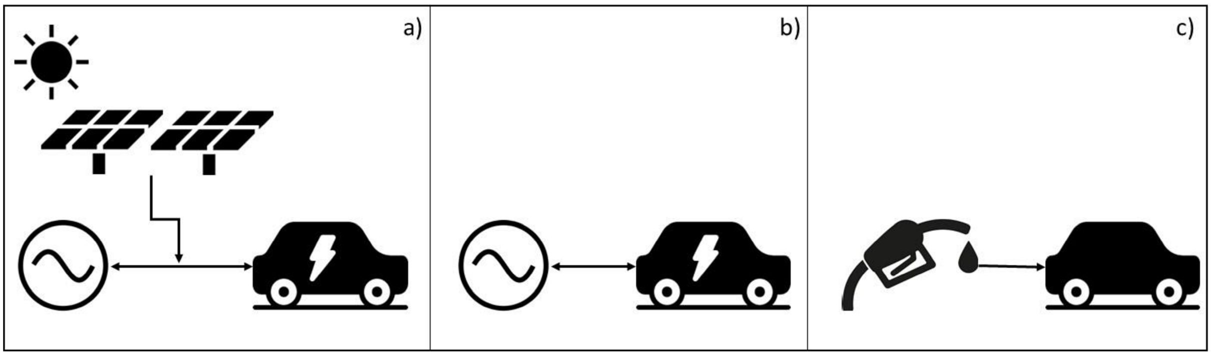


Figure 12 - Possible configurations in the model. a) Grid+PV b) Only grid c) Gasoline.
Source: Elaborated by the author

On the left it is showed a scheme of the PV + grid system assumed in the present study. As it will be better explained on the next chapter, different magnitudes of PV will be assumed and its consequences will be analyzed. At the center it is showed a scheme, where there is no PV and all energy comes from the grid. Lastly, on the right it is showed a conventional car powered by gasoline.

3.1. Technical sub-model

The objective of the technical model is to calculate all parameters regarding the performance of the PV system, local storage, charging station and the electric car in the different modelled scenarios. The model treats the envisaged simulation as a closed system, as shown in the Figure 13.

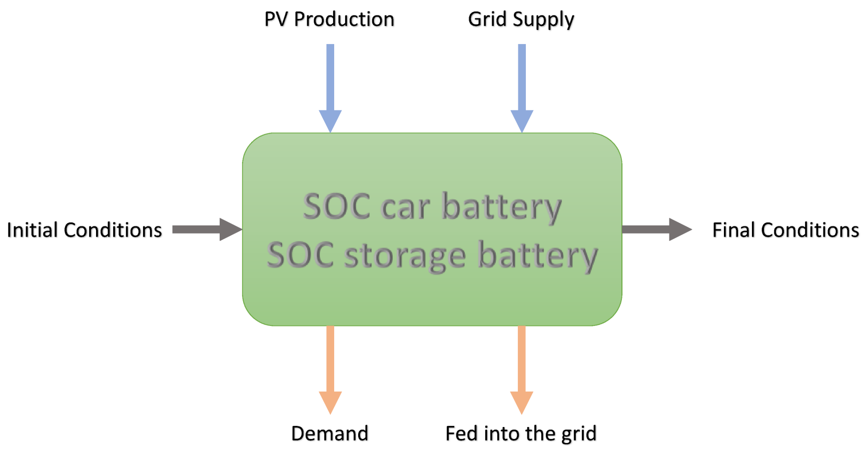


Figure 13 - Energy balance of the technical model.
Source: Elaborated by the author

In this representation, it can be seen the two sources of energy considered: the electricity being produced by the PV system (PV production) and the electricity which comes directly from the grid (Grid supply[3]). Additionally, the two ways of consuming this energy are identified: the energy used by the electric car to commute every day (Demand) and the electricity being injected back to the grid (Fed into the grid).

Inside the system, the parameters to be calculated are the state of charge of the car battery and of the storage battery. Furthermore, it is important to take into account the initial and final conditions of such parameters in order to keep the balance inside the simulation. The next step is to show how each of these parameters are calculated – or assumed - and which relations they have with each other.

[3] In this study the expression “grid supply” will always refer to electricity being provided by the grid to the car.

3.1.1. PV production

Data provided by the Photovoltaic Geographical Information System (PVGIS) is used in order to focus on the interaction between production and demand (and not on the PV performance), and, at the same time not giving up a reliable data source for the solar radiation and consequently the electricity production by PV modules.

PVGIS has collected solar radiation data from satellite that have been calculated for different spectral bands (Mueller, et al., 2012) to calculate the effect of spectrum changes on the PV energy output. Maps of the calculations results can be found in Gracia Amillo, et al., 2014 and Huld & Gracia Amillo, 2015. The spectral effects have been calculated for crystalline silicon modules.

PVGIS calculates the effects of irradiance and module temperature using a model described in Huld, et al., 2011, the power is assumed to depend on irradiance and module temperature. The coefficients used in PVGIS are based on measurements performed at the European Solar Test Installation (ESTI).

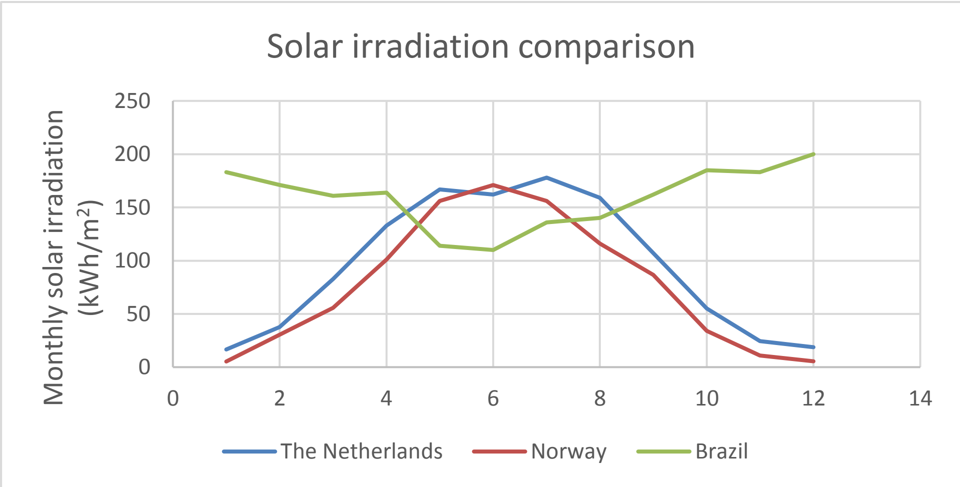


Figure 14 - Solar irradiation of The Netherlands, Norway and Brazil in 2016.
Source: PVGIS, 2018

In the Figure 14 the monthly irradiation for The Netherlands, Norway and Brazil is shown for the year 2016, representing an average annual irradiation of 1,294 kWh/m^2 for the Netherlands, 1,132 kWh/m^2 for Norway and 1,801 kWh/m^2 for Brazil. Nevertheless, the difference between the irradiation in the Summer and Winter is what calls the attention when comparing the three countries.

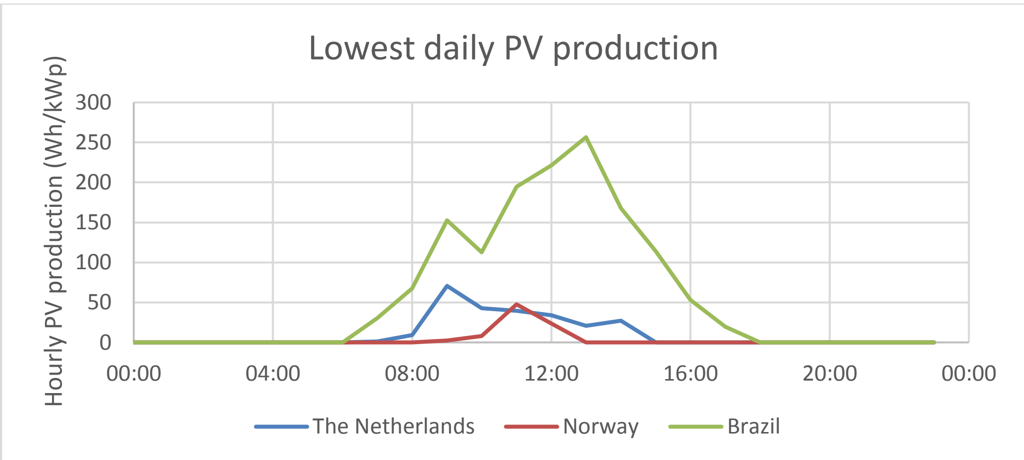


Figure 15 - Lowest daily PV production in The Netherlands, Norway and Brazil.
Source: PVGIS, 2018

In order to exemplify this, Figure 15 shows a comparison between the day with lowest PV electricity production in the whole year for each of the three countries. In this day, the daily PV electricity production is 245 Wh/kWp for The Netherlands, 81 Wh/kWp for Norway and 1,390 Wh/kWp for Brazil. This is due the fact that both The Netherlands and Norway are situated at high latitudes, while Brazil, as a tropical country, at low latitudes.

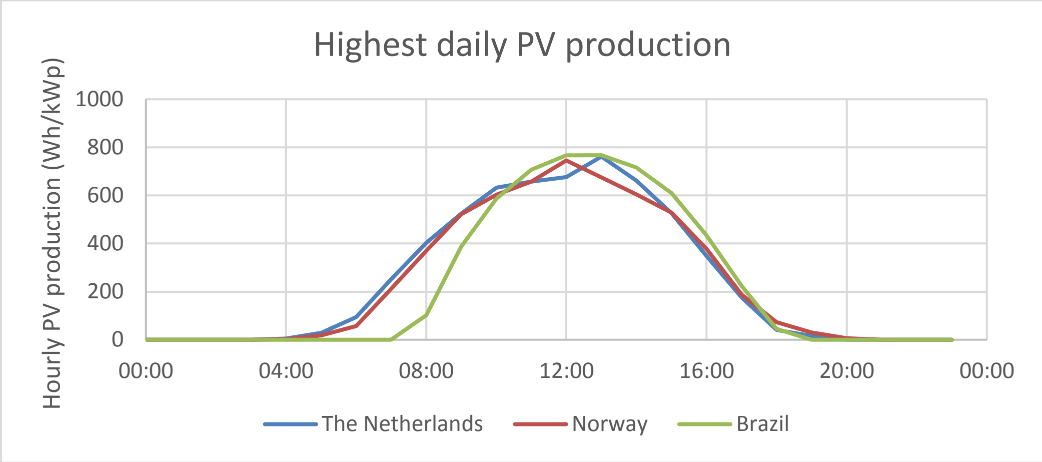


Figure 16 - Highest daily PV production in The Netherlands, Norway and Brazil.
Source: PVGIS, 2018

On the other hand, the Figure 16 shows the day with the highest PV production in all three countries. As it can be seen, they are very similar in magnitude except for a difference that in Norway and in The Netherlands (high latitudes), where the day is longer, there are more sun hours. In that day, the daily PV electricity production is 5,800 Wh/kWp for The Netherlands, 5,667 Wh/kWp for Norway and 5,344 Wh/kWp for Brazil. In summary, all three countries have similar solar irradiations during Summer, but very different ones during Winter.

In addition, the power of PV modules tends to decrease slowly with age. A large study (Jordan & Kurtz, 2013) found that PV modules typically lose about 0.5% of power per year of operation. This power decay is incorporated into the technical model.

Therefore, PVGIS provides the hourly data of electricity produced by 1kWp of a crystalline silicon module, which is considered in this model. In order to decrease the variability of solar irradiance every year, the value used on the simulation is an average between the data from 2012 and 2016. The array size is defined by each scenario and the total electricity produced by the system is directly proportional to it. Both the Figure 17 and the equation illustrate how the electricity produced by the PV system is calculated.

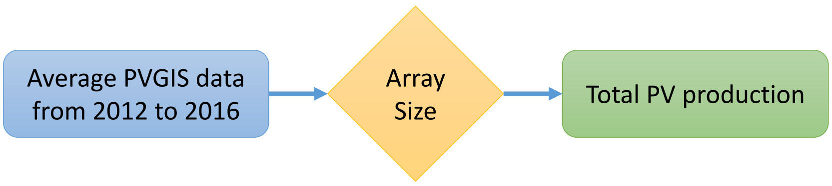


Figure 17 - Block diagram of PV production calculation.
Source: Elaborated by the author

$$E_{PV} = A_{PV} * \frac{E_{PVGis}}{P_{nom,PVGis}} \quad (1)$$

Where:
E_{PV} – Electricity produced by the PV system (kWh)
A_{PV} – Array size (kWp)
E_{PVGis} – Average hourly data provided by PVGIS (kWh)
$P_{nom,PVGis}$ – Nominal power used to calculate the average hourly data by PVGIS (kWp)

3.1.2. Power delivered by the grid

The power delivered by the grid, here called grid supply, is also calculated hourly and limited to 6.6kW as it is the limit defined by Nissan when a conventional charging station is charging a Nissan Leaf. (Nissan, 2016)

According to Marra, et al., 2010, in pure EVs, the battery is used for the entire driving cycle. For this reason battery manufacturers suggest a depth of discharge (DOD) levels of up to 80%. Therefore, this model considers that every time the car state of charge battery reaches a minimum of 20% of its capacity, the grid supply enters in action and charges the car. The charging should last until it reaches its full capacity (30 kWh), or if it is the time to disconnect the car from the charging station. The same study shows that discharging the battery in a level below that minimum reduces significantly the total number of cycles performed by the battery.

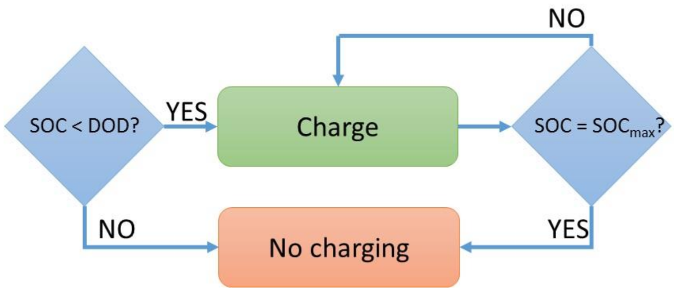


Figure 18 - Block diagram of grid supply calculation.
Source: Elaborated by the author

Where:
SOC – State of charge of the EV battery
DOD – Depth of discharge limit
SOC_{max} – Maximum battery capacity

3.1.3. Demand

Estimating when and how much the car will be used, are also relevant aspects which basically defines the system demand for electricity in the technical sub-model; one of its main advantages is taking into account the differences between the periods when the electricity is produced and used. Defining a driving pattern is important in order to better estimate when the car will spend the electricity stored in its battery. Usually people who live in cities have similar routines and consequently similar driving patterns; however local conditions also play an important role on these patterns.

Several studies tried to model the average daily driving patterns of a regular commuter. Speidel & Braunl, 2014 tracked eleven EVs in Western Australia in their regular daily routine. The peaks of distance travelled were at 7 am and 5 pm when the vehicles arrive at and leave from work.

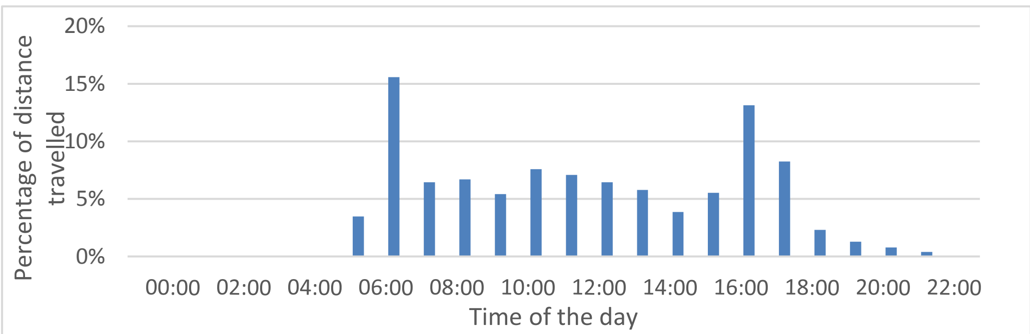


Figure 19 – Average driving pattern of 11 EVs in Australia.
Source: (Speidel & Braunl, 2014)

According to data of the National Travel Survey (NTS) in England, this same pattern repeats in the United Kingdom (UK); commuters concentrates their travel at 8am and 5pm.

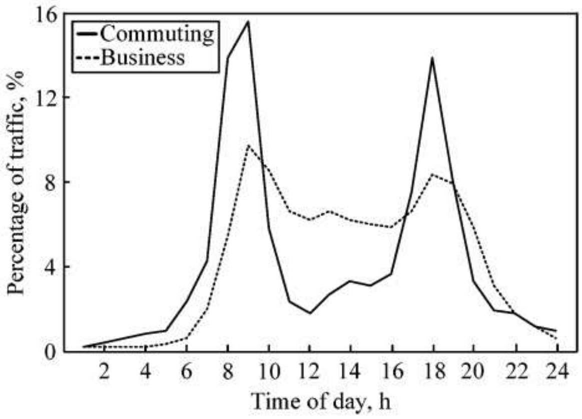


Figure 20 - Distribution of commuting and business trips by passenger cars in the UK in 2011.
Source: NTS, 2012

Another study in Sweden also tracked five cars that were driven by 29 randomly chosen families for two weeks each (Ericsson, 2000). This study also shows the patterns on Saturdays and Sundays. During working days the pattern repeats the two peaks in the morning and afternoon. However, during the weekends there is a constant increase during the morning and a constant decrease during the afternoon and night.

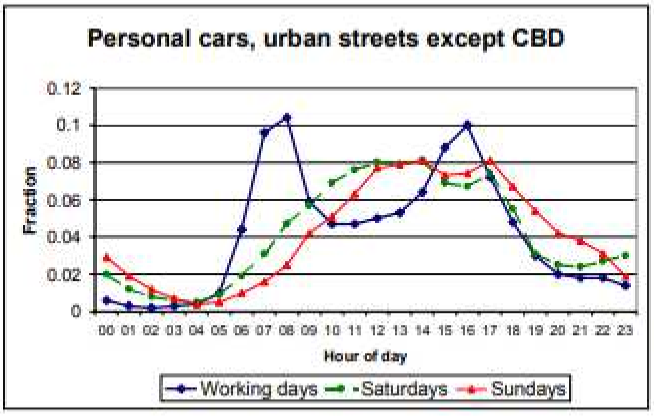


Figure 21 - Driving patterns during working days and weekends in Sweden.
Source: (Ericsson, 2000)

In a different study in Portugal (Goncalves, 2014), monitored 9 drivers in Lisbon for more than a month. The total time monitored were 842h resulting a total distance of 41,147km. The study also shows the aforementioned peaks during arrival and departure from work. However, in this case, part of the population come back from work a bit early at 13/14h showing two peaks in the afternoon.

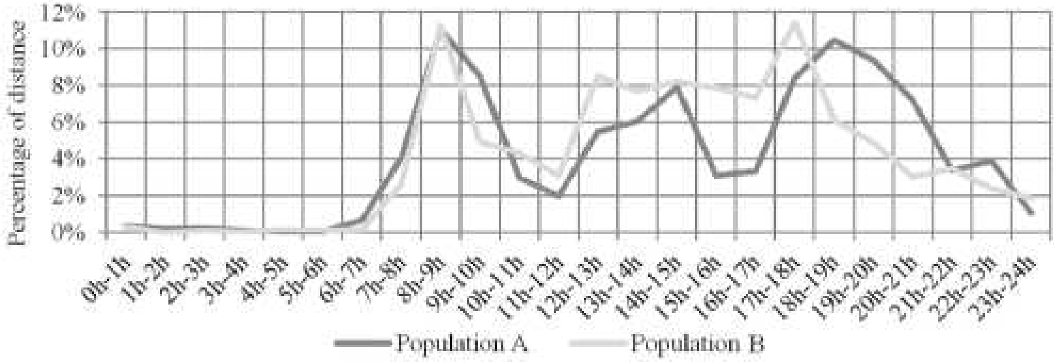


Figure 22 - Average distance distribution per hour in a week day in Lisbon.
Source: (Goncalves, 2014)

Based on all these studies, a daily routine was attributed to the electric car owner, for the purpose of the technical sub-model, resulting in the following driving pattern:

Table 1 - Driving pattern used in the model.

Time (h)	01	02	03	04	05	06	07	08	09	10	11	12
Share (%)	0	0	0	0	1	2	4	14	15.6	6	3	1.6
Time (h)	13	14	15	16	17	18	19	20	21	22	23	24
Share (%)	3	4	3.5	4	8	14	9	3.5	2	1.8	0	0

According to CBS, 2015 the Dutch travels 30 kilometers a day excluding professional transportation, such as the transport of goods, and excluding domestic holiday. The average Norwegian does 3.26 trips on an average day, with an average length of 14.7 km, which, sums up to 47.2 km of travel per day, according to the National Travel Survey (Figenbaum, 2018).

According to *Pesquisa de Mobilidade Alelo*, 2017, in the main capitals an average Brazilian travels 16 km from home to work, taking on average 47 min per trip. Therefore, it is assumed an average of 32km travelled by a car owner per day in Brazil.

Table 2 - Daily travelled distance per country used in the model.

Amsterdam	30 km
São Paulo	32 km
Oslo	47.2 km

Lastly, for the purpose of this model, it was defined the time during which the car would be connected to the PV system for charging, assuming a situation in which the system would be installed at a workplace (parking lot or rooftop), and the car would be connected after the worker arrives until he leaves the office.

It was considered a workday from 9:00 until 18:00 in all three reference locations in a way this condition could supply a nine hour charging interval. Consequently, the energy produced out from that period would not be used for charging the electric car if the charging station does not have any storage system. Additionally, during weekends, when the workplace is closed and the car is not connected to the charging station, the PV system is not being used to charge the car, but only the storage system is on, if applicable.

Other important data to define the electric demand are the type and efficiencies of the electric car used as reference. Among many existing electric cars models, the most known are from Tesla and Nissan manufacturers and the Nissan Leaf 2017, currently the most sold electric car in the world, seemed to be a good choice to meet the purpose of this methodological parameter.

Figure 23 - Nissan Leaf 2017
Source: Nissan website

According to Nissan specs report published by the manufacturer, the Nissan Leaf 2017 has a battery with a capacity of 30 kWh and a range, in the city, of 172 km (according to New European Driving Cycle (NEDC) standards). This means an average efficiency of 0.174 kWh/km.

Additionally, the Nissan Leaf 2017 counts up on two charging options, one on-board charger of 6.6 kW and a rapid charger port of 50 kW. This rapid charger port needs uncommon grid characteristics like more than 400 V and 100 A. Charger stations with these specs are hardly found and are much more expensive than regular charging stations. In this model, as already mentioned on section 3.1.2., the charging power will be considered using the on-board charger (6.6 kW) as it requires simple and easily found grid characteristics like 220V. (Nissan, 2016). The Figure 23 presents how the electric demand is calculated based on the information described above.

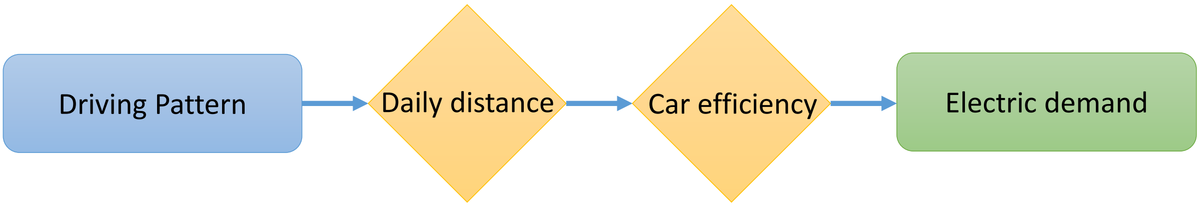


Figure 24 - Block diagram of Electric demand calculation
Source: Elaborated by the author

$$E_{EV} = DP * l * \eta_{EV} \quad (2)$$

Where:
E_{EV} – Electricity spent by the car (kWh)
DP – Driving pattern (%)
l – Daily distance (km)
η_{EV} – Electric car efficiency (kWh/km)

Internal combustion car

It is necessary to define the car specs in order to be able to compare the economic and environmental results of an electric car powered by solar power and conventional cars with internal combustion engine (ICE).

Differently from electric cars, ICE cars have a wide range of models which can have different engines technologies, fuels, efficiencies, ranges, etc. Therefore, in this study it was defined a car using Direct Injection Spark Ignition (DISI) and gasoline as fuel. A study from the International Council on Clean Transportation (ICCT), made in 2015, compared 20 different ICE models, in the European market in order to measure the fuel consumption of these cars. According to this study a conventional car, on average, have a fuel consumption of 7.2L/100km.

3.1.4. Fed into the grid

The electricity will be injected into the grid every time there is a surplus of electricity generated by the PV system that cannot be used neither by the car nor by the storage system. For example, at very early morning when the car is not connected to the grid and the storage battery is full all the energy produced goes back to the grid. The electricity injected will be calculated as follows:

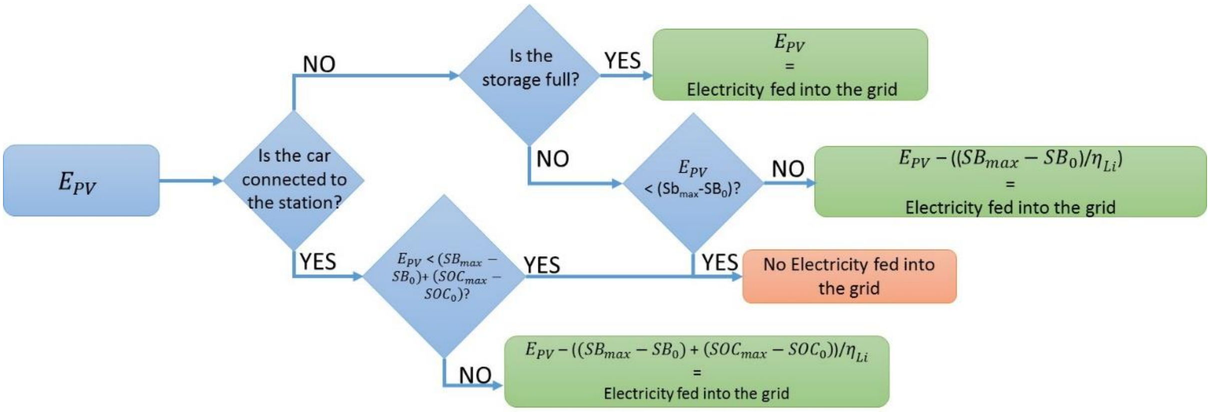


Figure 25 - Block diagram of Electricity fed into the grid calculation
Source: Elaborated by the author

Where:
SOC_0- State of charge of the car battery from the previous hour (kWh)
SOC_{max} – Maximum state of charge of the car battery (kWh)
SB_{max} – Maximum state of charge of the storage system battery (kWh)
SB_0 - State of charge of the storage system battery from the previous hour (kWh)
E_{PV}– Electricity generated by the PV system (kWh)
η_{Li} – Efficiency of charging a Li-Ion battery

3.1.5. SOC storage battery

The state of charge of the storage battery is calculated hourly based on the PV production, on the electric demand and on the need of energy from the car battery. Usually this system helps to decrease the electricity fed into the grid as it can store the surplus energy to be used later on. For example, if there is electricity production from the PV system and the car is not connected to the station, this energy is stored on the storage system and later, when the car connects to the station, this energy can be used to charge the car battery.

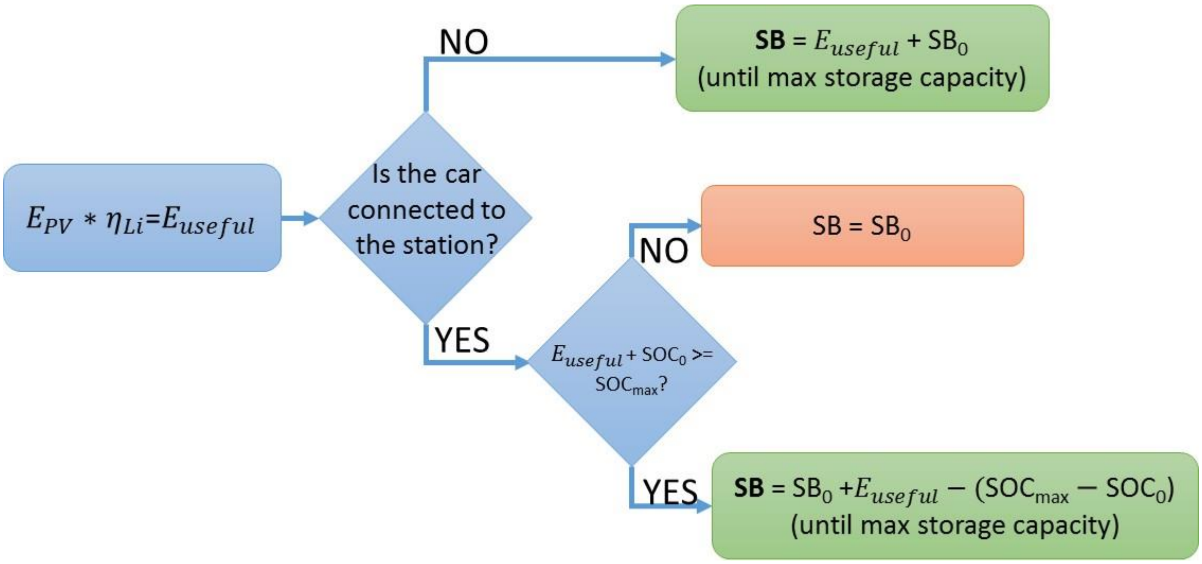


Figure 26 - Block diagram of State of Charge of the storage battery calculation
Source: Elaborated by the author
Where:
SB – State of charge of the storage system battery (kWh)
SOC_0 – State of charge of the car battery from the previous hour (kWh)
SOC_{max} – Maximum state of charge of the car battery (kWh)
SB_{max} – Maximum state of charge of the storage system battery (kWh)
SB_0 – State of charge of the storage system battery from the previous hour (kWh)
E_{PV}– Electricity generated by the PV system (kWh)
η_{Li} – Efficiency of charging a Li-Ion battery
E_{useful} – Useful electricity produced by the PV (kWh)

3.1.6. SOC car battery

The state of charge of the battery is the most important parameter to be estimated in the technical model. All the variables explained before have influence on it. Like all other variables, it is calculated hourly. When the car is not connected to the charging station the SOC will always decrease according to how much the car will spend (demand) in that respective hour. When connected, the SOC will increase according to the amount of energy produced by the PV system, by the storage system or by the grid. The calculation follows the logic below:

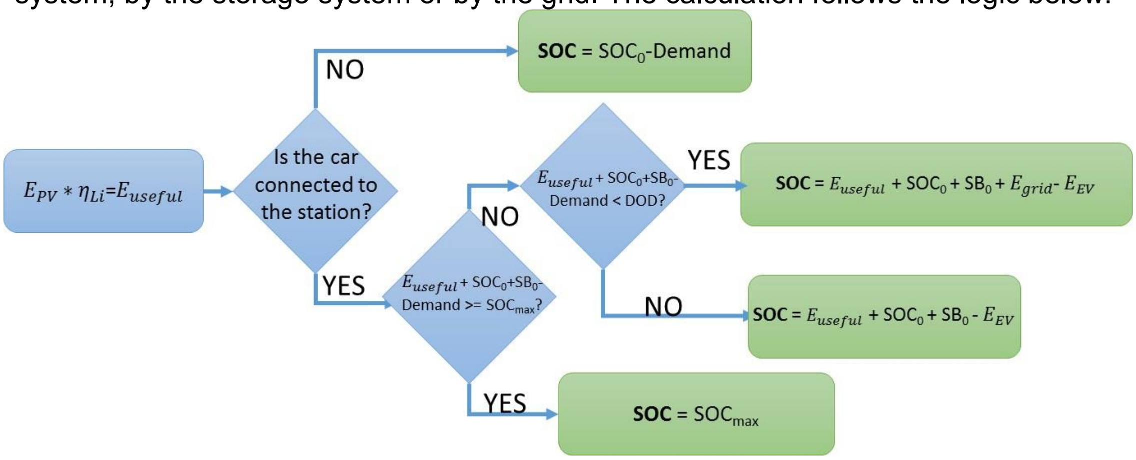


Figure 27 - Block diagram of State of Charge of the car battery calculation.
Source: Elaborated by the author
Where:
SOC – State of charge of the car battery (kWh)
SOC_0 – State of charge of the car battery from the previous hour (kWh)

SOC_{max} – Maximum state of charge of the car battery (kWh)
E_{PV}– Electricity generated by the PV system (kWh)
η_{Li} – Efficiency of charging a Li-Ion battery
E_{useful} – Useful electricity produced by the PV (kWh)
SB_0 – State of charge of the storage system battery from the previous hour (kWh)
E_{grid}– Electricity supplied by the grid (kWh)
E_{EV}– Electricity demand (kWh)

3.1.7. Efficiencies

Electric cars usually use Li-Ion batteries; despite the technology development, those batteries still present some losses when charging them. According to Battery University Group, 2016, the efficiency of current Li-Ion batteries is 90% for charging and discharging. As it could be seen in some formulas in the sections above, it was considered the term η_{Li}, which is exactly the efficiency of Li-Ion batteries and in the present study considered to be 90%. In order to make clearer where this efficiency is applied, a scheme of the efficiencies on each energy exchange of the system is shown the Figure 28.

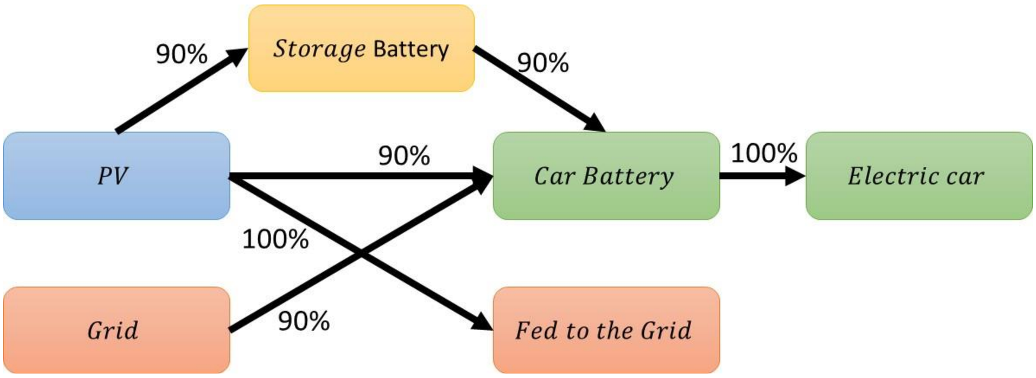


Figure 28 - Scheme showing all efficiencies on all energy exchanges inside the system. Source: Elaborated by the author

The PV - Fed to the grid is assumed to be 100% as the losses due to current inversion are already counted on the PVGIS data and the losses due to the transmission inside the grid are neglected. The Car Battery - Electric car is assumed to be 100% as the losses which occur are already counted in the car efficiency provided by Nissan. All others efficiencies (Grid-Car battery, PV-Car Battery, PV-Storage, Storage-Car battery) are assumed to be 90% as they always involve charging a Li-Ion battery.

To summarize how the technical sub-model was developed and illustrate the interactions of its variables and outcomes, Figure 29 shows an overview of the whole technical sub-model.

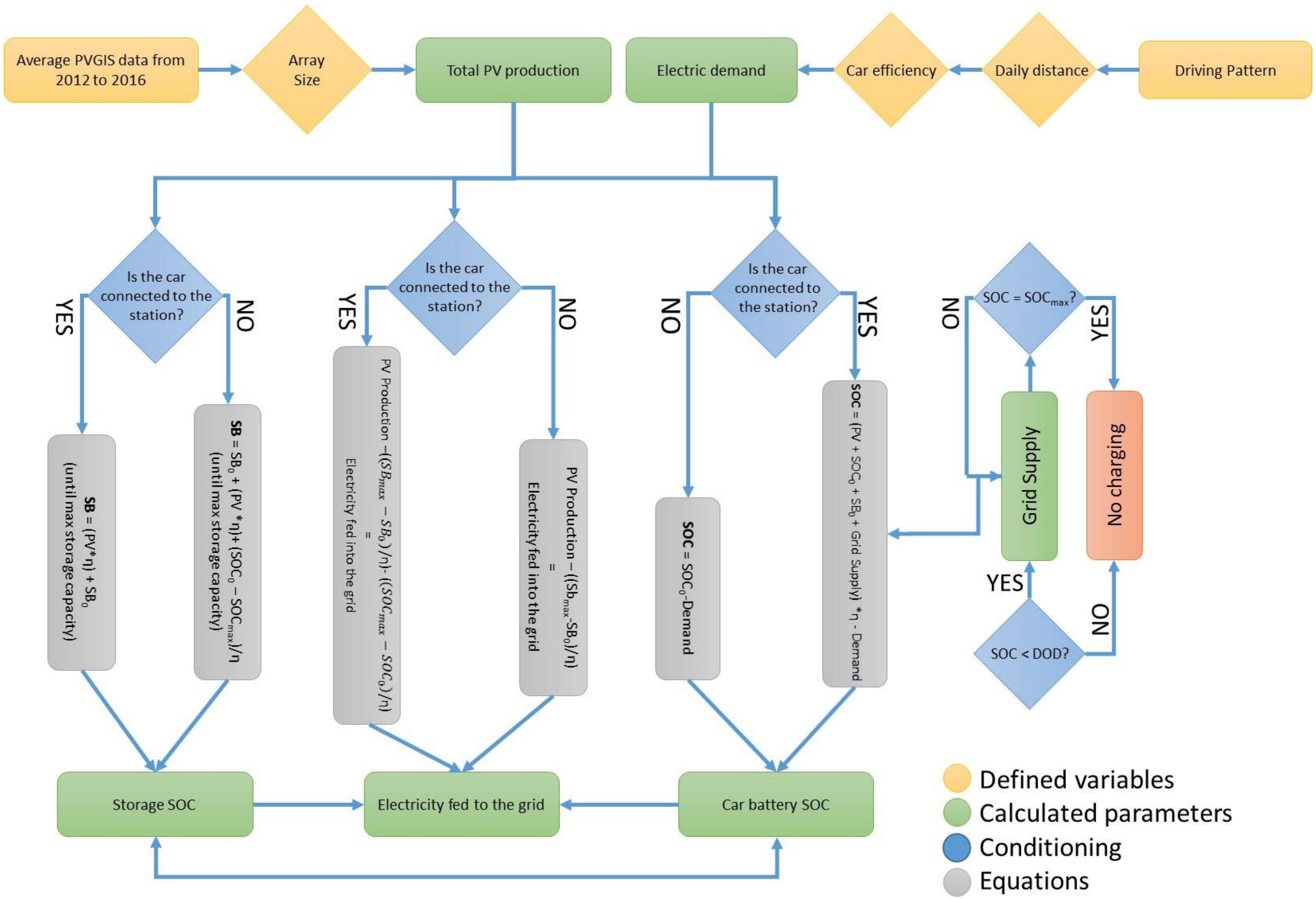


Figure 29 - Overview of the technical model variables interaction
Source: Elaborated by the author

3.2. Economic sub-model

The economic model aims to analyze the system from an economic perspective, treating it as an investment in which there are cash flows and its implementation is evaluated regarding its financial returns. In order to do that it is important to define the PV & storage costs, gasoline price, electricity price as well as the electricity schemes in force regarding the electricity injected back to the grid.

In a feasibility study it is always important to define what is being considered 'feasible'. In this study, the reference was a conventional car using gasoline. Nevertheless, every configuration has necessarily to be able to fulfil the demand defined by the driving pattern and the daily distance traveled (explained in the technical model). When a system can perform that task with less costs than a conventional car then it is considered economically feasible. Also, a system can be classified as more or less economically attractive depending on the difference costs magnitude in relation to a conventional car.

The costs for each scenario are defined by the sum of all costs in the year (electricity, PV, Storage, gasoline) accounting possible revenues (electricity fed into the grid). The cash flows are also defined yearly in the system, as they affect the economic analysis completely. The yearly cash flow is defined by the difference between the studied scenario costs and the conventional car assumption costs. Therefore, there will be a negative cash flow if the costs related to the electricity produced by the PV system are greater than the costs related to the gasoline. A positive cash flow happens in an opposite situation (yearly). In summary, the cash flow is defined by how much money the system can save within a comparison to a conventional car. Assuming all values positive, the equation to calculate the cash flow is:

$$FC = (E_{rev} - PV_{cost} - S_{cost} - G_{cost}) + (F_{cost}) \quad (3)$$

Where:
FC – Cash Flow (€)
E_{rev} – Electricity fed revenue (€)
PV_{cost} – Costs related to the entire PV system (€)
S_{cost} – Costs related to the storage system (€)
G_{cost} – Costs related to the electricity from the grid used (€)
F_{cost} - Costs related to the gasoline used in a conventional car performing the same distance as the EV (€)

Below there is a hypothetical example of one scenario using a PV system to power an electric car. In the Column 'Costs', the absolute costs of a conventional car and the absolute costs related to the Scenario X system are shown. In the Column 'Cash Flow', it is shown how much scenario X is saving yearly, when its costs are compared with the conventional car.

Table 3 - Example of the cash flows' calculation.

	Costs		**Cash Flow**
	Conventional car	**Scenario X**	**Scenario X**
Year 0	€ -	-€ 3,160.00	-€ 3,160.00
Year 1	-€ 1,324.51	€ 36.38	€ 1,360.89
Year 2	-€ 1,324.51	€ 30.07	€ 1,354.58
Year 3	-€ 1,324.51	€ 24.43	€ 1,348.94
Year 4	-€ 1,324.51	€ 23.80	€ 1,348.32
Year 5	-€ 1,324.51	€ 14.47	€ 1,338.98
Year 6	-€ 1,324.51	€ 14.98	€ 1,339.49
Year 7	-€ 1,324.51	€ 6.44	€ 1,330.96
Year 8	-€ 1,324.51	€ 1.71	€ 1,326.23
Year 9	-€ 1,324.51	-€ 3.02	€ 1,321.50
Year 10	-€ 1,324.51	-€ 7.75	€ 1,316.77
		Total	€ 10,226.65

For the scenario X in the year 0 an investment is needed, typically of PV systems, but not for the conventional car. In this moment, the cash flow is negative as the scenario X cost is higher than the conventional car cost. From the year 1 to 8, in the Column 'costs', there is a positive balance between the revenue received for the electricity sold to the grid and its costs (PV, storage and grid). So, it can be said that the cash flow is composed by how much the system 'saves' (not spending on gasoline) plus the net revenues in a given year. In the year 9 and 10 the hypothetical scenario X had a negative balance in the column 'costs', but they were lower than the conventional car costs. In this situation, the cash flow is still positive as the scenario X continued to save money when compared to a conventional car.

In the next sub sections all the values used in the economic model, together with its references will be presented, as well as cost and revenue calculations will be explained.

3.2.1. Electricity Price

According to *Energie vergelijken* in 2018, the average electricity price for households, in The Netherlands, was 0.23/kWh, including network costs and taxes. According to Statistics Norway in May 2018 the average electricity price for households, in Norway, was 0.16€/kWh, including grid rent and taxes. Lastly, according to the *Agencia Nacional de Energia Elétrica* (ANEEL) the electricity price for the low voltage consumers in Sao Paulo, Brazil is 0.15€/kWh.

Electricity Schemes

In The Netherlands a net mattering scheme was established. Therefore, the prosumers (electricity consumers injecting theirs own produced electricity into the grid) have an electricity compensation at retail price on an annual netting period. This means that the utility company balance all the electricity consumed from the grid with the electricity injected into the grid by the user. If the amount of electricity injected is higher than the amount consumed, the utility company does not pay or give any kind of compensation to the prosumers, but compensate this electricity surplus in the next months. (GfK Belgium Consortium, 2017)

In Norway, it is established a Feed-in-Tariff scheme in which the utility company negotiates with prosumers and pays a fixed amount per kilowatt injected into the grid. According to the same study from the European Commission in 2017, the price paid by the companies is on average 0.04€/kWh. This very low value is due to the Norwegian grid mix be very sustainable and cost effective with more than 98% coming from hydropower sources.

In Brazil a very similar system to The Netherlands is established; however, the netting period is 5 years. This means that the electricity injected can be compensated until 5 years after the month it was injected. Nevertheless, like in The Netherlands, if the amount of electricity injected is higher than the consumed (after 5 years), the utility company does not pay or give any kind of compensation to the prosumers. (ANEEL, 2015a).

$$G_{cost} = E_{grid} * r_{grid} \tag{4}$$

Where:

G_{cost} - Costs related to the electricity from the grid used (€)
E_{grid} – Total electricity used from the grid (kWh)
r_{grid}- Electricity rate (€/kWh)

$$E_{rev} = E_{fed} * r_{sold} \tag{5}$$

Where:

E_{rev} - Electricity fed revenue (€)
E_{fed} – Total electricity fed back to the grid (kWh)
r_{sold} – Electricity rate when selling back to the grid (€/kWh)

3.2.2. Gasoline Price

In order to be able to compare the costs of having an electric car with a conventional car, it is necessary to calculate the costs related to a conventional car. The most important conventional car source of cost, and the only one considered in this study, is the gasoline price.

According to Global petrol prices, in July of 2018 the gasoline price in The Netherlands was 1.68€/liter, in Norway it was 1.75€/liter and in Brazil was 1.06€/liter.

$$F_{cost} = F_{used} * r_{fuel} \quad (6)$$

Where:
F_{cost} - Costs related to the gasoline used in a conventional car performing the same distance as the EV (€)
F_{used} – Total gasoline used in a conventional car performing the same distance as the EV (L)
r_{fuel} – Gasoline price (€/L)

3.2.3. PV and Storage costs

The major costs involved in the use of photovoltaic systems are concentrated in the project beginning due to its equipment high investment costs, what contrasts to very low maintenance costs during its lifetime. On the other hand, the prices can vary from country to country as the products can be imported or produced nationally.

In addition, there are many technologies available for stationary storage; however, the one that is standing out lately due to its flexibility and easy use is Lithium Ion batteries. The batteries used in stationary storage are a bit different from the ones used in the electric cars; nowadays there are some models from Tesla and LG, which are designed specifically for installing in households. In this academic work Lithium-ion batteries is being considered every time a storage system is mentioned.

The costs in The Netherlands and in Norway are considered the same as both are in Europe and despite having different taxes schemes, the costs related to PV installations are very similar. According to Reinders et al., 2017 a generic fixed tilt system built in 2015 cost on average 1.33$/Wp, which is 1.14€/Wp.

A report from IRENA, 2017 studied prices of many storage technologies prices, including Li-ion for stationary proposes. The study concluded that in the Q1 of 2017 the average price for Li-ion storage systems was 880€/kWh (usable). The report focused on the German market; however due to the lack of specific information about the Norwegian and Dutch market, the costs estimated for Germany will be assumed for The Netherlands and Norway cases

In Brazil, a study from *Instituto ideal*, 2018 gathered information from more than 1800 companies that installed PV systems around the country in 2017. According to them, in Brazil, on average a fixed tilted system up to 30kWp costs 6.02 R$/Wp, which corresponds to 1.52 €/Wp. It is important to mention that in the Brazilian case, due to political instability, the currency is very devalued what can give a false impression about these systems real costs.

Despite Li-ion battery technology not be that new, the Brazilian market does not count on this storage technology availability yet. If a consumer wants to install this kind of system, he has to import by himself what becomes very expensive due to many taxes charged. However, specialized companies on the Brazilian market estimate that in 2019 this technology will be available at an estimated price of 920€/kWh as prices will vary depending on the capacity of the batteries.

$$PV_{cost} = A_{PV} * r_{PV} \quad (7)$$

Where:
PV_{cost} – Costs related to the entire PV system (€)
A_{PV} – Array size (kWp)
r_{PV} – Costs rate of PV systems (€/kWp)

$$S_{cost} = SB_{max} * r_{storage} \quad (8)$$

Where:
S_{cost} – Costs related to the storage system (€)
SB_{max} – Storage maximum capacity (kWh)
$r_{storage}$ – Costs rate of storage systems (€/kWh)

3.2.4. Indicators

Three economic variables such as the net present value (NPV), the mean internal return rate (MIRR) and the payback time are used for comparison with each other among scenarios in this academic work. They are defined as follows:

NPV

Net present value (NPV) is a widely used function in the feasibility analysis of projects and investments. It brings the inflows and outflows of capital, discounted a minimum rate of interest (MRI), to present values. It reflects the wealth in monetary values present (at the moment of investment), measured by the difference between the present value of inflows and outflows, at a given rate. The NPV in this study will be used to compare the investment in photovoltaic microgeneration with an investment which maintains monetary value and is corrected by the local inflation rate. Basically, if the NPV results negative, it means that the microgeneration system was less profitable than an investment that had returns equal to the inflation rate, and if it is positive it means that the microgeneration system was more profitable. In this report it will be used a MRI, or discount rate, of 2% for The Netherlands, and Norway cases, as this is the annual accumulated inflation rate for the Europe Union (Eurostat, 2018) and a 6,5% rate for the Brazilian case, as this is the current interest rate defined by the Brazilian Central Bank (Banco Central do Brasil, 2018).

$$VPL = \sum_{j=1}^{n} \frac{FC_j}{(1+i)^n} - FC_0 \qquad (9)$$

Where:
FC_j- Cash flows provided in the project for each time interval.
FC_0- Cash flow at time zero (Investment, loan, financing).
i – Discount rate
n – Investment time period

MIRR

The modified internal return rate (MIRR) of the investment is calculated by correcting positive and negative cash flows at pre-defined reinvestment and financing rates respectively. That is to say all positive flows are taken at the end of the period at a reinvestment rate and all negative flows are brought to the initial period at a financing rate. Thus, market reality is taken into account in calculating the internal rate of return avoiding possible discrepancies in the result (Barbieri, et al., 2007). The MIRR aims to quantify, in a plausible way, the profitability of the microgeneration systems studied. In such systems, this reinvestment in the system itself does not mean proportionately more revenue; so it was defined that the returns from it would be reinvested in an investment fund just to be corrected by the inflation rates. In this way, the profitability of the systems can be calculated closer to an investor practice who applies its remaining money in the financial market. The rate of financing should not be confused with a loan. In calculating the MIRR it is assumed that the investor already owns all the capital necessary for the investment including for future expenses. One may understand the rate of financing by imagining that the investor, knowing the expenses that he will have later, stores a sum of capital that yields at this rate "f" (rate of financing) will reach the amount of sufficient capital to cover possible expenses over the period studied. The MIRR is given by equation 12. In order to make a conservative estimation the investment rate, already described in the previous section, will be equal to the inflation rate of each country.

$$TIRM = \left(\frac{VFL_{FCp}}{VPL_{FCn}}\right)^{\frac{1}{n}} - 1 \qquad (10)$$

$$VPL_{FCn} = \sum_{j=1}^{n} \frac{FCn_j}{(1+f)^n} \qquad (11)$$

$$VFL_{FCp} = \sum_{j=1}^{n} FCp_j \cdot (1+r)^t \quad (12)$$

Where:
TIRM – Modified internal return rate
FCp – Positive cash flow
FCn – Negative cash flow
r – Investment rate
f – Financing rate
n – Investment time period
t – Remaining period of investment time

Payback Time

Corresponds to the period necessary for the reimbursements current value (return of capital) to be equal to the investment made disbursement aiming at the capital applied restitution. In brief, it is the time needed to recover the invested capital.

Similarly, to the way the technical section showed its overview, the Figure 30 below shows an overview of all variables involved and their interaction in the economic sub-model.

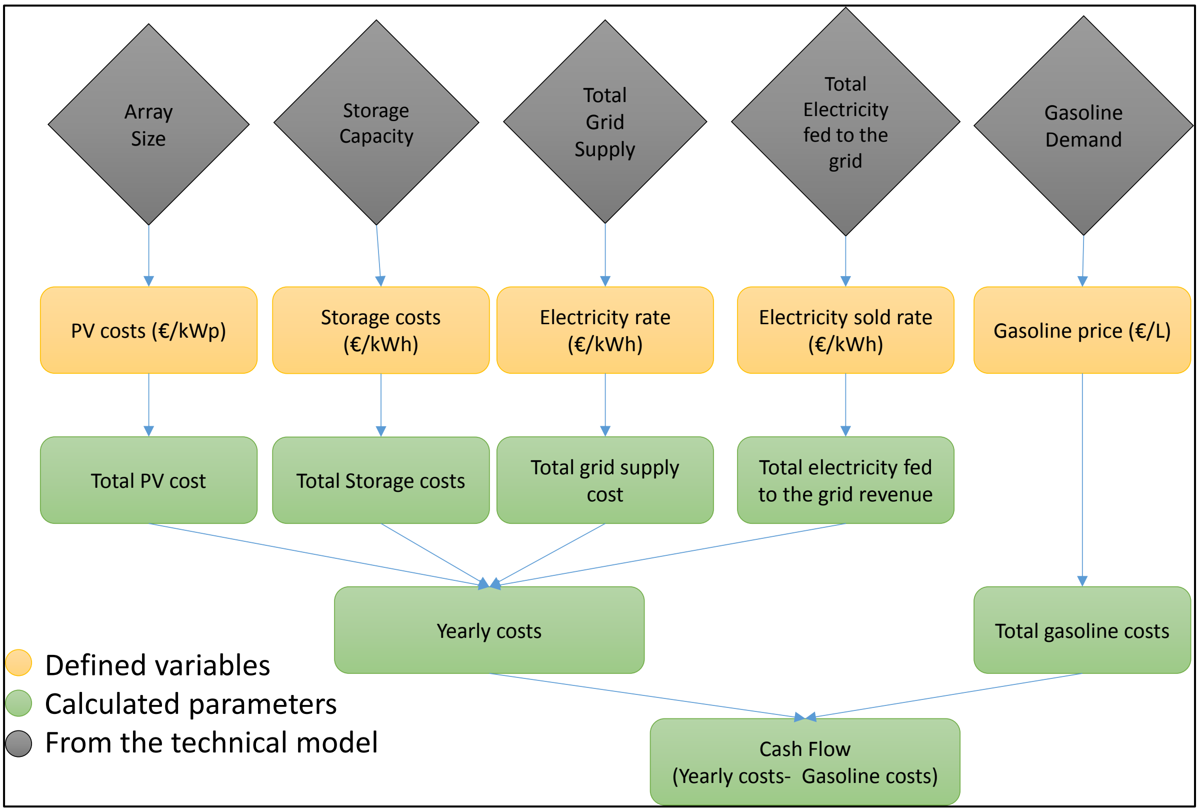


Figure 30 - Overview of the economic model variables interaction
Source: Elaborated by the author

3.3. Environmental sub-model

This model intends to make an environmental assessment by calculating the CO_2 footprint of the system, based on the local footprint of electricity sources and their respective consumption in each scenario.

In this kind of systems, the CO_{2eq} emissions are accounted during the electricity generation. In the hypothetical situation foreseen by this model, there are two ways to produce electricity: by the PV system and by the grid mix. All the energy provided by the mix is used in the car, but the electricity generated by the PV system can be used either to charge the electric car or to be injected back into the grid. The idea is to estimate the electric car CO_2 footprint using powered solar energy and electricity from the grid. The analysis will not consider the CO_2 footprint of any energy not used in the electric car.

The total CO_2 footprint of each scenario are the sum of the total CO_2 footprint from the electricity provided by the grid plus the CO_2 footprint from the share of electricity provided by the PV system to the car. Being so, the calculation needs the grid footprint of each country analyzed, the PV footprint and the storage footprint.

3.3.1. Grid CO_2 footprint

In order to estimate the environmental benefits of using solar power to charge electric cars it is important to define the grid mix CO_2 footprint. The CO_2 footprint of the grid mix is affected by those sources of energy which are used by the utility companies to generate the electricity they provide for the consumers. Countries that relies mostly on fossil sources like coal and natural gas have high grid CO_2 footprints and countries relying on renewable sources, like wind and hydropower, have low CO_2 footprints.

The Netherlands

The Netherlands still have an electricity production heavily based on fossil fuels; it accounts for about 80%, especially natural gas and a significant amount of coal as well. The renewables sources account for about 12% being wind power and biomass the most significant ones. Moro & Lonza, 2017 calculated the electricity CO_2 intensity in all European member states. According to them, the electricity consumed by the Dutch at the low voltage level has a CO_2 footprint of 569gCO2eq/kWh.

Norway

Also according to Moro & Lonza, 2017 the Norwegian electricity carbon intensity is 9 gCO2eq/kWh. This very low impact is due to a higher penetration of renewables (98%) and only 2% of fossil fuels. The main source, by far, is hydropower, which accounts for 95.1% of total electricity demand.

Brazil

Electricity generation in Brazil is also dominated by hydropower, however less than in Norway. In Brazil 64.5% of the electricity is produced by hydropower, while 13.1% by other renewables, especially biomass. Fossil fuels accounts for just 14.5% (EPE, 2017), but the power plants using them are very inefficient significantly increasing the grid CO_2 footprint. According to a study from Climate Action Tracker (CAT) in 2015, the carbon intensity of the Brazilian mix was 156.6 gCO2eq/kWh. Despite being a relative old value (from 2015), the sources share in Brazil has not changed significantly since then; therefore, this number can be assumed as its nowadays carbon intensity.

3.3.2. Gasoline CO_2 footprint

The gasoline footprint data will enable a comparison between electric cars and conventional cars among all the different scenarios. A very complete study, made by the European Commission, analyzed a wide range of car fuels with the well-to-wheel approach. According to them, the carbon footprint for gasoline used in DISI cars is 178 gCO_{2eq}/km. (Edwards, et al., 2014)

3.3.3. PV footprint

Many studies claim that renewables sources have no carbon footprint, however this is not true. Every source of energy presents some CO_2 footprint. Indeed, solar, wind and other renewables sources have a way lower impact than fossil fuels based ones, but that effect will never be null.

A study from the Parliamentary Office of Science & Technology, from 2011, made an overview of many reports that estimated the carbon footprint of renewable sources. Regarding solar PV, the carbon footprint ranged from 48 to 88 gCO_{2eq}/kWh for European conditions. (POSTnote, 2011). One very important parameter is the solar irradiation in the place where the system is installed. In places with high solar irradiation, the system can generate much more energy than in places with low irradiation, consequently decreasing its carbon intensity.

Therefore, regarding the PV footprint for Norway and for The Netherlands, values of 88 gCO_{2eq}/kWh and 68 gCO_{2eq}/kWh respectively are assumed, while a value of 29 gCO_{2eq}/kWh, is assumed for Brazil, as seen in Bhandari, et al., 2015.

3.3.4. Storage Footprint

Calculating the CO_2 footprint of storage systems involves many parameters like the inventory data that can highly change the result. In order to tackle that, Peters, et al., 2016 provides a review of LCA studies on Li-Ion batteries with a focus on the battery production process. The study computed the average impact scores for global warming and cumulative energy demand from 36 LCA studies on Li-ion batteries. The average impact scores obtained per 1 Wh of storage capacity are of 110 gCO_{2eq}.

3.3.5. Indicators

In this model two environmental indicators will be compared among scenarios: Total CO_{2eq} emissions after 10 years and CO_{2eq} per km.

Total CO_{2eq} emissions

Total CO_{2eq} emissions will be the sum of each year CO_{2eq} emissions. The yearly CO_2 footprint is given by the equation 13:

$$CF_{year} = (G_{CF} * E_{grid}) + \left(PV_{CF} * (E_{PV} - E_{fed})\right) + (SB_{max} * S_{CF}) \tag{13}$$

Where:

CF_{year} – Yearly carbon footprint (gCO_{2eq})

G_{CF} – Grid carbon footprint (gCO_{2eq}/kWh)

E_{grid} – Yearly grid supply (kWh)

PV_{CF} – PV carbon footprint (gCO_{2eq}/kWh)

E_{PV} – Yearly PV production (kWh)

E_{fed} – Yearly electricity fed into the grid (kWh)

SB_{max} – Maximum storage capacity (kWh)

S_{CF} –Storage carbon footprint (gCO_{2eq}/kWh)

CO_{2eq} emissions per km

The CO_{2eq} emissions per km is calculated taking into account all the period analyzed. The indicator is the rate between the total CO_{2eq} emissions per the total distance travelled by the car during the period in study.

$$CF_{relative} = \frac{CF_{total}}{l_{total}} \tag{14}$$

Where:

$CF_{relative}$ – Relative carbon footprint (gCO_{2eq}/km)

CF_{total} – Sum of all years carbon footprint (gCO_{2eq})

l_{total} – Total distance travelled during the whole period of calculation (km)

The Figure 31 below shows an overview of all variables involved and their interaction in the economic sub-model.

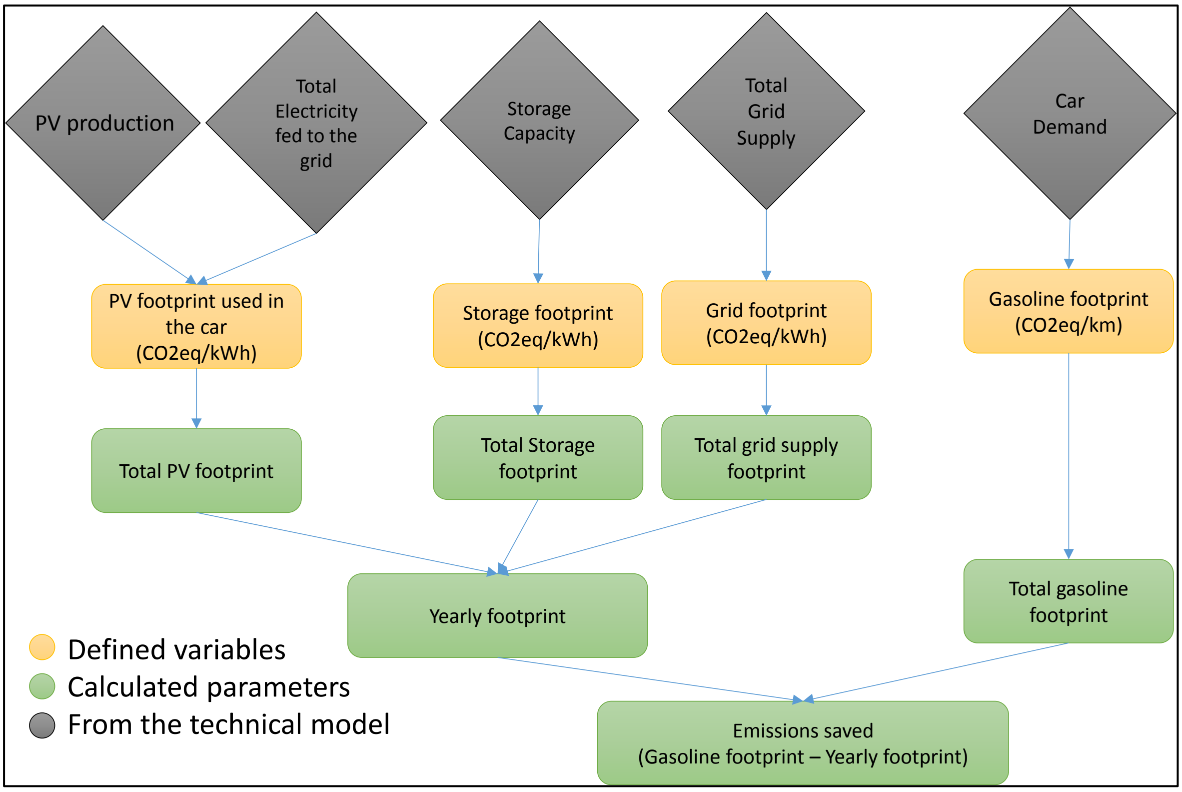


Figure 31 - Overview of the environmental model variables interaction
Source: Elaborated by the author

In order to create an easy way to access all the parameters just described and used in the whole model a summary is shown in the Table 4. This table contains all variables used in the following Results chapter, while their references can be found in the Methodology chapter.

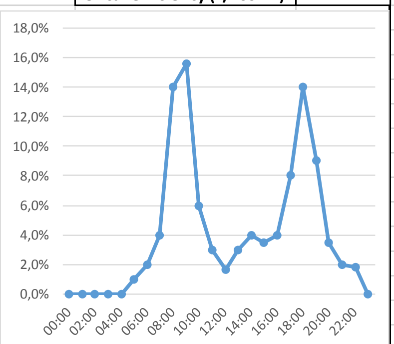
Table 4 - Summary of all parameters used in the model.
Source: Elaborated by the author

Technical Model

Relative Demand	
00:00	0,0%
01:00	0,0%
02:00	0,0%
03:00	0,0%
04:00	0,0%
05:00	1,0%
06:00	2,0%
07:00	4,0%
08:00	14,0%
09:00	15,6%
10:00	6,0%
11:00	3,0%
12:00	1,6%
13:00	3,0%
14:00	4,0%
15:00	3,5%
16:00	4,0%
17:00	8,0%
18:00	14,0%
19:00	9,0%
20:00	3,5%
21:00	2,0%
22:00	1,8%
23:00	0,0%

Average daily distance (km)	
The Netherlands	30
Norway	47,2
Brazil	32

Electric car Model	Nissan Leaf
Battery capacity (kWh)	30
Consumption (kWh/km)	0,174
Total Range (km)	172
ICE car efficiency (L/100km)	7.2



Economic Model

Gasoline Price (€/L)	
The Netherlands	1.68
Norway	1.75
Brazil	1.06

Electricity Price (€/kWh)	
The Netherlands	0.23
Norway	0.1605
Brazil	0.15

Feed-in-Tariffs (€/kWh)	
The Netherlands	0.23
Norway	0.04
Brazil	0.15

PV costs (€/Wp)	
The Netherlands	1,14
Norway	1,14
Brazil	1,52

Storage costs (€/kWh)	
The Netherlands	880
Norway	880
Brazil	920

Environmental Model

Grid Footprint (gCO2eq/kWh)	
The Netherlands	569
Norway	9
Brazil	156.6

Gasoline Footprint (gCO2eq/km)	
WTW Analysis	178

PV footprint (gCO2eq/kWh)	
The Netherlands	88
Norway	68
Brazil	29

Storage footprint (gCO2eq/Wh)	
Li-Ion Batteries	110

Results

The results from the simulation of one electric car being charged by solar energy will be presented in this chapter. The simulations assumed a timeframe of 10 years, as this is more or less the lifetime of an electric inverter and a lithium battery. In that way, the substitution of such components is not foreseen, even though solar panels and most of the other car's components have higher lifetimes.

As it was explained in the previous chapter, the main objective of this study is to analyze the main variables affecting the use of solar power in electric cars. For this purpose, four scenarios are explored in three different countries' situations (The Netherlands, Norway and Brazil) simulating the different configurations a PV system can assume. Additionally, the feasibility of using local storage was compared within the scenarios with a PV system. The scenarios are:

- **Scenario 1 – PV 100%:** In this scenario 100% of the generated energy comes from the PV system and, therefore, the system is independent from the grid.
- **Scenario 2 - PV 75% + 25% Grid:** In this scenario 75% of the generated energy comes from the PV system and 25% from the grid.
- **Scenario 3 – PV 50% + 50% Grid:** In this scenario 50% of the generated energy comes from the PV system and 50% from the grid.
- **Scenario 4 - 100% Grid:** In this scenario the car is powered entirely by electricity from the grid and there is no investment regarding a PV system.

The idea of comparing different countries' situations is to see how local variables such as solar irradiation, distance travelled, fuel prices, electricity price and local electricity schemes affects the energy balance, the economic and environmental results. In addition, the different configurations illustrated by four distinct scenarios are meant to show how the technical, economic and environmental feasibility can change depending on the share of PV in the system.

4.1. Technical sub-model

This section is separated by country and by scenario. In each one, the relative amount of electricity injected into the grid, the impacts of a local storage system and the necessary array size are shown. It is important to remark that in the technical model the costs and emissions related to the systems and, consequently, its economic and environmental feasibility are analyzed in the following sections.

In the figures below, the electric car battery SOC (blue) over the tenth year of simulation is shown, as the last year modeled represents the most critical situation due to the components performance decay over the years. Additionally, the first years are impacted by the start conditions (car and storage battery full).

4.1.1. The Netherlands

Scenario 1

The necessary system size to be totally independent from the grid is 10.2 kWp. As can been seen in the Figure 32, during all year the battery is almost full. The frequent decreases observed during all year are characterized by the weekends when the car spends two entire days without connection to the charging station. Only in January the battery SOC reached a minimum of 10 kWh. This means that the PV production is higher than its electric demand during the hours the car is connected to the station, all over the year.

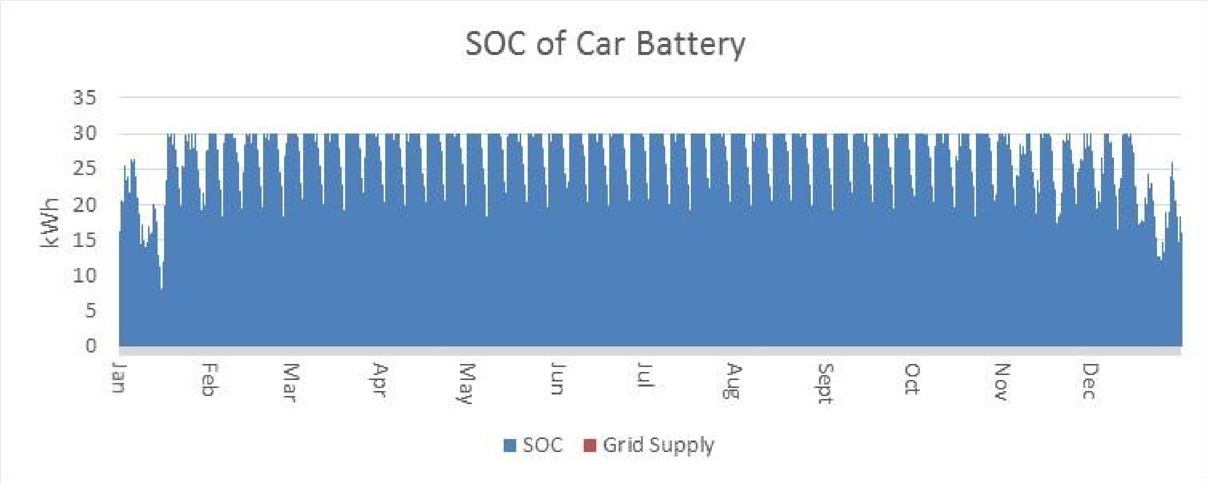


Figure 32 - State of charge of the car battery during the 10th year in scenario 1.
Source: Elaborated by the author

During all year, the system is able to provide all the required energy with no need from electricity from the grid. However, the consequence is that during the Summer a great amount of electricity is injected into the grid, as the system produces much more energy than can consumes. This can be better observed when comparing the PV production with the electricity fed into the grid (Figure 33). Summer, Autumn and Spring are periods when most of the electricity are being fed into the grid. In some hours, almost all electricity produced is injected into the grid as the electric car has its battery full. Looking at January and December, the energy generated is not big enough to inject electricity into the grid. However, during the weekends, on this month, the only option is to feed the electricity produced back to the grid and that is why a few red lines can be observed.

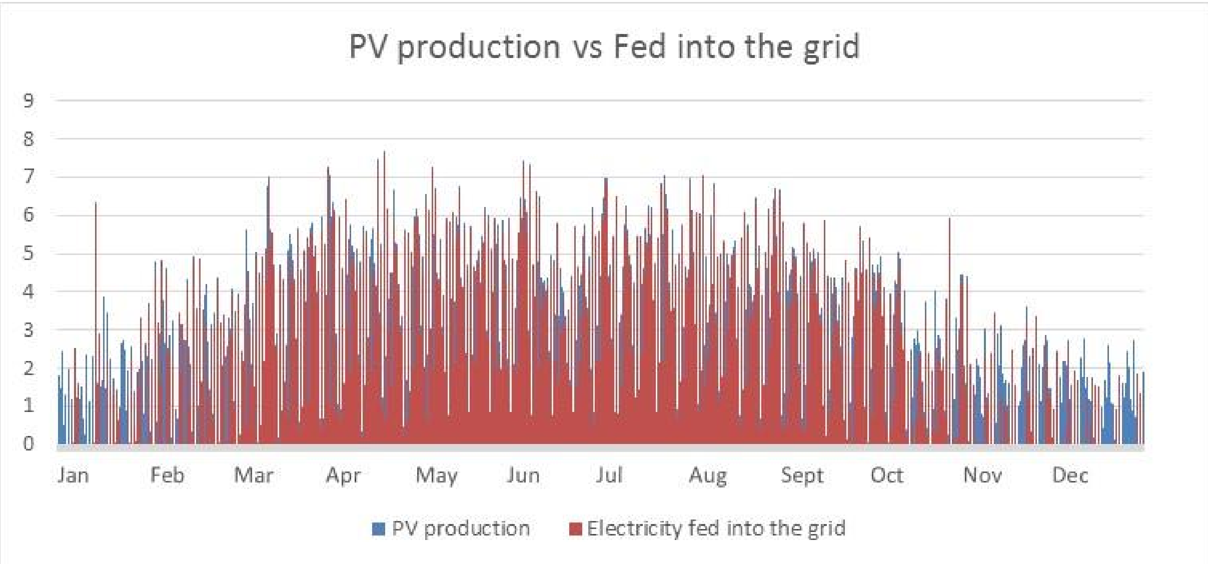


Figure 33 - Comparison between PV yield and electricity fed to the grid during the 10th year in scenario 1.
Source: Elaborated by the author

To show this pattern in a better perspective the Figure 34 presents the relative amount of electricity being used on the car (demand) and fed into the grid (fed) each month. During all year, 81% of the electricity being generated is injected into the grid and just 19% is used on the car. However, as already mentioned these shares changes significantly depending on the month. For example, in December 33% of the electricity is used on the car and in July (the highest month) 87% is injected into the grid.

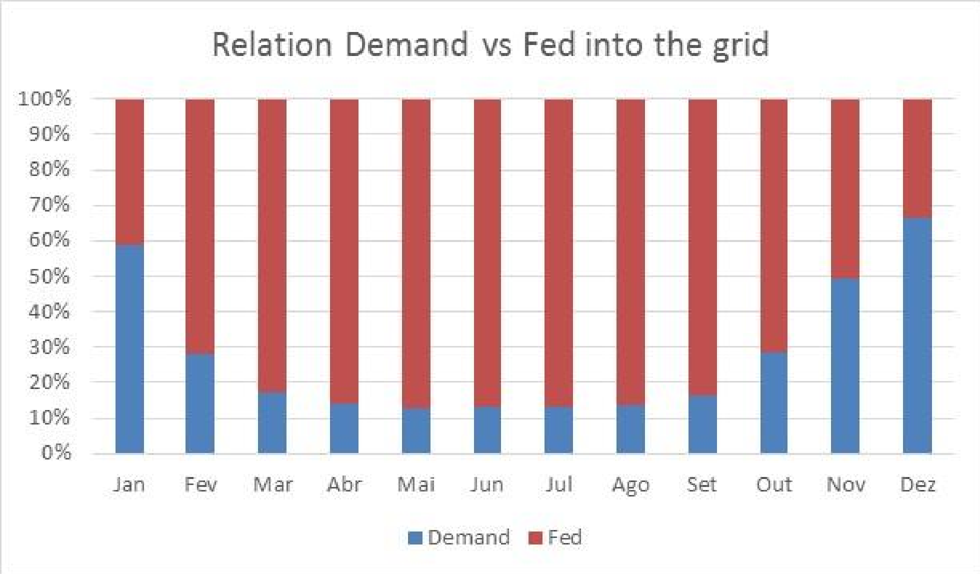


Figure 34 - Comparison between the amount of energy being used on the car (demand) and fed into the grid (fed) during the 10th year in scenario 1.
Source: Elaborated by the author

Now, the impact of a local storage on this scenario is analyzed. The idea is to check how much the PV array size can be reduced by using a storage system. In the Figure 35, it is possible to see that a local storage is not much effective in this scenario. To decrease only 0.6 kWp (from 10.2 to 9.6 kWp) on the array size it is necessary a storage capacity of 2 kWh. By decreasing the array size even more, the necessary storage capacity increases exponentially. For example, in order to decrease 3.6 kWp (from 10.2 to 6.6 kWp) the necessary storage capacity is 40 kWh. Other impact of a local storage in the system is on the amount of electricity being fed into the grid. Nevertheless, the impact on this variable is not very significant. In this scenario a 40 kWh would mean a decrease of 11% of electricity being injected into the grid when compared with a system with no storage.

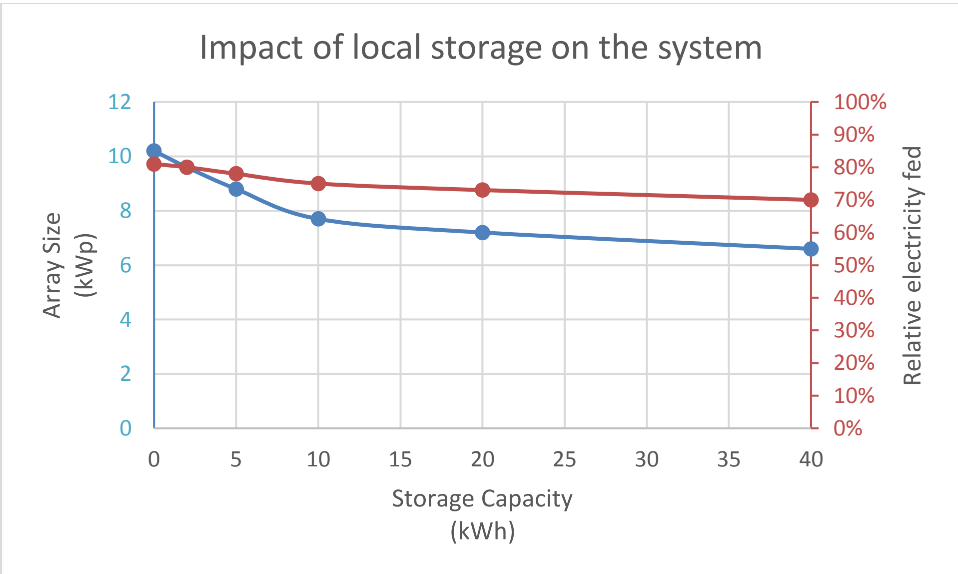


Figure 35 - Impact of adding a local storage on the array size (blue) and electricity fed into the grid (red) in scenario 1.
Source: Elaborated by the author

This possible slight decrease on both parameters is due to the fact that the storage system allows the use some of the electricity surplus into the car later on, avoiding the need to higher production or feeding to the grid. For example, during weekends the system is “free” to produce electricity and inject it back to the grid. With the addition of a storage system this energy can be used to charge the storage and, during weekdays, to charge the electric car.

However, the observed stabilization of the decrease in the array size and the amount of electricity fed into the grid is due to fact that the storage system has to be bigger and bigger in order to store the surplus of energy produced during the Summer for using it during the Winter. Nevertheless, at some point all electricity produced by the PV will not be enough to fulfil the car demand, not mattering the storage size anymore.

Therefore, a storage system can, technically, reduce the necessary array size for an independent PV system just until a certain level and increase the relative amount of the generated electricity used on the car, in theory, until 100%, but achieving those levels would require enormous storage systems. As already mentioned, this section it is not meant to discuss the scenarios' economic and environmental feasibility yet. This is will be object of the economic model.

Scenario 2

In this scenario, the PV system provides 75% of the electricity and the grid supports with 25%. The necessary array size, with no storage, is 2.1 kWp. As it can been seen in the Figure 36, between April and September, the PV is able to provide almost all the energy to the electric car, just needing to be recharged twice. Nevertheless, between October and March much more electricity from the grid is needed to compensate the lower solar irradiation during that period. In total, the car needs 26 full charges from the grid over the year. These charges are more frequent during December and January and become more spaced in the warmer months.

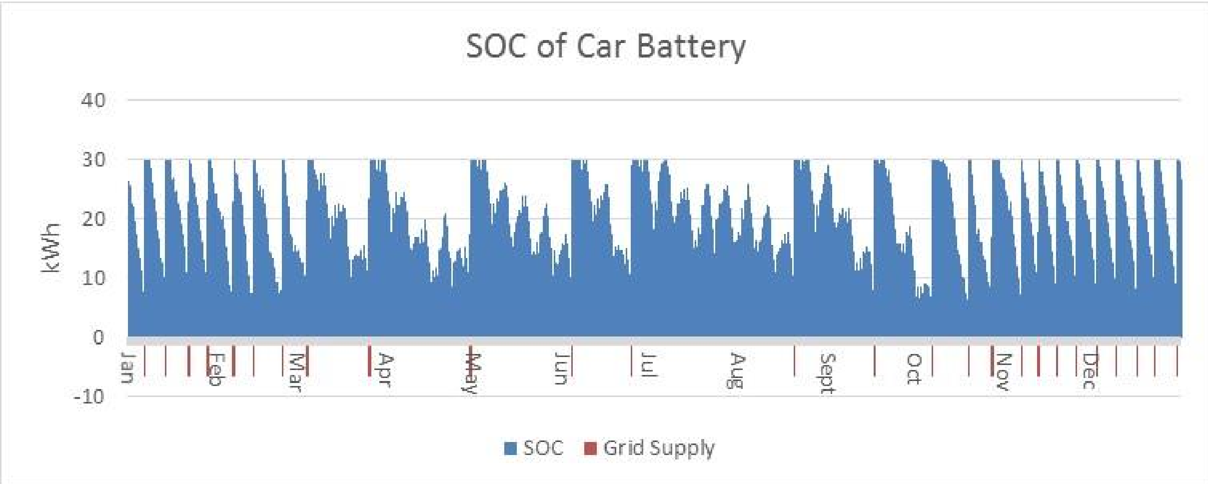


Figure 36 - State of charge of the car battery during the 10th year in scenario 2.
Source: Elaborated by the author

Regarding the electricity injected into the grid, a different situation is now observed. Way less energy is fed and even during the Summer most of the energy is being used on the electric car. This can be clearly seen in Figure 37, as much more blue lines appear. During Winter, as happened in scenario 1, almost no energy is injected into the grid, apart from the weekends.

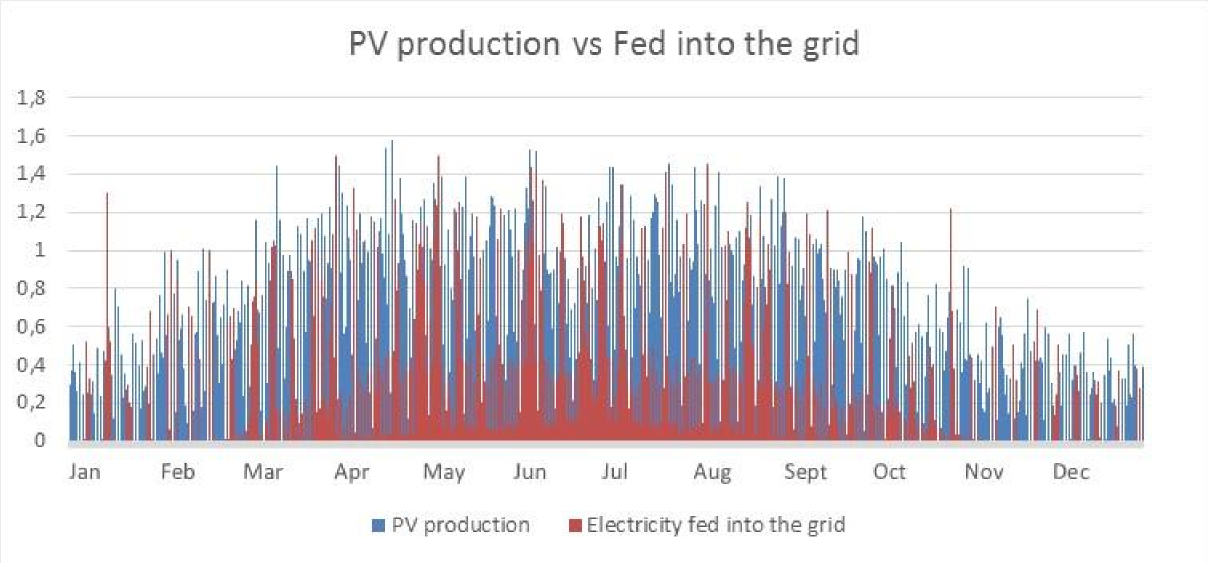


Figure 37 - Comparison between PV yield and electricity fed to the grid during the 10th year in scenario 2.
Source: Elaborated by the author

Following the same approach, the Figure 38 shows more specifically this change. On average, the system uses 72% of the electricity generated by the PV on the electric car (demand) and just 28% is fed back into the grid. In January, for example, just 9% is injected into the grid and in June (highest month) this comes to 43%. A great change when compared to scenario 1 when during Summer the shares of electricity being fed were more than 80%.

This shows that this scenario is much more feasible in the sense that the system's objective is being achieved, namely providing energy for an electric car, while in scenario 1 the system works much more similarly to a solar power plant providing electricity to the grid.

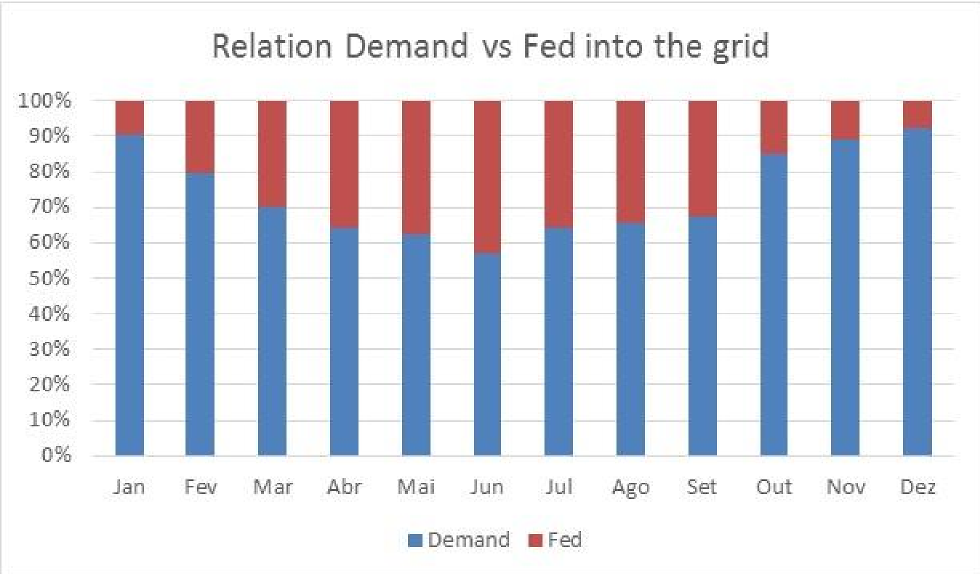


Figure 38 - Comparison between the amount of energy being used on the car (demand) and fed into the grid (fed) during the 10th year in scenario 2.
Source: Elaborated by the author

The impact of installing a storage system is analyzed in scenario 2 and represented by the Figure 39. Adding a 2 kWh storage capacity enables to decrease the array size in just 0.2 kWp. In order to decrease 0.4 kWp it is necessary to add a storage capacity of 20 kWh. On the other hand, a storage system will affect more significantly the amount of electricity fed into the grid. On the same analysis, a storage system of 2 kWh reduces the relative amount of electricity fed into the grid from 28% to 21%. A capacity of 40 kWh would decrease from 28% to 2%. At this point, the system gets very close to reach the reduction limit of array size and electricity fed into the grid. The stabilization of both parameters regarding the increase of storage size, as mentioned on the previous scenario, this time becomes even clearer.

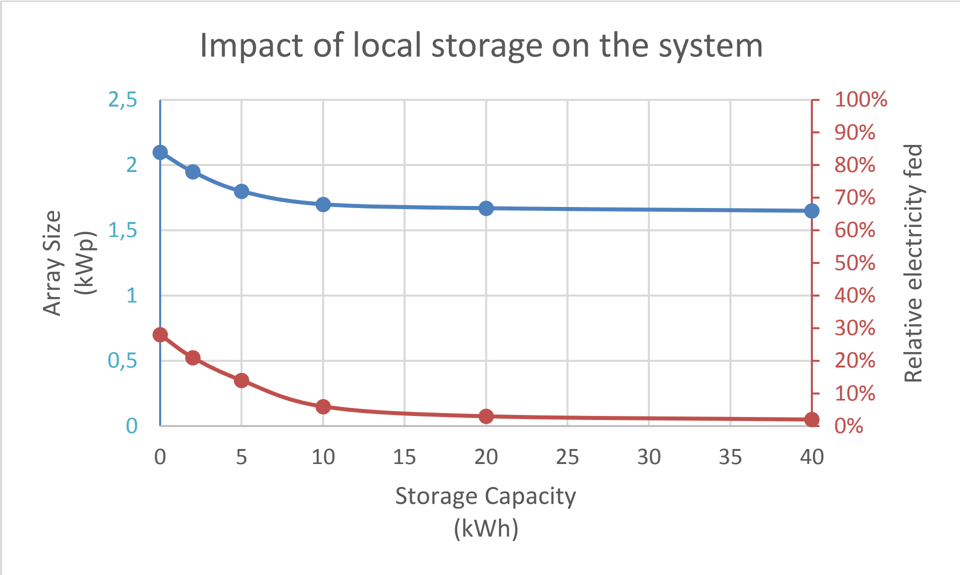


Figure 39 - Impact of adding a local storage on the array size (blue) and electricity fed into the grid (red) in scenario 2.
Source: Elaborated by the author

Scenario 3

Differently from the previous scenarios in which PV and grid contributed the same magnitude (50% each), there is not a big period over the year during which the electric car can be supplied just by the solar panels. In this scenario the minimum array size (without storage) is 1.2 kWp and a total of 43 charges are needed to supply enough energy to the car. The difference between the warm and cold months is the charging frequency. During January an average of 4 charges are needed, meanwhile in June or July only 2 charges are necessary. This shows that the PV system is still supporting electricity supply to the electric car, notwithstanding the system need for grid supply during all year.

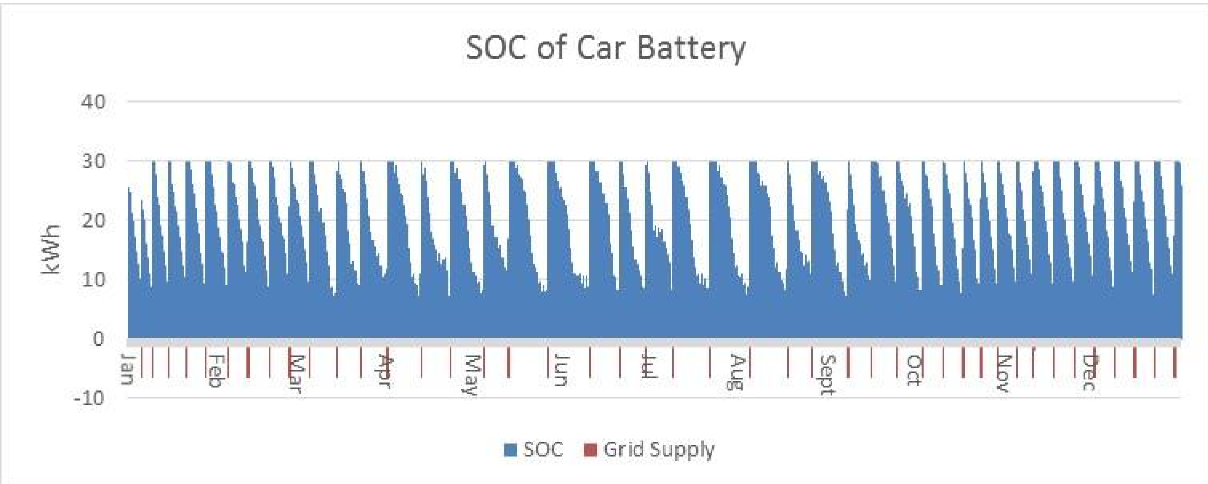


Figure 40 - State of charge of the car battery during the 10th year in scenario 3.
Source: Elaborated by the author

Regarding the electricity fed into the grid it is possible to see a similarity with the previous scenario 2, as shows the Figure 41. Most of the electricity is injected during Summer and during Winter as happened in the other scenarios; almost all energy produced is used on the electric car. During all 10 years simulation only 18% of the total energy used on the car (PV + grid) is injected into the grid.

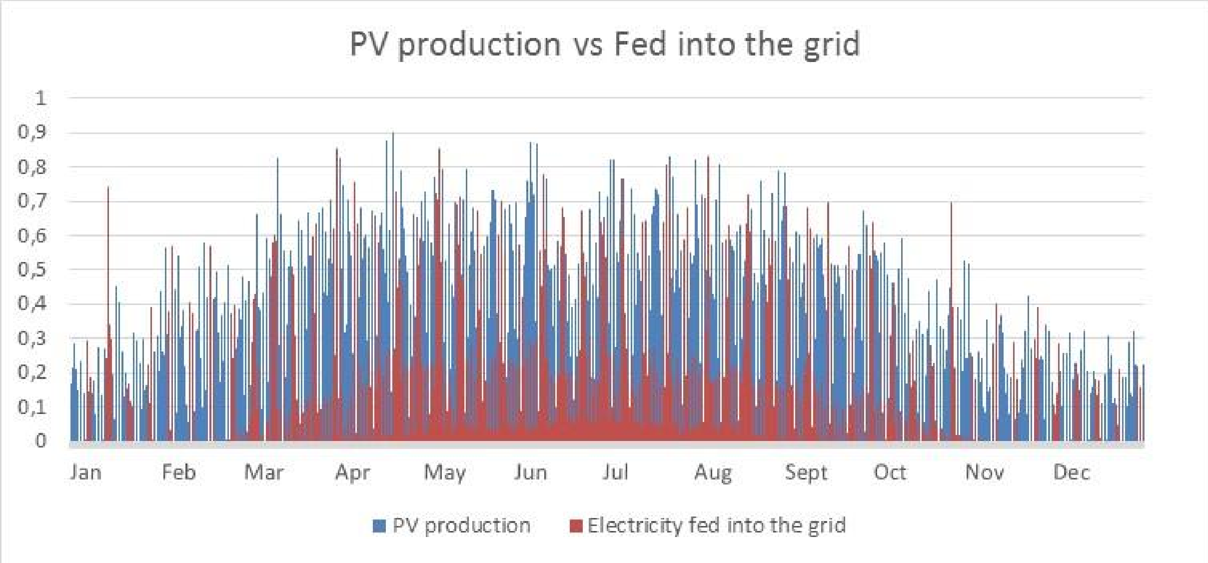


Figure 41 - Comparison between PV yield and electricity fed to the grid during the 10th year in scenario 3.
Source: Elaborated by the author

In Figure 42 the month by month relation on the 10th year is showed. In January, the amount of electricity fed into the grid is 6% and in June, the highest month, it is 25%. A variation similar to scenario 2, but with a bit more energy being used in the car.

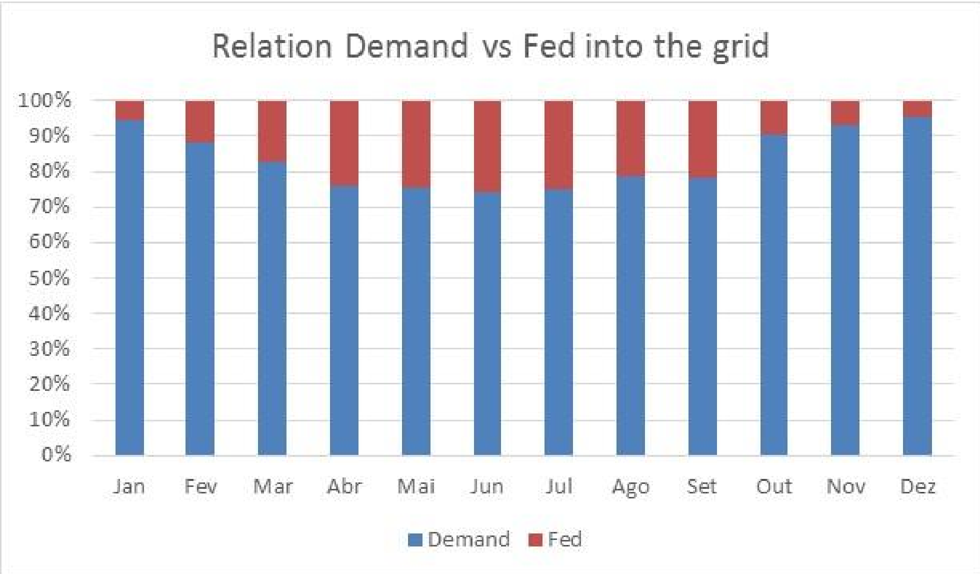


Figure 42 - Comparison between the amount of energy being used on the car (demand) and fed into the grid (fed) during the 10th year in scenario 3.
Source: Elaborated by the author

The minimum array size, as said before, is just 1.2 kWp; by adding 1 kWh of storage less than 0.05 kWp can be decreased. Furthermore, as it can be seen in Figure 43, more than that becomes very unfeasible. For example, by adding 40 kWh storage capacity, the array size comes to 1 kWh and the share of electricity fed to the grid comes to 0.1% (reaching the maximum as already explained).

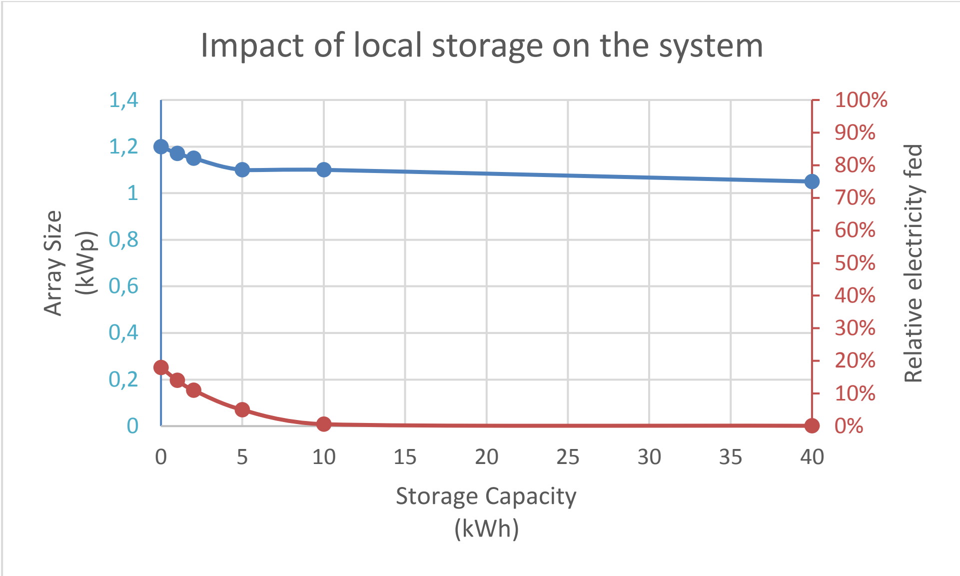


Figure 43 - Storage system state of charge variation during the 10th year in scenario 3.
Source: Elaborated by the author

Scenario 4

In this last scenario, it is assumed no PV system so that the grid provides all the energy to the car. In the Figure 44 it can be seen that there is no seasonality because the influence of solar irradiance is totally neglected. In order to supply enough electricity to fulfil the electric car demand 52 charges are necessary each year. There is no energy fed back into the grid as no energy is produced.

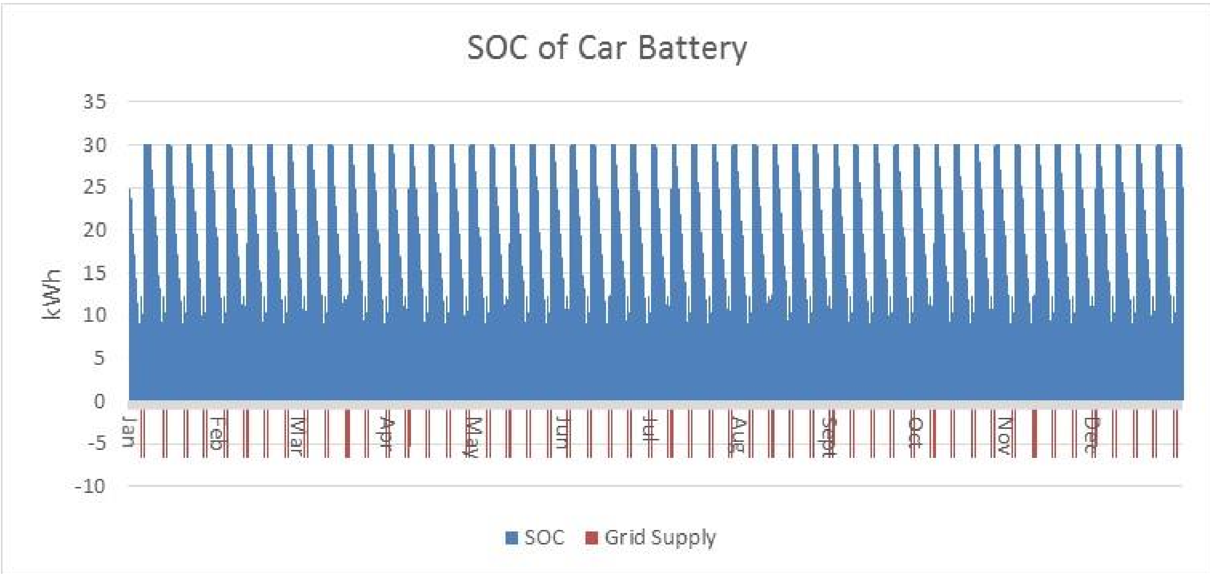


Figure 44 - State of charge of the car battery during the 10th year in scenario 4.
Source: Elaborated by the author

4.1.2. Norway

Norway is a country situated at high latitudes what results in very long days during Summer and very long nights during Winter. This seasonality causes a big difference between the solar irradiance during the colder months when compared with the warmer months. The impact of it is evidenced by the following results.

Scenario 1

In order to have a PV system able to provide 100% of the required energy with no storage an array size of 79 kWp is necessary. This very big system is required because during Winter the solar irradiation is very low; therefore, a big array has to be installed in order to compensate it. The state of charge of the car battery, as can been seen in Figure 45, stays very stable during the whole year, just decreasing during weekends when the car is not connected to the PV system. However, during weekdays its SOC charges again and reaches its maximum even during Winter.

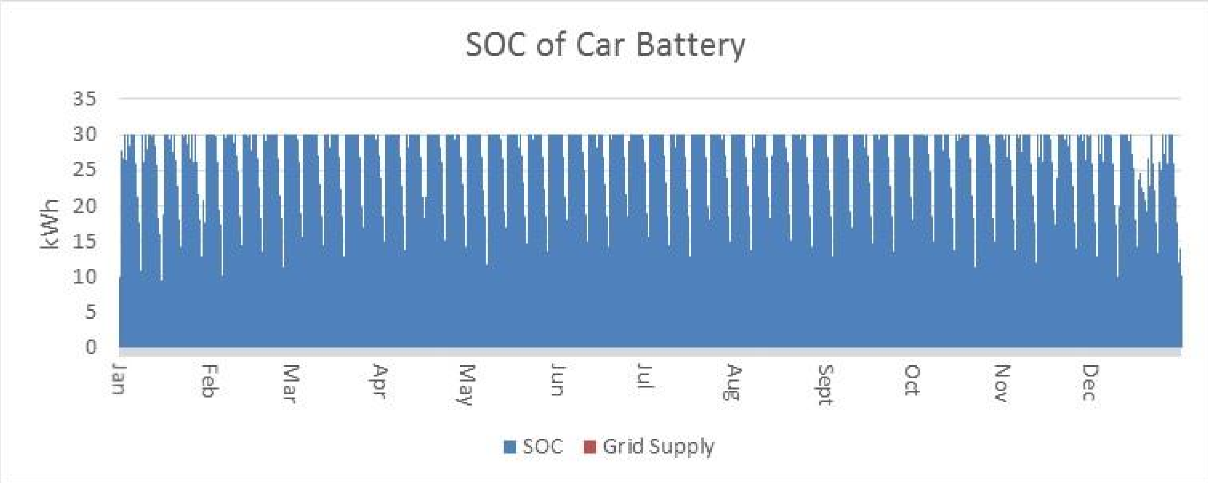


Figure 45 - State of charge of the car battery during the 10th year in scenario 1.
Source: Elaborated by the author

The consequence of designing the system to cope with the low solar irradiation during Winter is the great amount of electricity surplus produced during the rest of the year. In Figure 46 it is possible to see most of the electricity being fed to the grid during all year. It is almost impossible to see the blue lines indicating that a very small amount of the energy produced by the PV is used on the car. Even during Winter the electricity fed to the grid represents the majority of the energy produced.

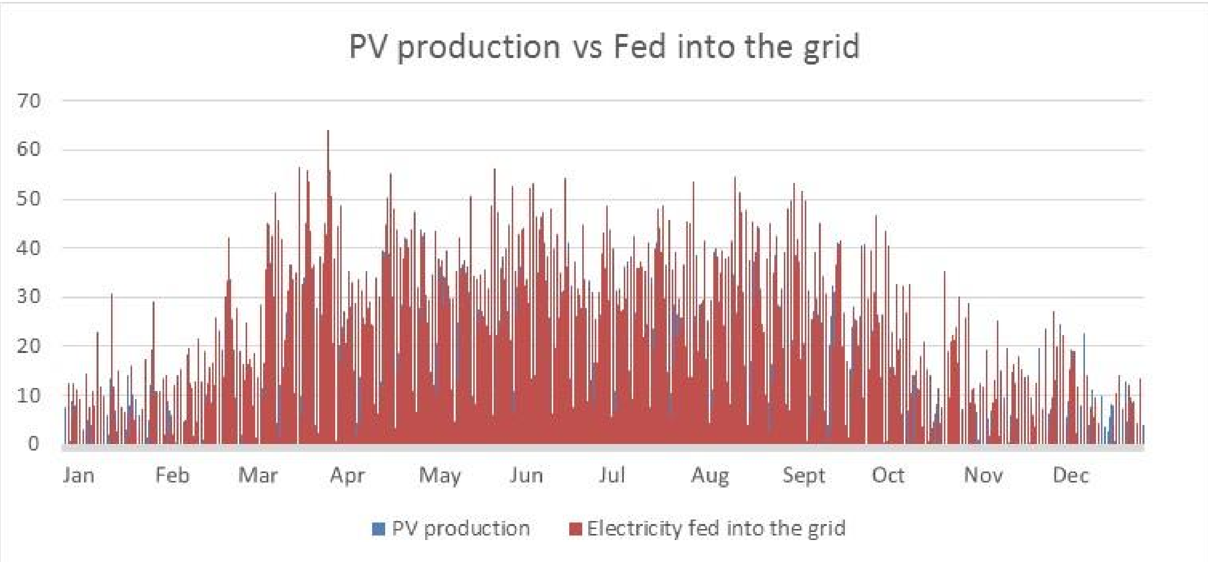


Figure 46 - Comparison between PV yield and electricity fed to the grid during the 10th year in scenario 1.
Source: Elaborated by the author

In order to better observe this relation the Figure 47 shows the share of energy being used on the car along with the energy being fed to the grid on each month of the tenth year. In June, this share reaches a maximum of 97% of energy injected back into the grid. Nevertheless, even during January, a cold month with low solar irradiation, this share is 75%. In total, during the 10 years simulation, 96% of the energy produced was fed into the grid and only 4% was used on the car.

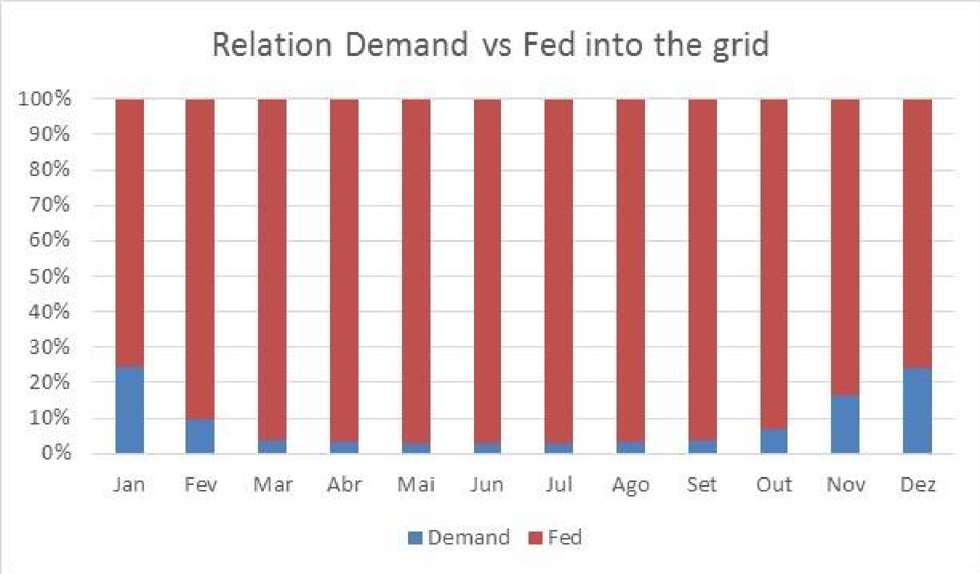


Figure 47 - Comparison between the amount of energy being used on the car (demand) and fed into the grid (fed) during the 10th year in scenario 1.
Source: Elaborated by the author

In Figure 48 it is possible to see the impact of a local storage in the system. Differently from the scenarios seen until this point, this time a local storage can impact very significantly the array size. Just 2 kWh of storage would mean a decrease of 6 kWp in the array size. A storage of 20 kWh would mean a decrease of 29 kWp. Nevertheless, this decrease tends to stabilize, requiring increasingly bigger storage capacities to decrease even more the array size.

The share of electricity fed to the grid is also impacted by the storage system; however, in this scenario the array size is in the order of dozens, which results in an energy production way higher than that needed on the car. Therefore, even with big storage systems, the share of electricity being injected into the grid continues to be very high. For example, for a storage system for 80 kWh (which is very big) the share would decrease to only 85%.

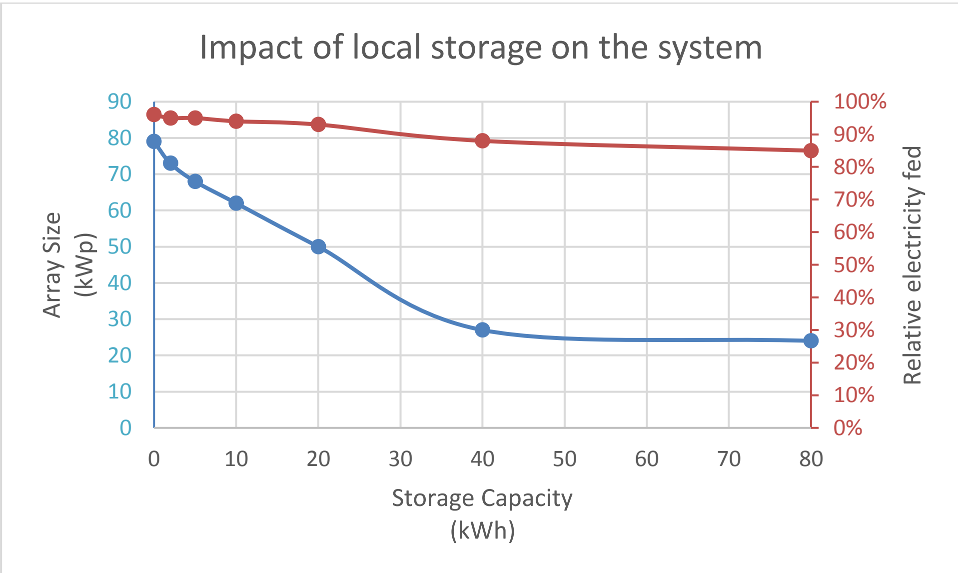


Figure 48 - Storage system state of charge variation during the 10th year in scenario 1.
Source: Elaborated by the author

Scenario 2

In this scenario, the PV system provides 75% of the electricity and the grid supports with 25%. The necessary array size, with no storage, drops to 4 kWp. As it can been seen in the

Figure 49 between April and September the PV is able to provide almost all energy to the electric car, just needing to be charged three times. Nevertheless, between October and March much more electricity from the grid is needed to compensate the lower solar irradiation during that period. In total, the car needs 35 full charges from the grid over the year. These charges are more frequent during December and January and become more spaced in the warmer months.

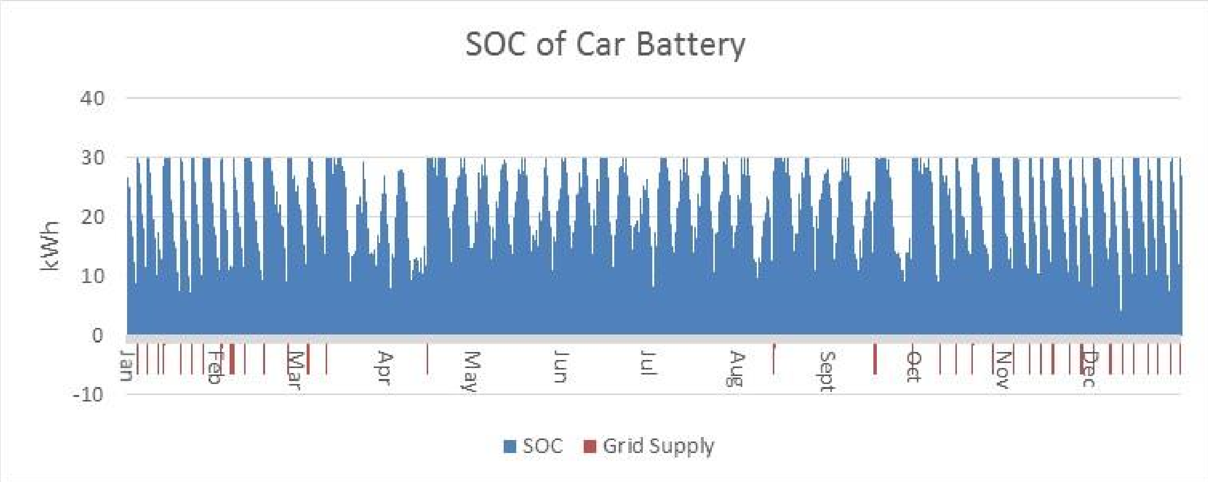


Figure 49 - State of charge of the car battery during the 10th year in scenario 2.
Source: Elaborated by the author

Regarding the electricity fed to the grid, in this scenario the situation is very different from scenario 1. Now, it can been observed many more blue lines on the Figure 50 which means that a significant part of the energy produced by the PV is not fed into the grid. Nevertheless, again, during Summer, due to higher solar irradiations, the amount of electricity being fed is higher when compared to the Winter months. In total, over 10 years a 31% of the energy produced by the PV system was injected back into the grid.

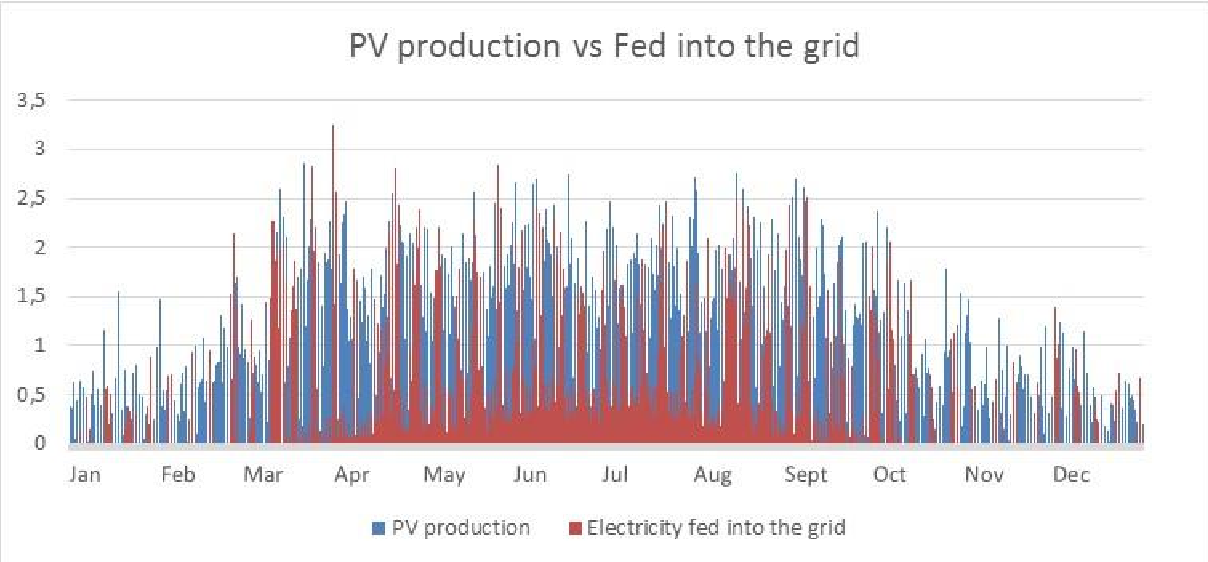


Figure 50 - Comparison between PV yield and electricity fed to the grid during the 10th year in scenario 2.
Source: Elaborated by the author

Using the same approach, in Figure 51 there is the share of electricity breakdown per month. Again, it becomes clear how the higher solar irradiation during Summer makes the system inject more electricity into the grid during this period and during Winter almost all energy is used on the car. In January, this share is 4% injected into the grid and 96% used on the car, and in June 46% injected and 54% used on the car.

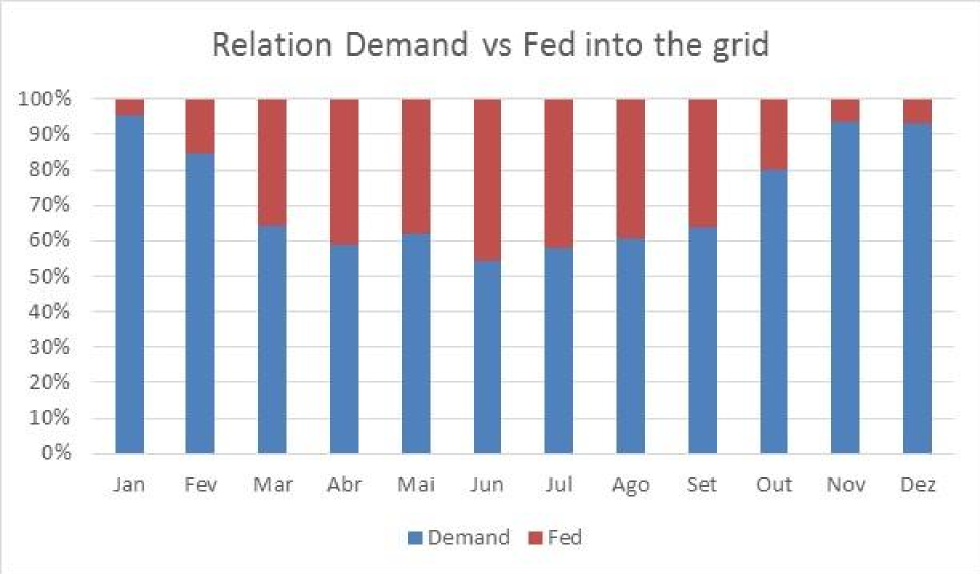


Figure 51 - Comparison between the amount of energy being used on the car (demand) and fed into the grid (fed) during the 10th year in scenario 2.
Source: Elaborated by the author

In this scenario, the impact of the local storage is not as significant as in scenario 1. This happens because the system with no storage is already working on relatively optimal conditions regarding the amount of electricity produced and electricity used on the car. This means there is not as much energy excess as in scenario 1. For example, with 2 kWh the array size can be reduced in 0.2 kWp, while in scenario 1, with the same storage capacity, it could be reduced in 6 kWp. A big storage capacity of 20 kWh would reduce the array size from 4 kWp to 3.4 kWp.

Regarding the share of electricity fed into the grid, in this scenario the reduction is more significant exactly because the array size order is lower than in scenario 1. So, a small difference on the array size has a more impactful reduction on the share of electricity being fed to the grid. For example, the 2 kWh storage capacity can reduce 3% (from 31% to 28%), while in scenario 1 a reduction of more than 4% is achieved with a storage capacity of 20 kWh. However, the stabilization present in all scenarios is evidenced here as well.

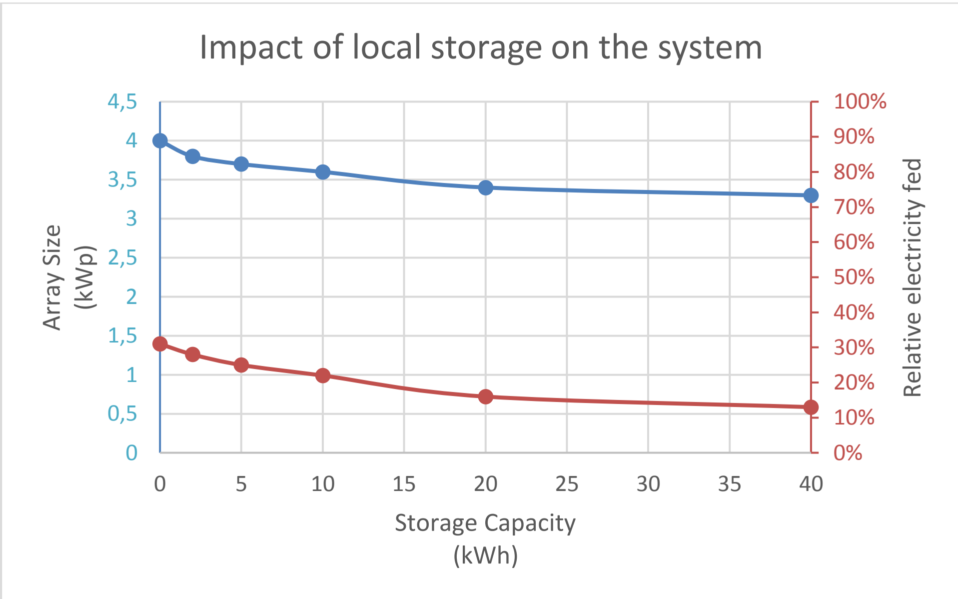


Figure 52 - Storage system state of charge variation during the 10th year in scenario 2.
Source: Elaborated by the author

Scenario 3

In scenario 3, the grid and the PV provide the same share (50%). Therefore, the minimum array size (without storage) is 2.2 kWp and a total of 66 charges are needed to supply enough energy to the car. The difference between the warm and cold months is the charging frequency. During January an average of 8 charges are needed, meanwhile in July or August only 4 charges are necessary. This shows that the PV system is important to support the electric car demand, despite the system grid supply need during all year.

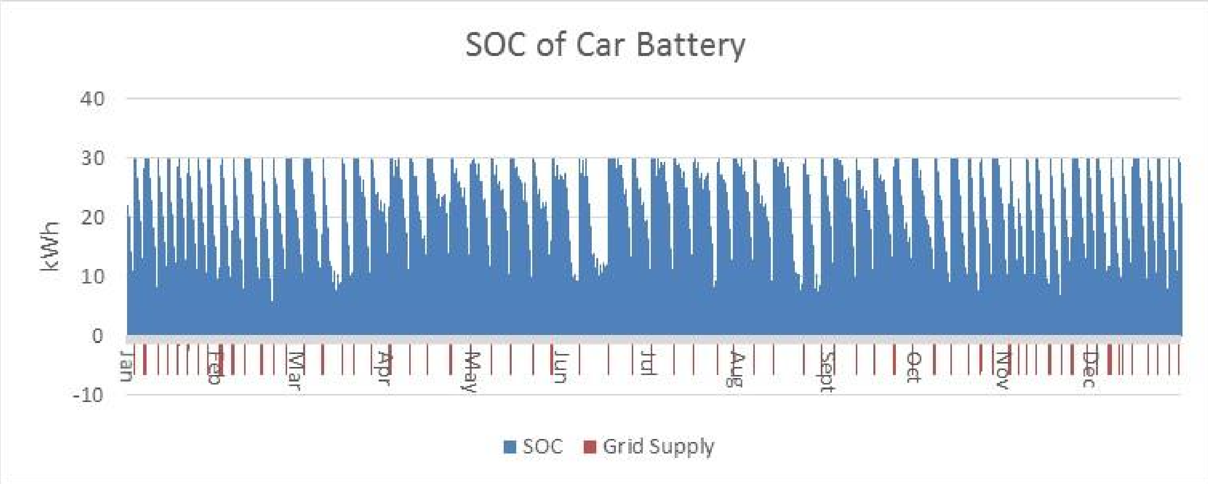


Figure 53 - State of charge of the car battery during the 10th year in scenario 3.
Source: Elaborated by the author

As in scenario 2, the Figure 54 shows a similar trend. Still a significant amount of energy is fed to the grid, but most of the energy produced by the PV is used on the car. The electricity injected to the grid is concentrated between April and September, when the solar irradiation is higher. In total, over 10 years 18% of the energy produced by the PV system is injected back into the grid. Analyzing this relation, but this time per month, in Figure 55, the seasonality becomes clearer. Only 2% is injected to the grid in January, while this gets to 28% in June.

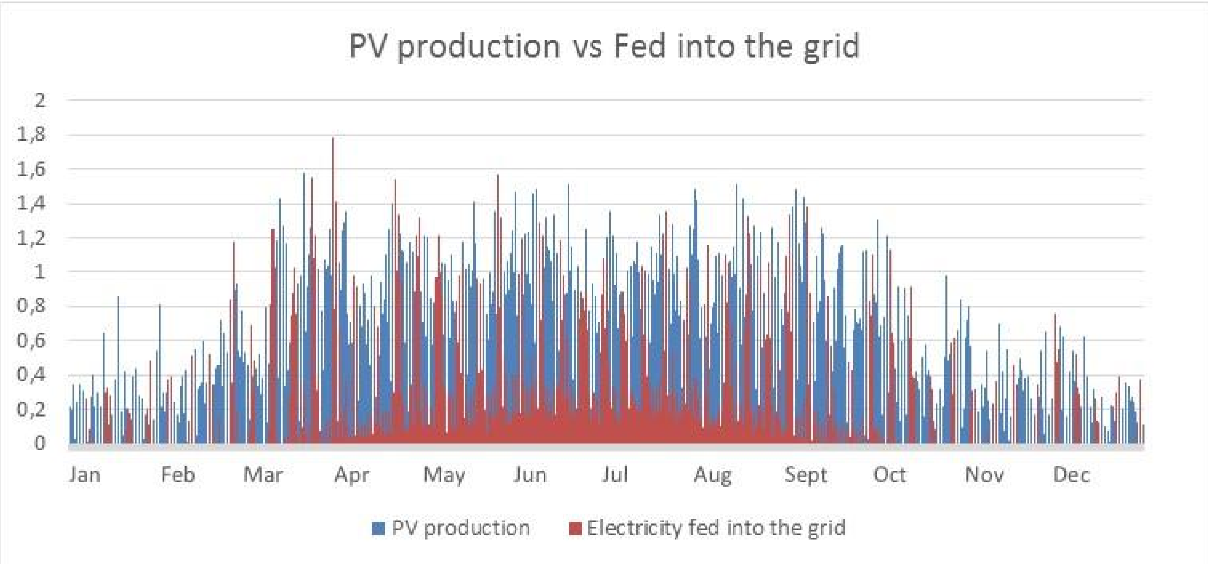


Figure 54 - Comparison between PV yield and electricity fed to the grid during the 10th year in scenario 3.
Source: Elaborated by the author

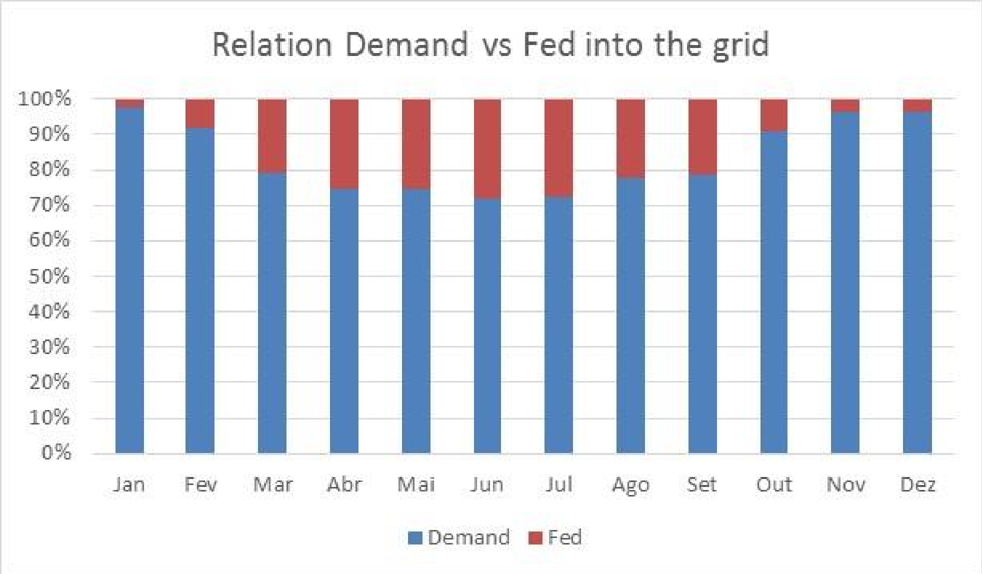


Figure 55 - Comparison between the amount of energy being used in the car (demand) and fed into the grid (fed) during the 10th year in scenario 3.
Source: Elaborated by the author

As already happened in scenario 2, in this scenario the impact of a local storage is also not much significant. The share of electricity is already relatively low, so this share, with storage, approximates to 0%. At this point (when the share of electricity fed is 0%), increasing the local storage is totally insignificant. Furthermore, as it can be seen in the Figure 56, with a storage capacity of 20 kWh the share of electricity fed into the grid decreases to 1%, but the array size does not change much - just decreasing from 2.2 kWp to 1.9 kWp.

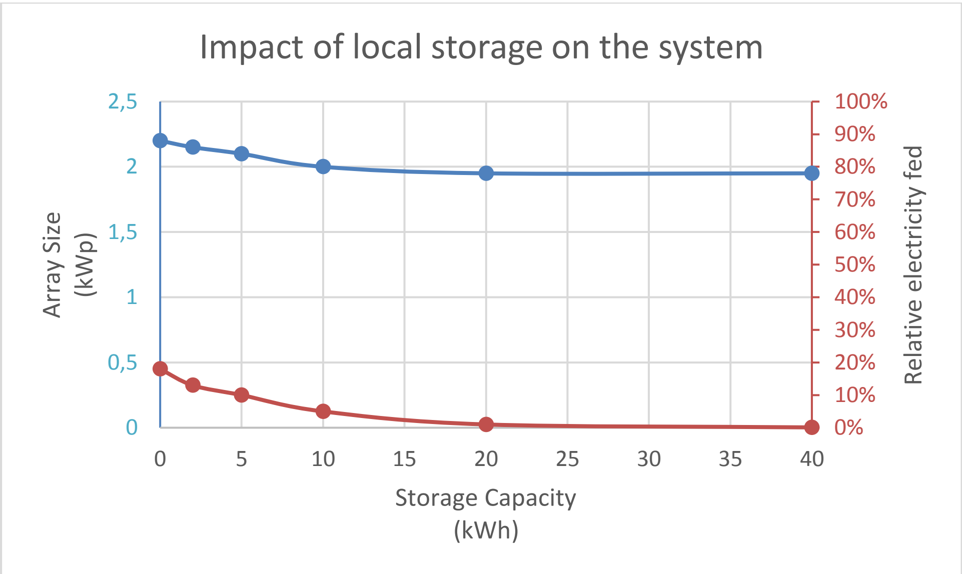


Figure 56 - Storage system state of charge variation during the 10th year in scenario 3.
Source: Elaborated by the author

Scenario 4

In this last scenario, it is assumed no PV system so that all the energy for charging the car is provided by the grid. In the Figure 57 it is possible to see that there is no variation between seasons throughout the year, as the influence of solar irradiance is totally neglected. In the case of Norway, where the car travels on average 47.2 km a day, 114 charges are necessary each year to supply enough electricity in order to fulfil the electric car demand. This represents almost one charge every three days. As no energy is produced, there is no energy fed back into the grid.

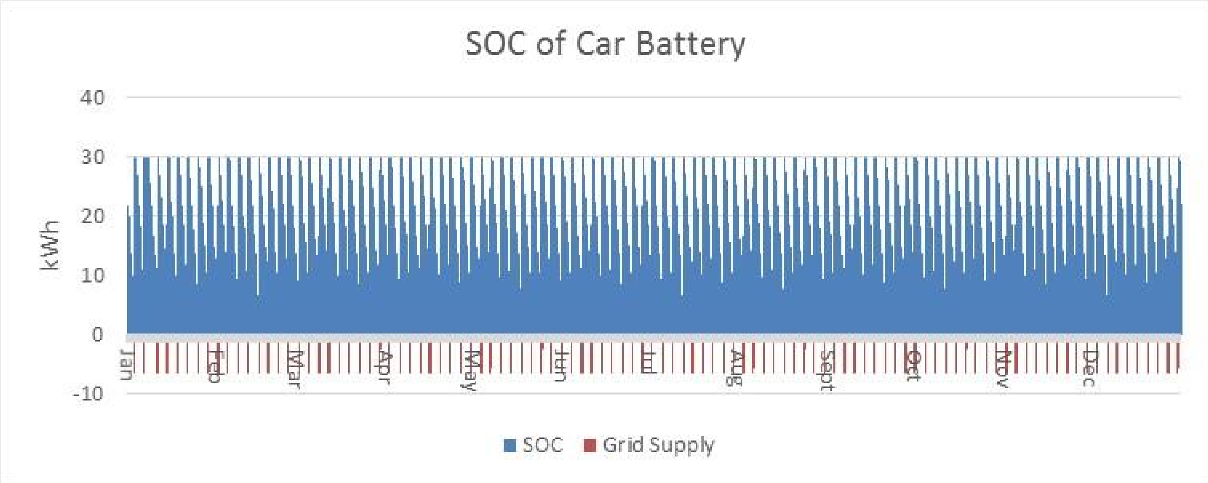


Figure 57 - State of charge of the car battery during the 10th year in scenario 4.
Source: Elaborated by the author

4.1.3. Brazil

Brazil has most of its territory located between the Equator line and the Tropic of Capricorn. This tropical geographical location gives the country some inherent advantages regarding the solar radiation like more stability during the year and less variability between Winter and Summer. Additionally, there is not much difference in the daily light duration throughout the year. Sao Paulo for example, a city considered to be on the Southeast part of the country, has on average 13 sun hours in Summer and 11 sun hours in Winter.

Scenario 1

Given the Brazilian conditions, the necessary system size to be totally independent from the grid is 4 kWp. As it can been seen in the Figure 58 during all year the battery is almost full. Differently from the previous countries studied, Brazil is on the Southern Hemisphere, which means that the Winter is between June and September. That is the reason why only in June (lowest solar irradiation) the battery SOC reached a minimum of 10 kWh. As expected, the tropical country needs a smaller array size to provide all energy to the car; this is due much more to the low variability between Summer and Winter radiations than to a higher annually solar radiation, which also contributes but not as much.

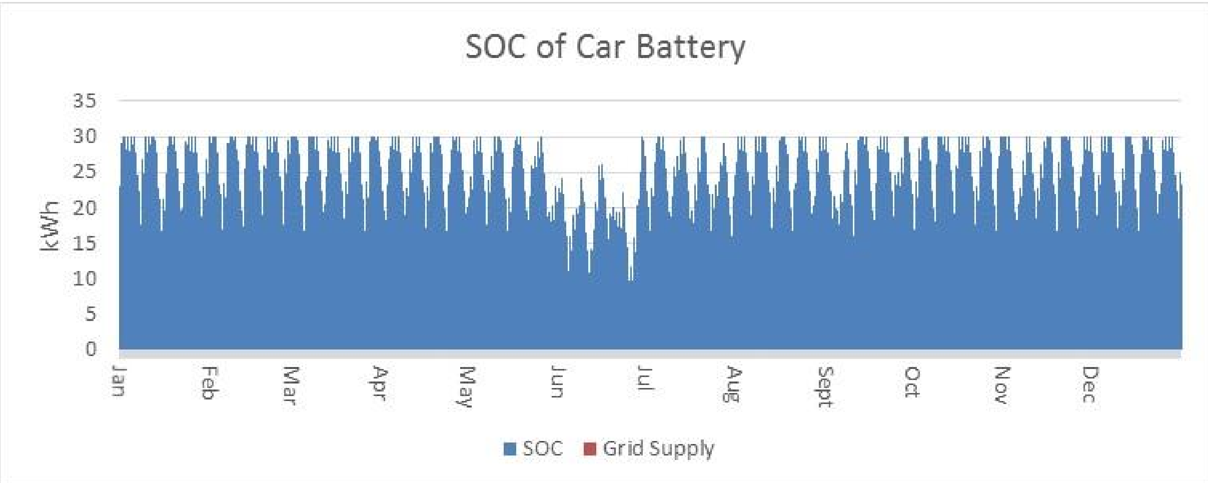


Figure 58 - State of charge of the car battery during the 10th year in scenario 1.
Source: Elaborated by the author

Nevertheless, as it happened in the other countries, providing 100% of the energy from a PV system results in excess of electricity production. In Figure 59 this can be better observed: over the whole year the amount of electricity being injected is very significant. In this scenario, 61% of the total electricity produced by the PV is injected into the grid.

In addition, in this same figure, the low variation of the PV production can be well observed. There is only a small depression between May, June and July, which explains the drop on the SOC of the car in this period. But when compared to The Netherlands and Norway, this drop is almost not noticeable

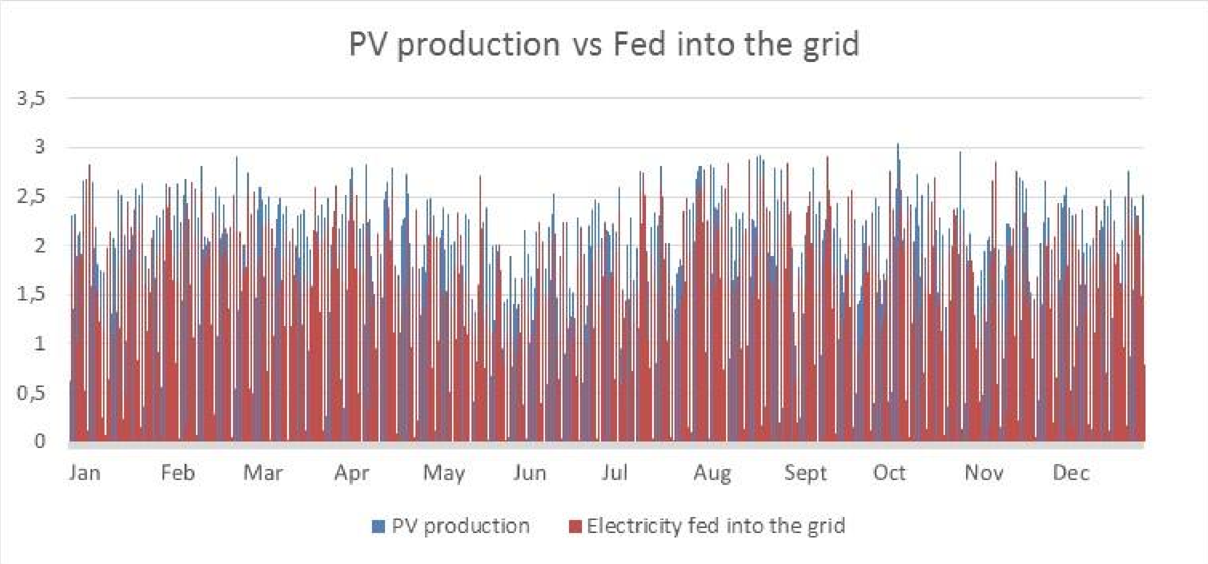


Figure 59 - Comparison between PV yield and electricity fed to the grid during the 10th year in scenario 1.
Source: Elaborated by the author

In Figure 60 the electricity share breakdown that is used on the car and injected into the grid is observed. Contrarily to the other countries, where this same analysis showed a great variation among the months, in this situation the share remains almost the same throughout the year. In June the share is 50% - the lowest in the year, meanwhile in February - the highest, 64% of the energy is not used on the car.

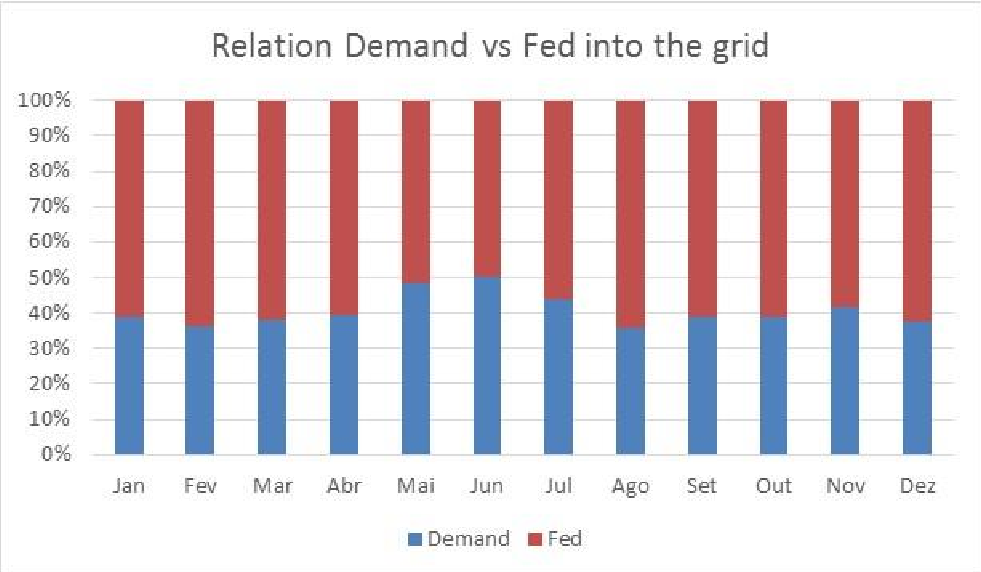


Figure 60 - Comparison between the amount of energy being used in the car (demand) and fed into the grid (fed) during the 10th year in scenario 1.
Source: Elaborated by the author

In the Figure 61 it is possible to see the impact of a local storage in the system. In this scenario, the local storage fairly impacted the array size. A capacity of 2 kWh would mean a decrease of 0.9 kWp in the array size. A storage of 20 kWh would mean a decrease of 1.8

kWp. Nevertheless, this decrease tends to stabilize requiring increasingly big storage capacities to decrease even more the array size.

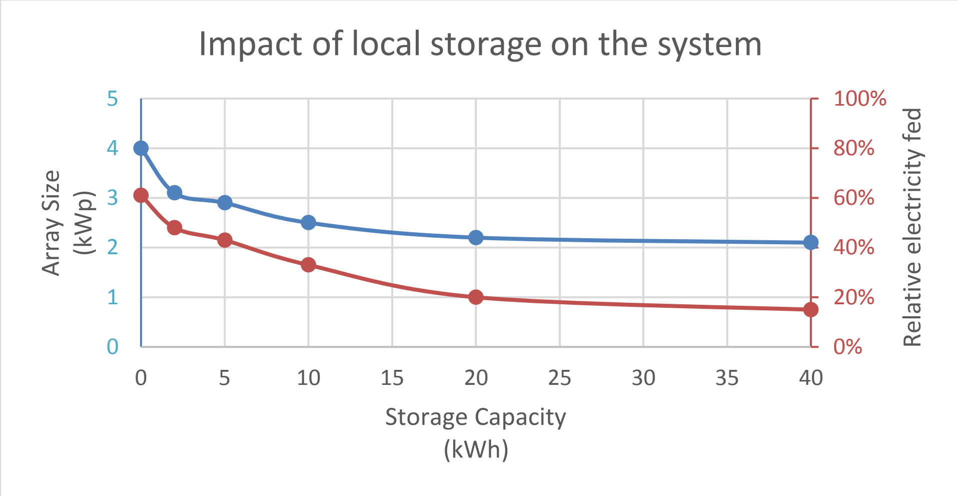


Figure 61 - Storage system state of charge variation during the 10th year in scenario 1.
Source: Elaborated by the author

The share of electricity fed to the grid is also impacted by the storage system in the same order as it impacted the array size. A storage of 10 kWh would decrease the share from 61% to 33%, which is a low share when compared to the other countries in this same scenario. Similarly, to The Netherlands, in Brazil the net-mattering system is in force, which requires the user to consume the electricity fed into the grid in order to make use of it. Therefore, with the help of a storage system, in Brazil, a system providing all energy necessary to an electric car can work more similarly to a charging station than to a power plant, as most of the energy produced by the PV system is used on the car and the excess being fed is feasibly consumed by other sources.

Scenario 2

In this scenario, the PV system provides 75% of the electricity and the grid supports with 25%. The necessary array size, with no storage, is 1.9 kWp. As it can been seen in the Figure 62, between the warmer months (October to April), the charges needed are less frequent than in May and in June when they are very frequent. In total, the car needs 31 full charges from the grid over the year. It is curious that, differently from the other countries, in this scenario there is no big period that the car does not need the grid; however, during the colder months, in the Brazilian case, it is needed much less grid supply than in the other two countries cases.

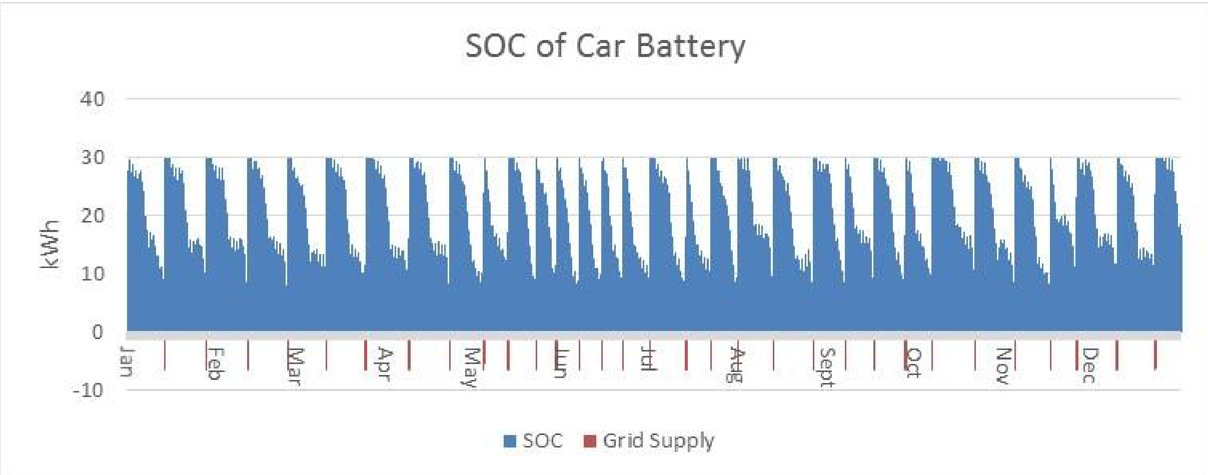


Figure 62 - State of charge of the car battery during the 10th year in scenario 2.
Source: Elaborated by the author

Regarding the electricity fed to the grid, in this scenario the situation is still similar to scenario 1. Many red lines can be observed in Figure 63, which means that a significant part of the energy produced by the PV is still fed to the grid. In temperate countries, during Winter, the day is very short and when there is sunlight the car usually is connected to the station. Though, in tropical countries, even in Winter, there are times when the PV system produces energy out of the period during which the car is connected, increasing the amount of electricity being fed in this period. In total, over 10 years, a 38% of the energy produced by the PV system was injected back into the grid.

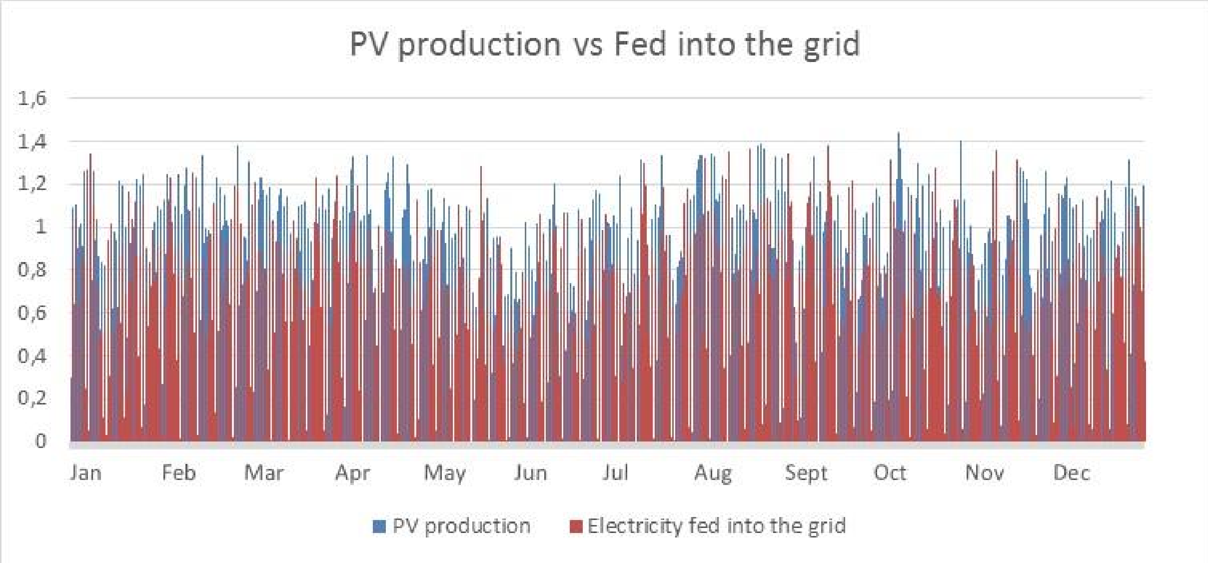


Figure 63 - Comparison between PV yield and electricity fed to the grid during the 10th year in scenario 2.
Source: Elaborated by the author

Following the same approach the Figure 64 shows more specifically this reduction on the share, but keeping the same trend. In February 40% is injected into the grid, while in June this contribution drops to 34%, evidencing the low variability between months.

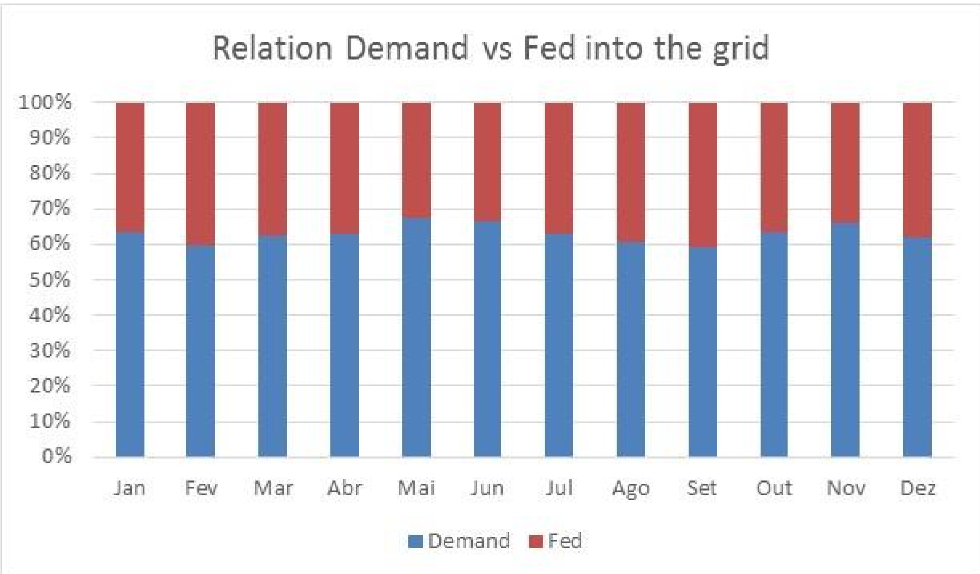


Figure 64 - Comparison between the amount of energy being used on the car (demand) and fed into the grid (fed) during the 10th year in scenario 2.
Source: Elaborated by the author

In this scenario, the impact of the local storage is not as significant as in scenario 1. This happens because the system with no storage is already working relatively close to its limit regarding the amounts of electricity produced and electricity used in the car. This means there is not as much excess of energy as in scenario 1. For example, with 1 kWh the array size can be reduced in 0.2. A big storage capacity of 20 kWh would reduce the array size from 1.9 kWp to 1.3 kWh, reaching the limit because, at this point, there is no electricity fed into the grid.

Regarding the share of electricity fed into the grid, in this scenario its reduction is also significant. This means that a feasible storage system size can better spread the amount of energy produced over the week. For example, the 1 kWh storage capacity can reduce 9% (from 38% to 29%) the share of electricity fed back to the grid. A storage capacity of 20 kWh is capable of zeroing the electricity fed into the grid; after that, any additional storage will be useless.

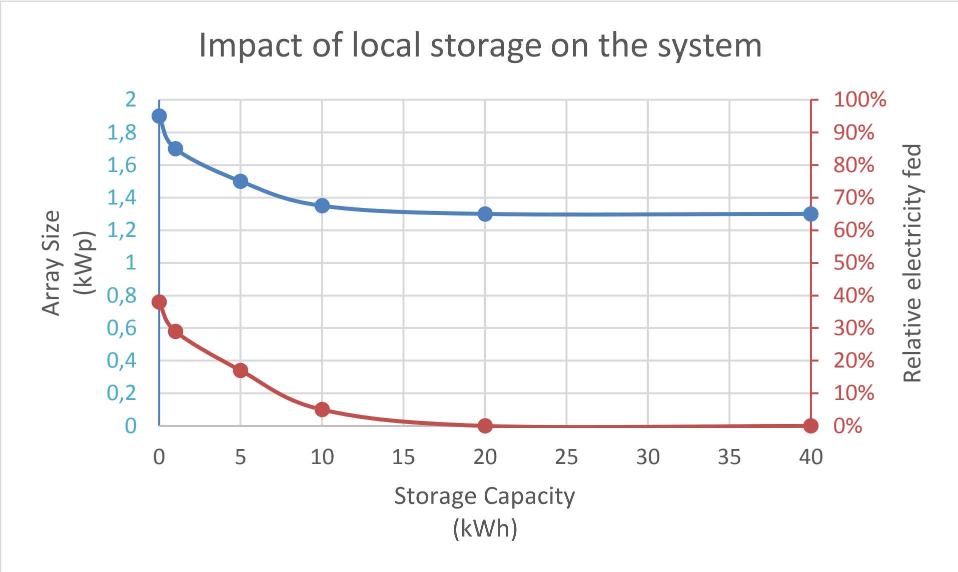


Figure 65 - Storage system state of charge variation during the 10th year in scenario 2.
Source: Elaborated by the author

Scenario 3

In scenario 3, the grid and the PV provide the same share (50%). Therefore, the minimum array size (without storage) is 1.05 kWp and a total of 53 charges are needed to supply enough energy to the car. The difference between the warm and cold months is, again, the charging frequency; however, in the Brazilian case this difference is much more subtle.

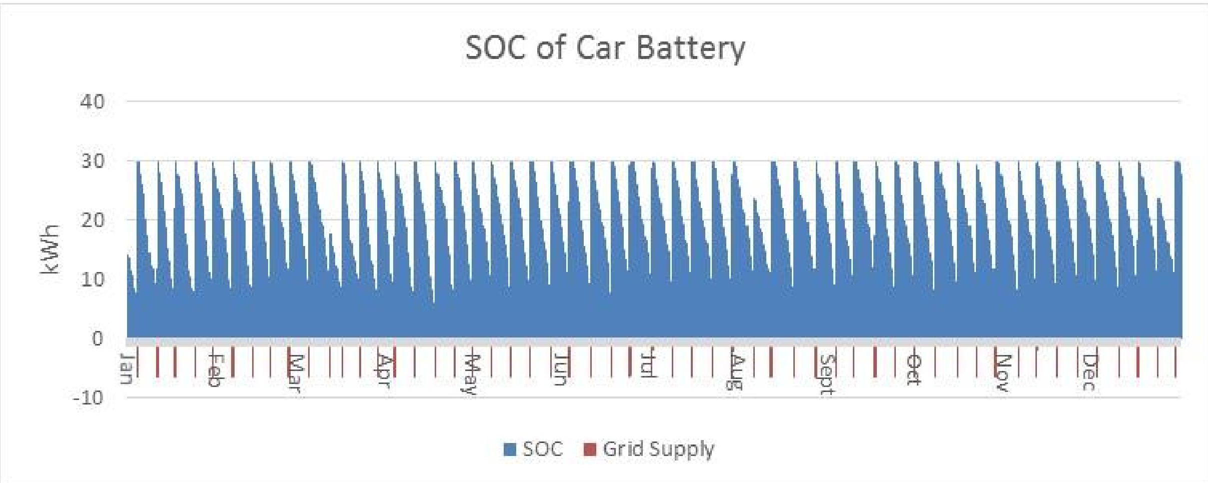


Figure 66 - State of charge of the car battery during the 10th year in scenario 3.
Source: Elaborated by the author

Regarding the energy fed to the grid, the situation is very similar to scenario 2. In this scenario, the electricity fed to the grid represents 25% of the total electricity produced by the

PV. Therefore, a reduction from 38% to 25% (scenario 2 to 3) is spread all over the year, differently from the other countries where the reduction was better observed as it was concentrated in Winter months. In Figure 67 the monthly breakdown shows the same trend in which the values are around the average (25%) in all months.

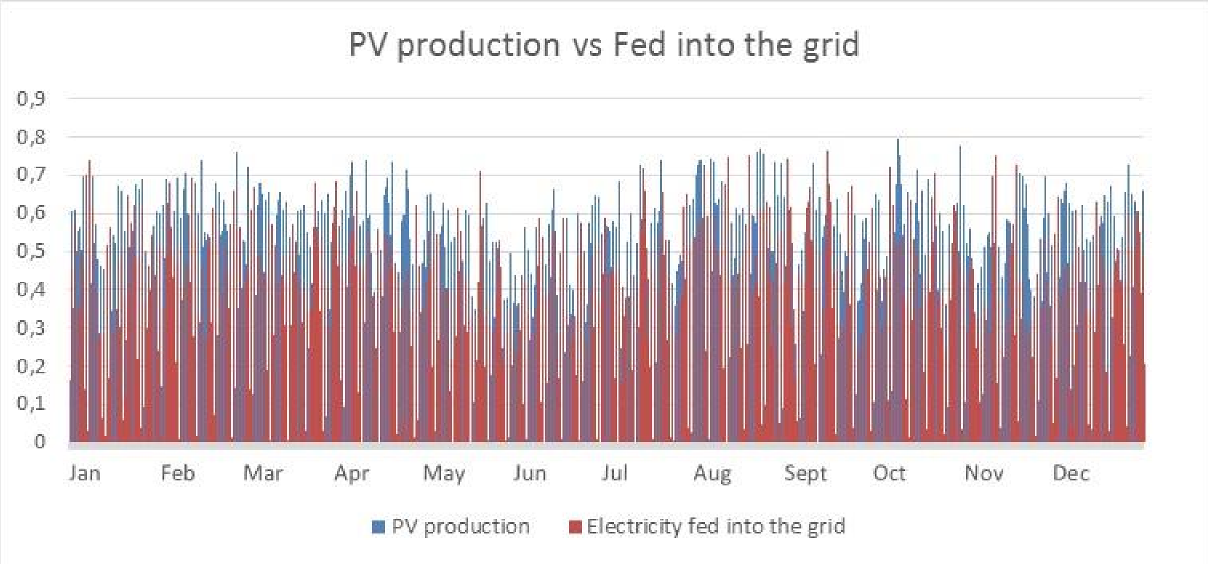


Figure 67 - Comparison between PV yield and electricity fed to the grid during the 10th year in scenario 3.
Source: Elaborated by the author

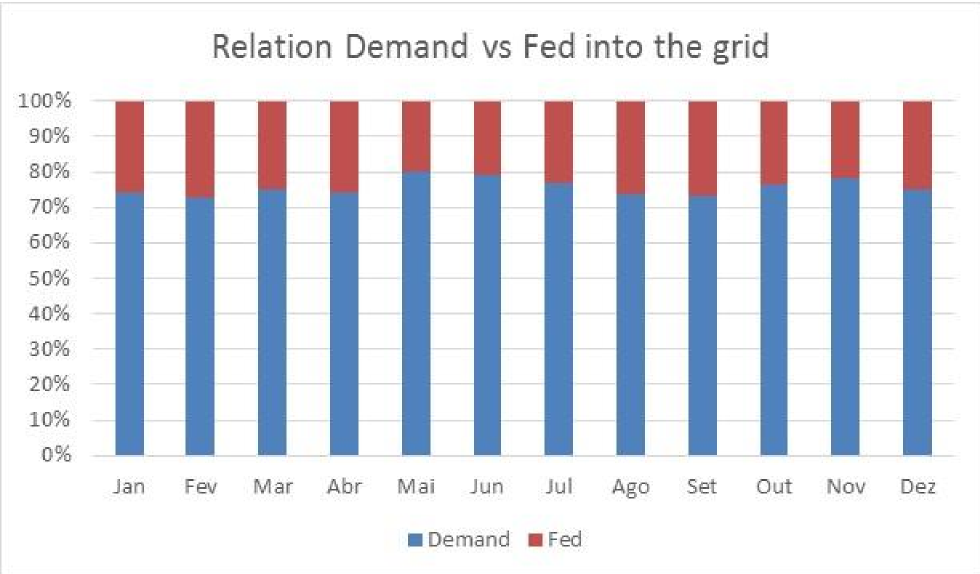


Figure 68 - Comparison between the amount of energy being used in the car (demand) and fed into the grid (fed) during the 10th year in scenario 3.
Source: Elaborated by the author

The impact of the storage system, as expected, is very similar to scenario 2 as well. The only important difference is that, in this case, the limit of reduction in the array size is at the point when the storage capacity reaches 10 kWh, instead of 20 kWh reached in scenario 2. At this point there is no electricity fed to the grid and all energy produced by the PV system is used on the electric car.

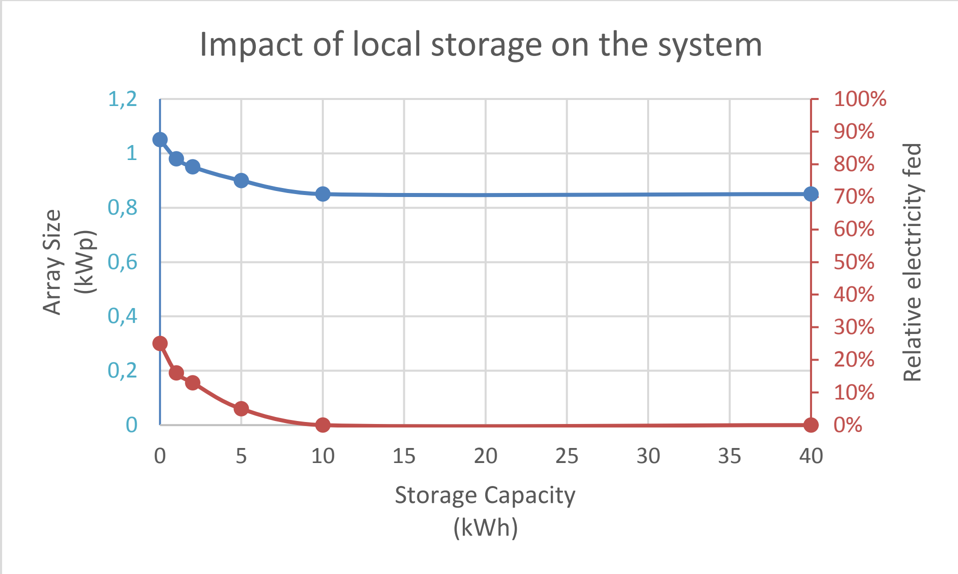


Figure 69 - Storage system state of charge variation during the 10th year in scenario 3.
Source: Elaborated by the author

Scenario 4

In this last scenario it is assumed no PV system; all the energy for the car is provided by the grid. In the Figure 70 it is possible to see that there is no variation between seasons. The only variable influencing in this scenario is the total distance travelled. As in Brazil it was assumed 32 km per day, it is expected more need for charges than The Netherlands (30 km/day) and less than Norway (47.2 km/day). In the Brazilian case, it is necessary 78 charges each year in order to supply enough electricity in order to fulfil the electric car demand.

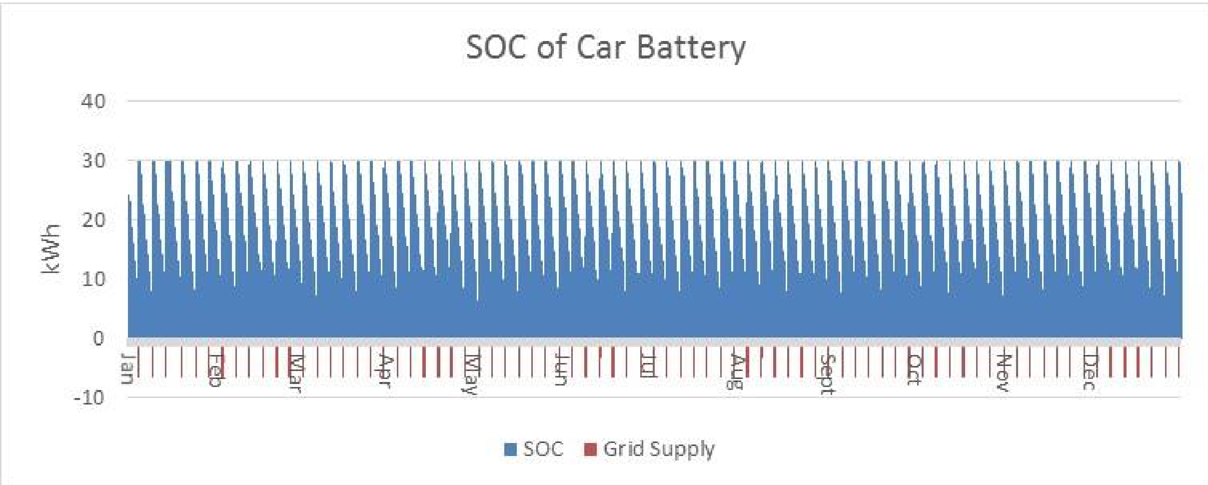


Figure 70 - State of charge of the car battery during the 10th year in scenario 4.
Source: Elaborated by the author

4.2. Economic sub-model

The main objective of this section is showing the economic results which will be the base to evaluate the economic feasibility of the different scenarios. In the figures below, the electric accumulated costs of each scenario, their cash flows and the respective financial indicators, including a simulation of an ICEV using gasoline, over the entire period of the simulation (10 years) are shown.

It was defined a storage system of 5 kWh for all the scenarios considering the use of a storage system. Therefore, it is important to observe the change that adding a storage system causes on the economic performance of each scenario, and remarking that a bigger storage means more initial costs, but also smaller array size and less energy fed into the grid as seen in technical model results.

4.2.1. The Netherlands

Despite some progress in the last years, the main energy source for transportation is still gasoline in The Netherlands. The Figure 71 shows a comparison among the accumulated costs, through 10 years, in all scenarios. All three scenarios show different profiles which evidences the different origin and approach among them. The scenario 1 - without storage - is the only one which results in a significant revenue after 10 years; this is saying that after 10 years the amount of money that was saved by the electricity fed to the grid was higher than the total system costs. Additionally, the scenario 1 - with storage - presents nearly 0 accumulated costs. In all other scenarios the total costs are higher than the total revenue from injecting electricity to the grid. The gasoline scenario was the most costly after 10 years. The trend observed is that the scenarios with storage have significant higher investment costs than their respective scenarios without storage. After 10 years just 3 situations presented more costs than the 100% grid - scenario 4 (purple); they are: scenario 2 - with storage, and scenario 3 - with storage and gasoline.

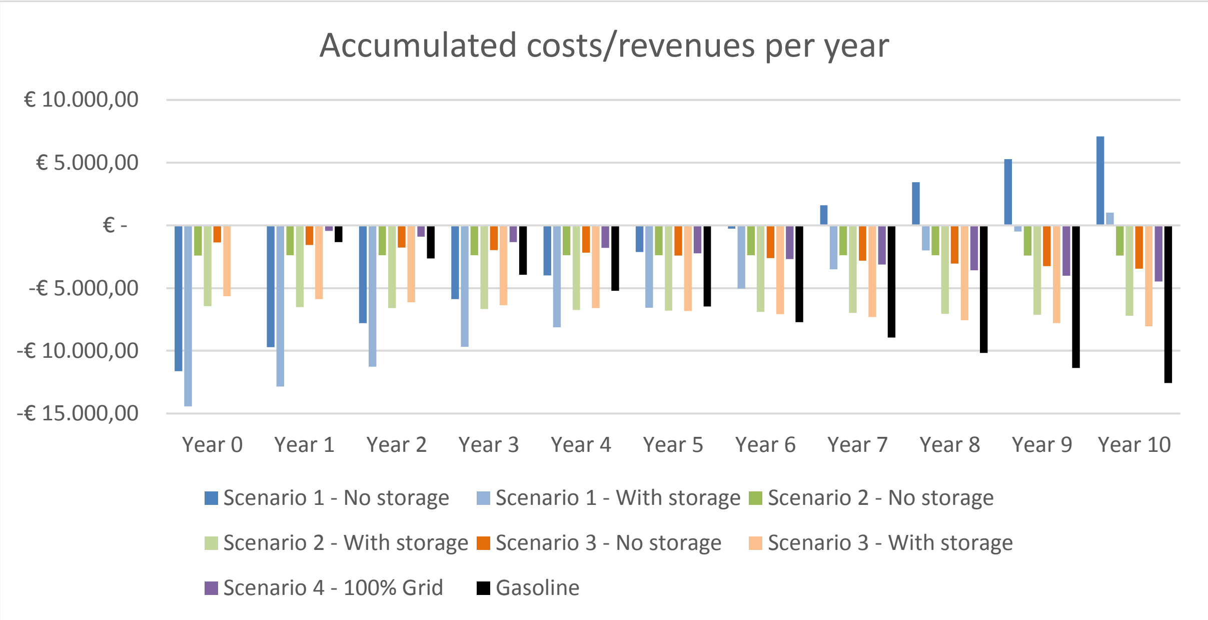


Figure 71 - Accumulated costs per scenario over 10 years.
Source: Elaborated by the author

Following the simulations, each scenario was analyzed regarding the money saved when compared with the costs of a gasoline car. The revenue of each year is defined by the difference between the costs saved by not using gasoline and the actual costs of the scenario analyzed. Additionally, the 100% grid will be shown to serve as reference between scenarios. The idea is to treat the transition to a more sustainable energy source for transportation as an investment and the simulation intend to analyze its profitability.

Scenario 1

Figure 72 depicts the higher investment costs (€14,432 with storage and €11,628 without storage) that the local storage option has, resulting in a difference of €2,804. This means that the additional costs related to the storage system are not compensated by the reduction of the array size and, consequently, neither are the costs related to the PV system.

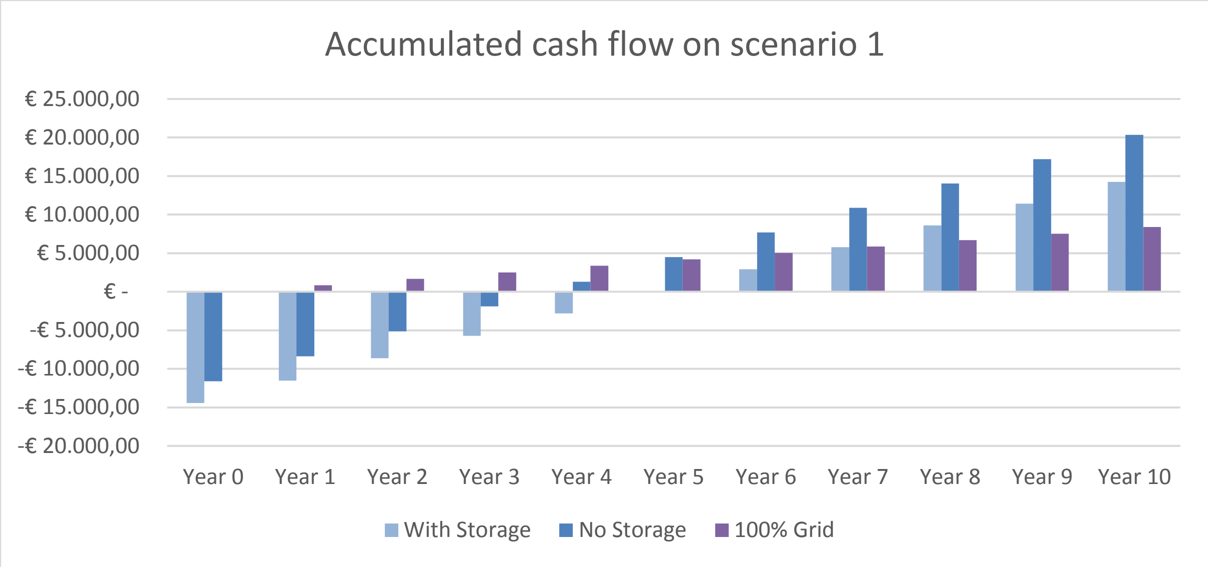


Figure 72 - Accumulated cash flow over ten years for scenario 1.
Source: Elaborated by the author

Apart from the reduction of the array size, it was observed in the technical model that a storage system also reduces the amount of electricity fed into the grid. In the example used in this analysis this reduction is 3%. For this reason, the use of a local storage system results in the decrease of revenues, consequence of not selling this excess of energy back to the grid. This condition also contributes to less attractive results when compared to a scenario without storage.

This can be observed by the difference in the total accumulated cash flow after 10 years, which is €20,332 in the 'no storage' option and €14,255 in the 'with storage' option (difference of €6,077). These differences are even clearer when the three financial indicators are analyzed in Table 5.

Table 5 - Financial indicators scenario 1.

	Scenario 1		
	With Storage	**No Storage**	**100% Grid**
NPV	€ 11,218.90	€ 16,949.93	€ 7,840.99
MIRR	8%	12%	-
Payback	5 years	4 years	-

The NPV is lower than the accumulated cash flows, because the investment costs are made initially when the money has a higher monetary value, meanwhile the revenues from selling back the electricity are spread over the years when the money has a lower monetary value due to inflation (used as discount rate). In order to make a long/medium term investment, the money depreciation over the years has to be taken into account. Therefore, the respective return should be compensated in order to make this investment economically feasible. As can be observed, both options are feasible and more profitable than a scenario with 100% grid, even with the values corrected by the inflation rate.

Regarding MIRR, the option without storage has a higher rate as it necessitates less initial costs and has more revenues due to more electricity being fed to the grid. Additionally, the payback time for the without storage option is lower.

In this scenario, it is important to remember, as seen in the technical section, that 81% (in the option without storage) of all energy produced is being sold to the grid which in absolute terms is 81,371 MWh. Therefore, this system works much more as a power plant to fed electricity into the grid than to power the electric car. Additionally, the company/household installing such system has to consume this 81,371 MWh surplus electricity in ten years otherwise its compensation is not possible due to the net-mattering system in force in The Netherlands.

Scenario 2

In Figure 73 the same trend as in scenario 1 can be observed. The option with a local storage has significantly higher investment costs (€6,452 with storage and €2,394 without storage), resulting in a difference of €4,058. Again, the costs related to the storage system are not compensated by the reduction of the array size.

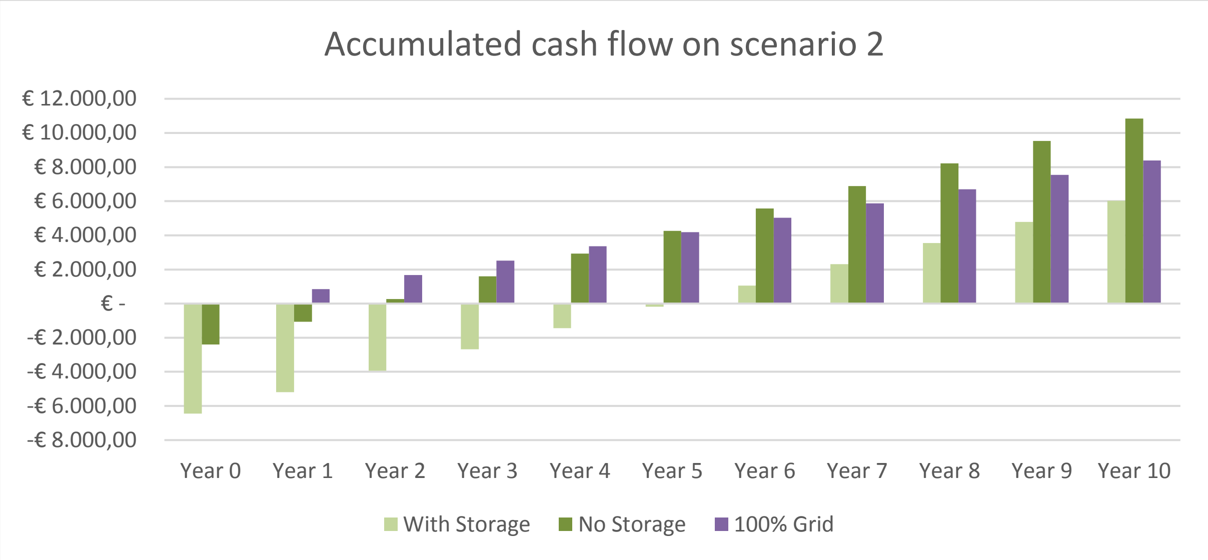


Figure 73 - Accumulated cash flow over ten years for scenario 2.
Source: Elaborated by the author

Following the same approach as in scenario 1, in this case the storage system resulted in a 14% reduction in the share of electricity fed to the grid. This means a more significant impact on the energy fed back into the grid which decreases the system's revenues. This explains the €4,810 difference between both results options in terms of accumulated cash flow which were €10,837 for the 'without storage' option and €6,027 for the 'with storage' one.

Table 6 - Financial indicators scenario 2.

	Scenario 2		
	With Storage	**No Storage**	**100% Grid**
NPV	€ 4,702.62	€ 9,433.54	€ 7,840.99
MIRR	8%	20%	-
Payback	6 years	2 years	-

Analyzing the financial indicators once more it becomes clear that the use of a local storage is not economically effective when compared to similar systems not using local storage, even when correcting the values. Furthermore, in this scenario the option with storage is not more profitable than the scenario using 100% grid. This means that the user would save more money by charging its electric car every time in the grid than charging it in a system with the conditions set for scenario 2 with storage. Nevertheless, all options are still feasible, or still present profits, when compared to using a conventional ICEV.

Regarding MIRR and payback, the with storage option did not change, but the without storage option increased its MIRR to 20% and the payback time was reduced to only 2 years. All this is due to the very low investment costs related to its return.

Additionally, this scenario is much more realistic in the sense that just 28% of the electricity produced is fed to the grid (in absolute values 7,356 MWh), making the system much more focused on producing energy for the car than selling it to the grid. This amount means an average of 61.3 kWh per month which is easily consumed by any company or household.

Scenario 3

In the scenario 3 a very similar situation to the scenario 2 is observed. This is not a surprise since the array size on both scenarios have similar magnitudes. Furthermore, as already happened in previous scenarios, the local storage contributes negatively in an economic perspective. The option with a local storage has €5,654 investment costs and the option without storage has €1,368 investment costs resulting in a difference of €4,286.

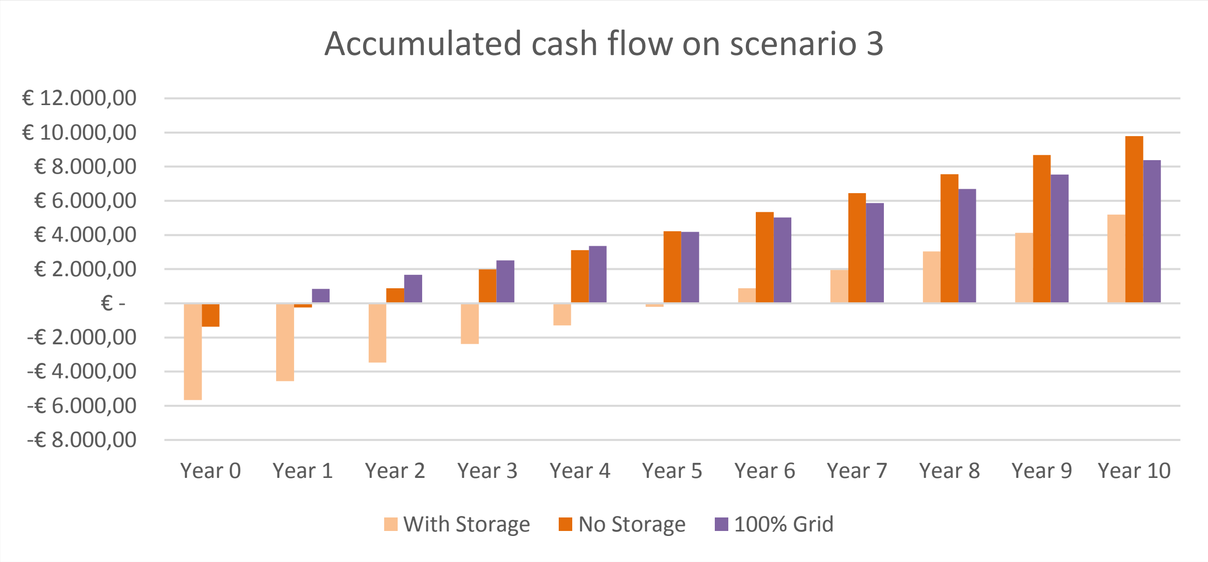


Figure 74 - Accumulated cash flow over ten years for scenario 3.
Source: Elaborated by the author

Additionally, the storage system reduced the share of electricity fed into the grid in 13% reducing the economic performance of such option. Again, the option with storage has a lower accumulated cash flow, after 10 years, than the scenario using 100% grid (purple). As can be seen in Figure 74, all options are very similar to scenario 2. Nevertheless, in this scenario 75% of the energy used in the system comes from the grid. Therefore, it is expected that its results would be similar to a scenario where 100% of the energy comes from the grid giving even more evidence to the negative economic impact of using local storage.

Table 7 - Financial indicators scenario 3.

	Scenario 3		
	With Storage	**No Storage**	**100% Grid**
NPV	€ 4,046.31	€ 8,598.85	€ 7,840.99
MIRR	8%	25%	-
Payback	6 years	2 years	-

Those similarities are also seen when the financial indicators are analyzed. Regarding the with storage option, all three parameters have almost the same value. For the without storage option, there is a slight increase in the MIRR, again because the decrease in the investment costs does not impact the cost saving in the same proportion.

In summary, all scenarios and its respective options are feasible when compared to an ICEV. Using storage on scenarios 2 and 3 in which most of the energy is used in the car and not sold back to the grid turns out to be less profitable than using 100% electricity from the grid. Lastly, the higher returns (NPV) are given when more electricity is sold to the grid (scenario 1), but higher profitability (MIRR and payback) is found when investment costs are lower (scenario 3).

4.2.2. Norway

Norway is one of the most advanced countries regarding the introduction of electric cars in its fleet, despite having an important share still using fossil fuels as its main energy source. The Figure 75 shows an accumulated cost comparison of all scenarios over 10 years. The costs regarding scenario 1 (with and without storage) are the ones, which first come to sight. Due to the very big array size required, its initial costs are equally high; nevertheless, the excess of electricity produced is not transformed in revenues like in The Netherlands and, consequently, these costs are not waived over the years. This happens due to the very low value utility companies pays to consumers for the energy they inject into the grid. Another important aspect to be observed is that, just in this scenario 1, the option with storage presented less costs than the without storage option, resulting in an economical benefit on using a local storage system in this particular scenario.

The second most costly scenario is the one using gasoline. It is still much lower than scenario 1, but significantly higher than all others. Differently from scenario 1, in scenario 2 and 3 the without storage options presented less accumulated costs than their respective with storage options. Additionally, the scenario using 100% grid presented less costs than all scenarios with storage options and very similar costs when compared with the without storage options of scenarios 2 and 3. Those scenarios reached around € 5,000 on accumulated costs after 10 years.

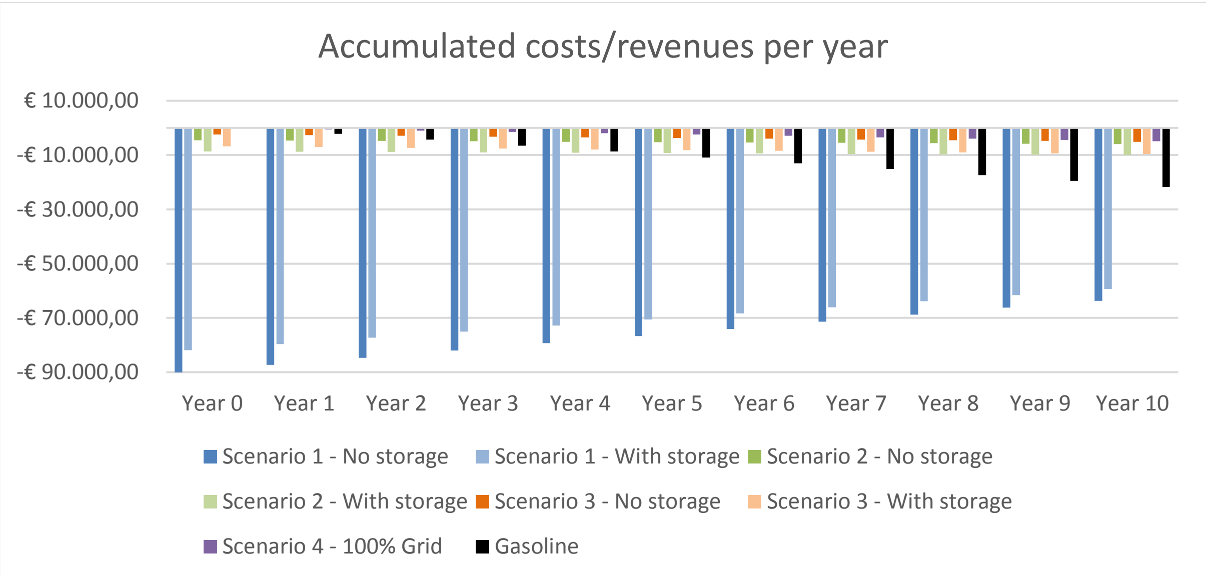


Figure 75 - Accumulated costs per scenario over 10 years.
Source: Elaborated by the author

Following the same Dutch analysis approach, each scenario is analyzed regarding the money saved when compared with the costs of a gasoline car. The revenue of each year is defined by the difference between the costs saved by not using gasoline and the actual costs of the scenario analyzed.

Scenario 1

Figure 76 depicts the option with a local storage with lower investment costs (€90,060 without storage and €81,920 with storage) resulting in a difference of €8.140. This means that the additional costs related to the storage system are compensated by the reduction of the array size and, consequently, the costs related to the PV system; in this case the storage system saved more than 8,000 thousand euros in initial costs.

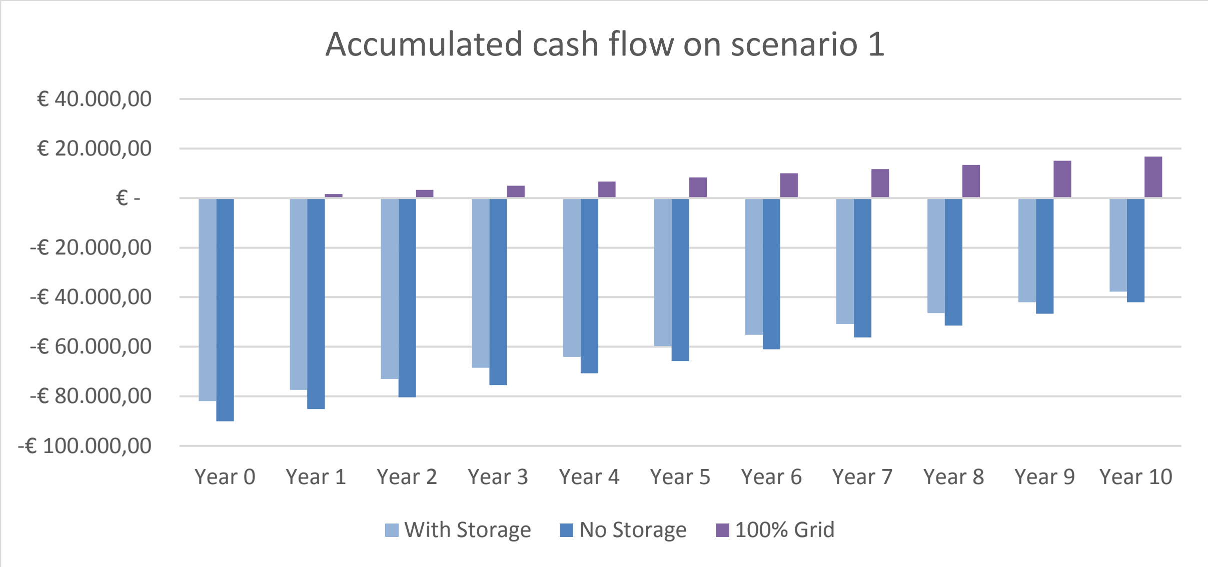


Figure 76 - Accumulated cash flow over ten years for scenario 1.
Source: Elaborated by the author

Additionally, this reduction on the investment costs results in less costs accumulated over the 10 years. As it was seen on the technical model, the storage system reduces the amount of electricity fed to the grid; however, this reduction did not impact the final result as the revenues from injecting electricity into the gird in Norway are very low. However, both options presented negative accumulated cash flow over the years which means that these options are more costly than using a conventional car powered by gasoline.

When analyzing the NPV and the MIRR, the economic unfeasibility of this scenario becomes clearer. Both options present negative values of NPV and MIRR indicating that they brought more costs than the gasoline scenario (ICEV – Gasoline). Meanwhile, the scenario with 100% grid presented a very good result showing a significant NPV of more than 15,000 euros. Regarding the payback, both options were not able to compensate their investments after ten years; therefore, there were no payback period.

Table 8 - Financial indicators scenario 1.

	Scenario 1		
	With Storage	**No Storage**	**100% Grid**
NPV	-€ 42,191.17	-€ 46,846.83	€ 15,090.11
MIRR	-5%	-5%	-
Payback	-	-	-

Scenario 2

In Figure 77, a trend different from scenario 1 can be observed. The option with a local storage had higher investment costs (€8,618 with storage and €4,560 without storage), resulting in a difference of €4,058. Therefore, the costs related to the storage system are not compensated by the reduction of the array size and, consequently, the costs related to the PV system.

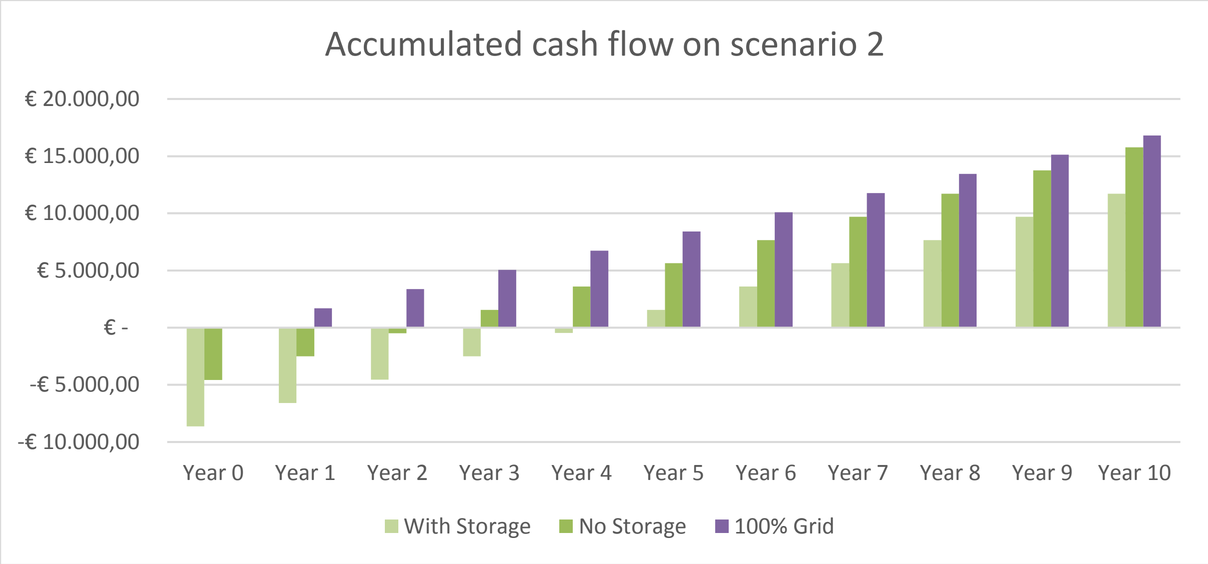


Figure 77 - Accumulated cash flow over ten years for scenario 2.
Source: Elaborated by the author

In this scenario both options present positive results after 10 years which means that the implementation of such PV system is feasible economically when compared to an ICEV using gasoline. The with storage option has a more costly outcome due to the higher investment costs and the decrease of electricity fed into the grid - especially the latter whose contribution is very little. Nevertheless, both options are still more costly than using all energy from the grid.

Analyzing the financial indicators, the MIRR of the without storage option presents impressive 17%, while the with storage option presents 10%. These differences can be seen also in the payback time in which the investment is recovered in three years in the no storage option, while in the with storage option five years are necessary. Regarding the NPV, the no storage option and 100% grid option present very similar results.

Table 9 - Financial indicators scenario 2.

	Scenario 2		
	With Storage	**No Storage**	**100% Grid**
NPV	€ 10,116.92	€ 14,170.20	€ 15,090.11
MIRR	10%	17%	-
Payback	5	3	-

Scenario 3

In the scenario 3 a very similar situation to scenario 2 is observed. This is not a surprise as the array size in both scenarios are of similar extent. Furthermore, also as happened in the previous scenario, the local storage contributes negatively in an economical perspective. The option with a local storage has investment costs of €6,794 and the without a storage option has €2,508 in investment costs, resulting in a difference of €4,286.

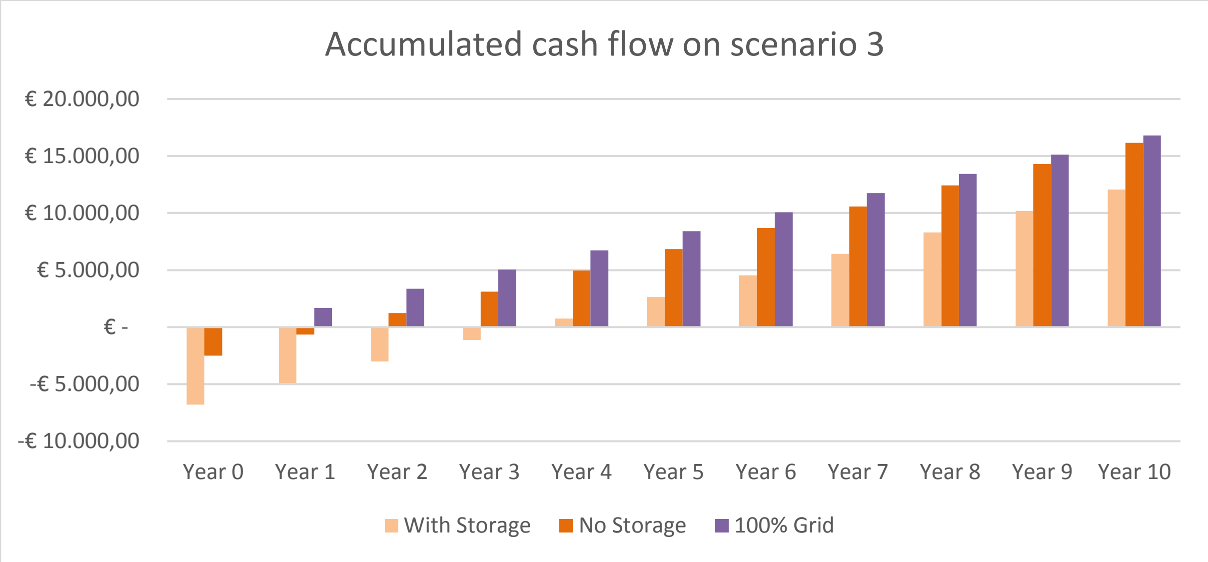


Figure 78 - Accumulated cash flow over ten years for scenario 3.
Source: Elaborated by the author

The higher investment costs also resulted in a less attractive economic outcome than the with storage option. However, both options are still economically better than using gasoline as the vehicle power source. Howsoever, both options are worse than using all energy from the grid. The without storage option presents very similar economic results what was expected since 75% of the energy used in the system comes from the grid in this scenario; therefore, its results have to be similar to a scenario in which 100% of the energy comes from the grid.

Table 10 - Financial indicators scenario 3.

	Scenario 3		
	With Storage	No Storage	100% Grid
NPV	€ 10,144.16	€ 14,260.52	€ 15,090.11
MIRR	12%	23%	-
Payback	4	2	-

Despite the lower investment costs in this scenario, when compared to the scenario 2, the NPV here is a bit higher. The consequence of that is a significant increase in the MIRR, as the same amount of revenues were gathered with less investment, especially for the without storage option which presented two times the MIRR of the with storage option. The payback time also improved in this scenario decreasing to just two years for the option without storage. Regardless the good results, it is still economically worse than using 100% of the energy from the grid, when compared with previous scenarios.

In summary, economically speaking, in Norway the best option is using all energy from the grid. This option requires no investment and brings the best results. This happens due to the fact that the electricity from the grid is not much more expensive than the PV and the value utility companies pays for the energy injected back into the grid is very low. Therefore, solar systems which inherently produce excess of energy cannot convert it in significant revenues waiving its high initial costs. Additionally, local storage turned out to be a good option in the scenario 1, though producing all necessary energy in a country with such solar irradiation variability is neither economically nor technically feasible.

4.2.3. Brazil

Brazil is very far from having a significant share of electric cars in its fleet. In this county most of the cars have a flex technology which allows the use of fossil fuels (diesel and gasoline) or biofuels (bioethanol). Given the actual international and national conditions, gasoline is today the most preferred source of energy for transportation. Nevertheless, electricity in Brazil is relatively cheap due to its high share of hydropower in the mix which is responsible for around 70% of the electricity production. Therefore, this can open opportunities to electric cars.

The Figure 79 shows a comparison of the accumulated costs of all scenarios through 10 years. In Brazil the costs of all scenarios are, in general, lower than the other countries; no scenario surpass €10,000, for example. This is explained by the fact that the array size in all scenarios are lower when compared to the other countries; therefore, the initial costs are also lower. Gasoline and electricity prices are also lower.

Looking closely it can be seen that all options with storage present significant higher costs accumulated. This means that the reduction on the array size did not compensate the extra costs regarding the storage system. The same trend was observed in the previous countries, but it is remarkable that storage systems in Brazil are more expensive than in Europe which explains the more negative result in the Brazilian case.

The other important tendency noted is that, among the scenarios without storage, more PV participation means less accumulated costs. This is explained by the fact that a bigger PV system is needed in order to increase the PV participation; consequently, more electricity is fed to the grid and more revenues the system has. Nevertheless, all three scenarios resulted in less accumulated costs than the scenario using 100% grid.

The most costly scenario is the one using gasoline. When compared with the scenarios without storage and especially with the 100% grid one, very significant differences are found. These circumstances show the potential this country has to prioritize electric cars.

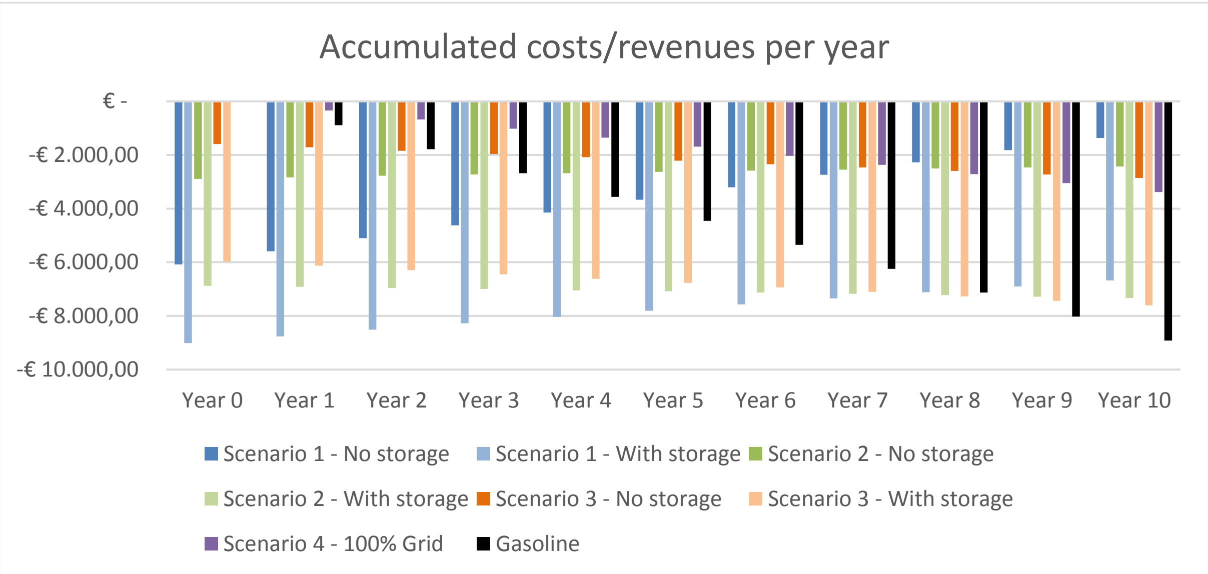


Figure 79 - Accumulated costs per scenario over 10 years.
Source: Elaborated by the author

At this point each scenario is analyzed regarding the money saved when compared with the costs of a gasoline car. The revenue of each year is defined by the difference between the costs saved by not using gasoline and the actual costs of the scenario studied.

Scenario 1

The Figure 80 depicts that the option with a local storage has higher investment costs (€9,008 with storage and €6,080 without storage), resulting in a difference of €2,928. As already mentioned, the additional costs related to the storage system are not compensated by the reduction of the array size neither are the costs related to the PV system.

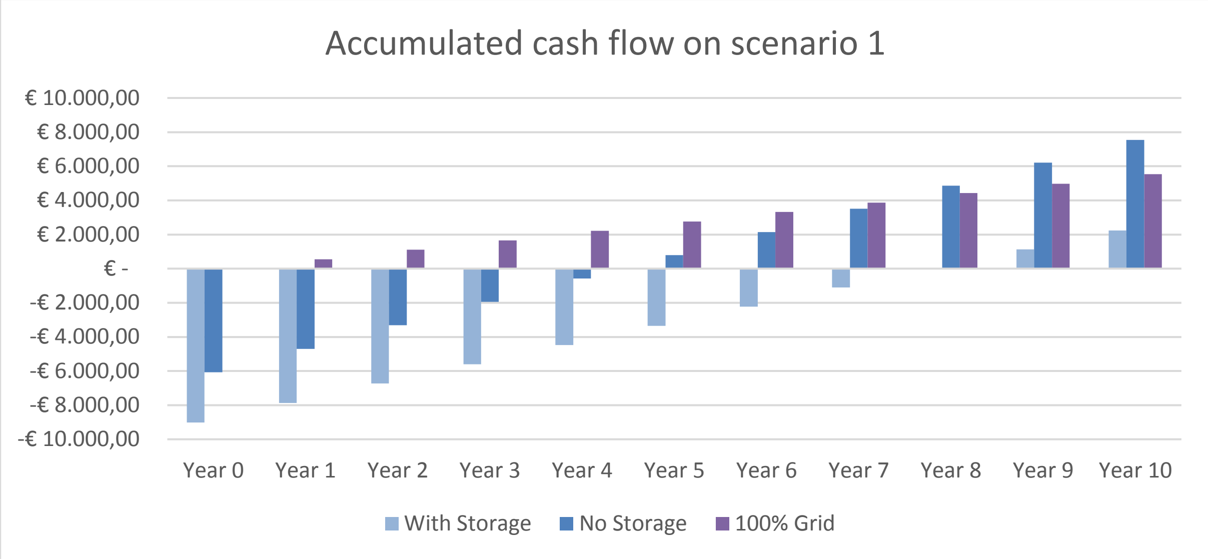


Figure 80 - Accumulated cash flow over ten years for scenario 1.
Source: Elaborated by the author

Apart from the reduction of the array size, through the technical model it was possible to observe that a storage system also reduces the amount of electricity fed into the grid. A reduction of 18%, in this case. Because of this, the use of a local storage system results in a decrease of revenues, consequence of selling less energy excess back to the grid. This condition worsens even more the option economic performance. The difference in the total accumulated cash flow after 10 years can be clearly expressed by the without storage value (€7,549) and the with storage value (€2,235) - therefore a €5,313 difference. These differences are even clearer when the three financial indicators are analyzed in Table 11.

Table 11 - Financial indicators scenario 1.

	Scenario 1		
	With Storage	**No Storage**	**100% Grid**
NPV	-€ 914.17	€ 3,733.28	€ 3,974.13
MIRR	5%	12%	-
Payback	8 years	5 years	-

The NPV on the with storage option is negative despite the accumulated cash flows without monetary correction being positive. This big difference between both values happens because Brazil is a country less economically stable with higher inflation rates (in this study it is considered a 6.5% annual rate) that means the revenues in the subsequent years have lower monetary values each year. Furthermore, this negative NPV means that at present day values investing in such system to power the electric car instead of using gasoline would result in losses. Looking at the 5% MIRR the same is demonstrated as the profitability of the investment was lower than the inflation rate.

The option without storage presented profits in present values in relation to gasoline with its MIRR (12%) being almost the double of the inflation rate. However, its NPV is lower than the NPV of the 100% grid scenario meaning that this option is not more profitable than charging the car entirely in the grid. Again, the not corrected values on Figure 80 can give a false impression about the better option, but the real result is different due to the currency devaluation over the years.

Scenario 2

The Figure 81 shows the same trend observed in the scenario 1. The option with a local storage has significantly higher investment costs (€6,880 with storage and €2,888 without storage), resulting in a difference of €3,992. Again, the costs related to the storage system are not compensated by the reduction of the array size, consequently, neither are the costs related to the PV system.

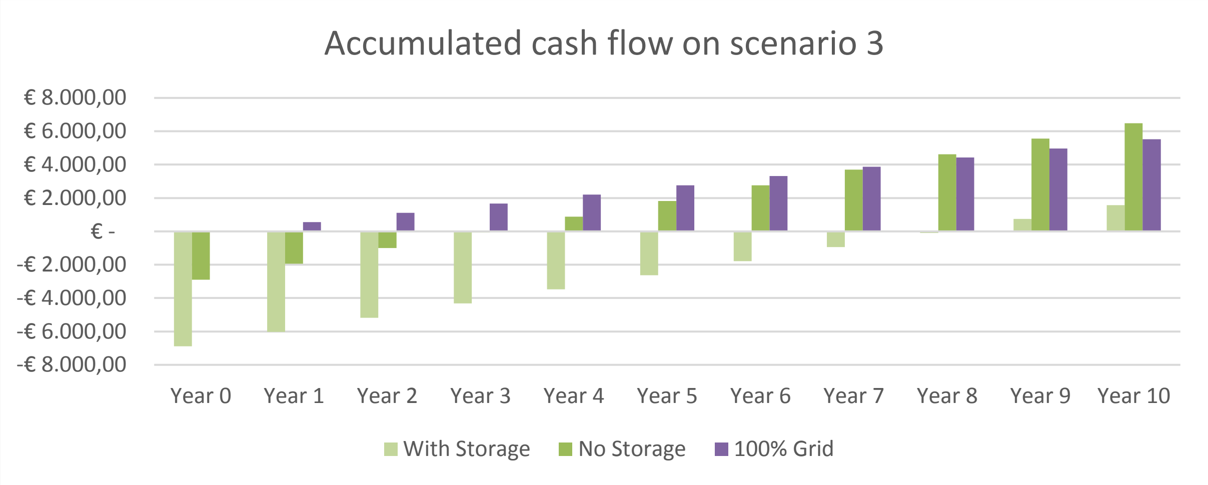


Figure 81 - Accumulated cash flow over ten years for scenario 2.
Source: Elaborated by the author

Following the same scenario 1 approach, the storage system, in this case, resulted in a reduction of 12% of the electricity fed share. This means a more significant impact on the energy fed back into the grid which decreases the system's revenues. The result is a €4,651 difference between both options as the no storage option is €6,489 and the one with storage is €1,581.

Table 12 - Financial indicators scenario 2.

	Scenario 2		
	With Storage	**No Storage**	**100% Grid**
NPV	-€ 791.19	€ 3,860.47	€ 3,974.13
MIRR	5%	16%	-
Payback	9 years	4 years	-

Analyzing the financial indicators, once more it becomes clear that the use of a local storage is not economically effective when compared to similar system not using local storage. When correcting the values the option with storage presented a worse result than using gasoline (negative NPV). Furthermore, the option without storage, despite having positive results, is still economically less attractive than the 100% grid scenario.

Regarding MIRR and payback, the option with storage did not change much, but the option without storage increased its MIRR to 16% and the payback time was reduced to only 4 years (comparing with the scenario 1). All this is due to the lower investment costs related to its return.

Scenario 3

In the scenario 3, a very similar situation to the scenario 2 is observed. This is not a surprise as the array size on both scenarios have similar magnitudes. Furthermore, in an economical perspective, the local storage contributes negatively as happened in the previous scenarios. The option with a local storage requires investment costs of €5,968 and the without storage one requires investment costs of €1,596 resulting in a difference of €4,372.

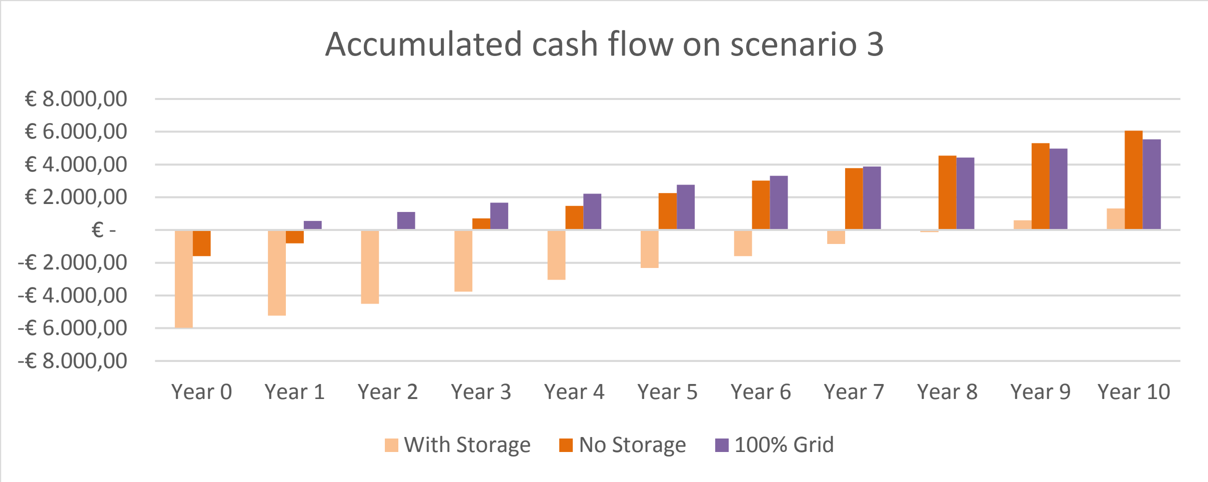


Figure 82 - Accumulated cash flow over ten years for scenario 3.
Source: Elaborated by the author

The without storage option presents very similar economic results when compared to the 100% grid scenario. This was expected as 75% of the energy used in the system comes from the grid in this scenario; a similar situation to a scenario in which 100% of the energy comes from the grid.

Table 13 - Financial indicators scenario 3.

	Scenario 3		
	With Storage	No Storage	100% Grid
NPV	-€ 732.17	€ 3,910.42	€ 3,974.13
MIRR	5%	21%	-
Payback	9 years	3 years	-

As in the previous two scenarios, the same happened in the scenario 3 to the with storage option, resulting in a negative NPV. This gives evidence to the negative economic impact of implementing such system. The option without storage continued to be profitable, even a bit more than the other scenarios, but economically less attractive than the 100% grid scenario. Its MIRR also increased to 21% and its payback time decreased to three years.

In summary, in economic terms, for Brazil the best option is using all energy from the grid as it was for Norway. However, this scenario advantage is not as big as in the Scandinavian country. This is due to the relatively cheap electricity from the grid (not much more expensive than the PV). Despite the net-mattering system, the revenues obtained did not result in a big advantage especially because in Brazil there are relatively high inflation rates which decrease the real value of this income source. Additionally, local storage did not turn out to be a good option requiring higher investment costs and giving less returns in any scenario.

4.3. Environmental sub-model

The main objective of this section is to analyze the studied environmental result which is, essentially, showing the CO_2 emissions related to each scenario. In the figures below it is shown the accumulated CO_2 footprint, the relative CO_2 footprint proportional to the amount of km travelled, and how much could have been saved in each scenario when they were compared to a conventional car using gasoline, over a period of 10 years.

A capacity of 5 kWh was defined for the scenarios considering the use of a storage system, as already have been used in the economic model. Therefore, it is important to observe the trend caused on the environmental performance of each scenario by adding a storage system.

4.3.1. The Netherlands

As already mentioned in the methodology chapter, the electricity mix in The Netherlands is still heavily fossil based. The result is a high CO_2 footprint related to the scenarios that make more use of the grid supply. In the Figure 83, it is shown (in purple) the scenario where all electricity used in the car is provided by the grid, which is the most carbon intense, when compared to the scenarios where PV power was used. However, when compared to the scenario where gasoline is the energy source, all other scenarios seem to be very sustainable as the ICEV has an accumulated CO_2 footprint almost the double the second most carbon intense scenario (100% grid) and almost fifteen times the least carbon intense scenario (Scenario 1 - No storage).

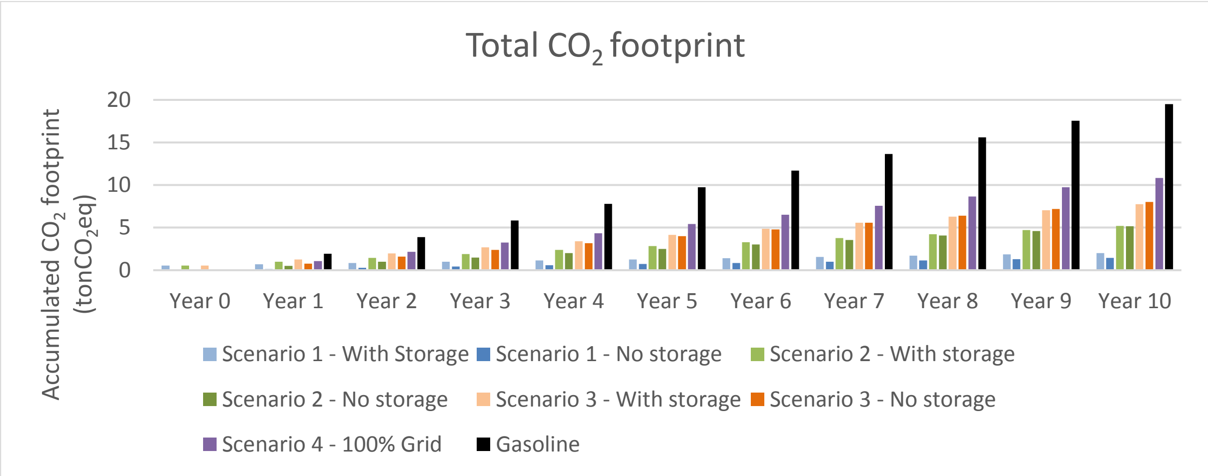


Figure 83 - Accumulated CO_2 footprint of all scenarios over 10 years.
Source: Elaborated by the author

When comparing scenarios using PV power it is clear that the less is their use of solar energy, the higher is their carbon footprint. Scenario 1, the one in which all energy comes from the PV, is the least intense being followed by scenario 2 with 75% of energy coming from PV. Therefore, among the scenarios using PV, the scenario 3 is the most intense one because just 50% of its energy is coming from the PV system.

The storage system's influence was negative in all scenarios increasing their respective total accumulated CO_2 footprint. Nevertheless, this difference is almost not noticeable when scenarios are compared all together.

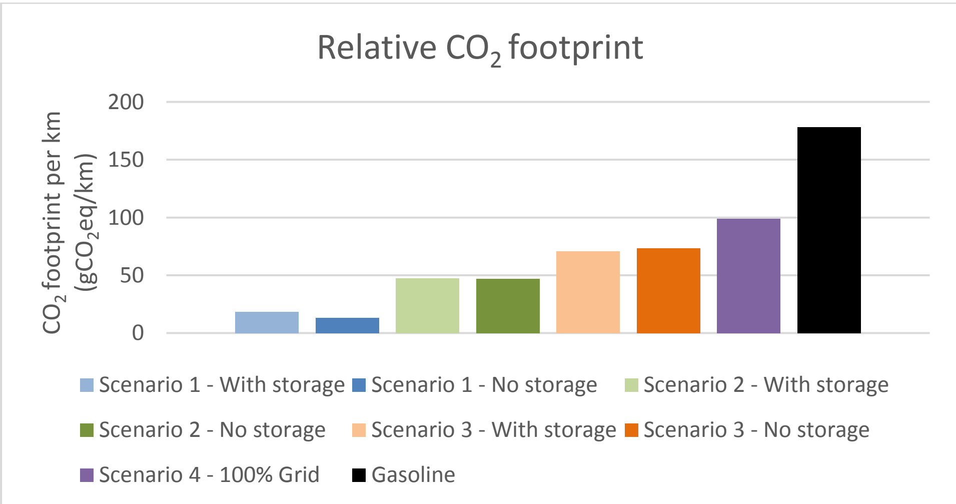


Figure 84 - Relative CO_2 footprint in all scenarios.
Source: Elaborated by the author

When relative CO_2 footprint in relation to total kilometers travelled are compared, the same trend can be observed. The ICEV has a carbon intensity of 178 gCO_2eq/km, meanwhile this amount comes down to 99 gCO_2eq/km if an electric car is powered only by the grid. This means that despite the prevailing of a fossil based electricity mix in The Netherlands, it is more sustainable, regarding CO_2 emissions, to use electric cars than conventional ones based on gasoline.

By using PV systems, this carbon intensity can drop until just 13 gCO_2eq/km (by using a 10.2 kWp PV system). Furthermore, not just big PV systems are effective, even a small PV system of just 1.2 kWp (used on scenario 3) can decrease the electric car carbon intensity to 70 gCO_2eq/km, almost 3 times less than gasoline.

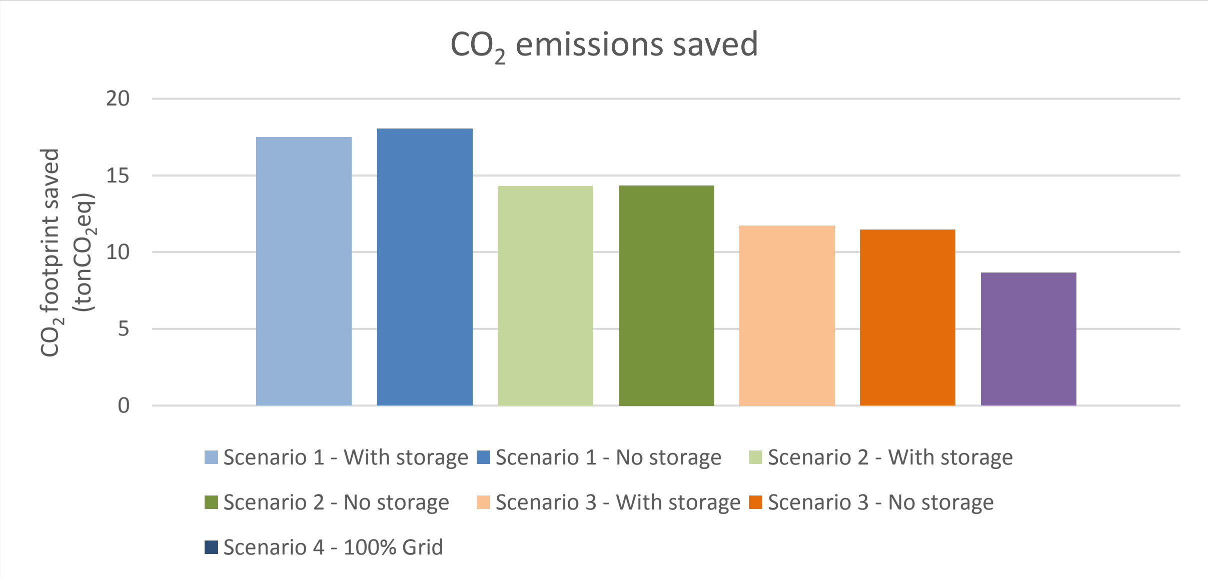


Figure 85 - CO_2eq emissions saved in all scenarios.
Source: Elaborated by the author

Crossing the scenarios results proposed in this study with the CO_2 footprint of an ICEV using gasoline, it can be seen the amount of CO_2eq emissions which is possible to save by using more sustainable energy sources. Over the 10 years simulation a maximum of 18 $tonCO_2eq$ was saved by substituting one single conventional car by one fully electric car powered by Solar PV. The emissions saved can reach 8.65 $tonCO_2eq$ per car by using an electric car fully powered by the grid, besides not requiring any investment regarding energy generation.

4.3.2. Norway

Norway possesses one of the cleanest electricity mix in the whole world. This country has 98% of its electricity being produced by hydropower with a CO_2 footprint of just 9gCO_2eq/kWh generated. These results in a very low CO_2 footprint related to the scenarios that make more use of the grid supply. The difference among all CO_2 footprint scenarios and the CO_2 footprint gasoline scenario is extremely high, as can be seen on Figure 86. An ICEV using gasoline has a carbon footprint 10 times bigger than the scenario 1 with storage (the less optimistic among all using PV).

All PV scenarios have CO_2 footprints around 2 $tonsCO_2eq$ in 10 years which is already a very sustainable result for vehicles. Looking at the Figure 86 it is possible to observe that elevated participation of the PV means higher CO_2 footprint. Lastly, the most impressing result comes from the scenario using 100% energy from the grid. This scenario has the lowest CO_2 footprint, emitting just 0.275 $tonCO_2eq$ in ten years.

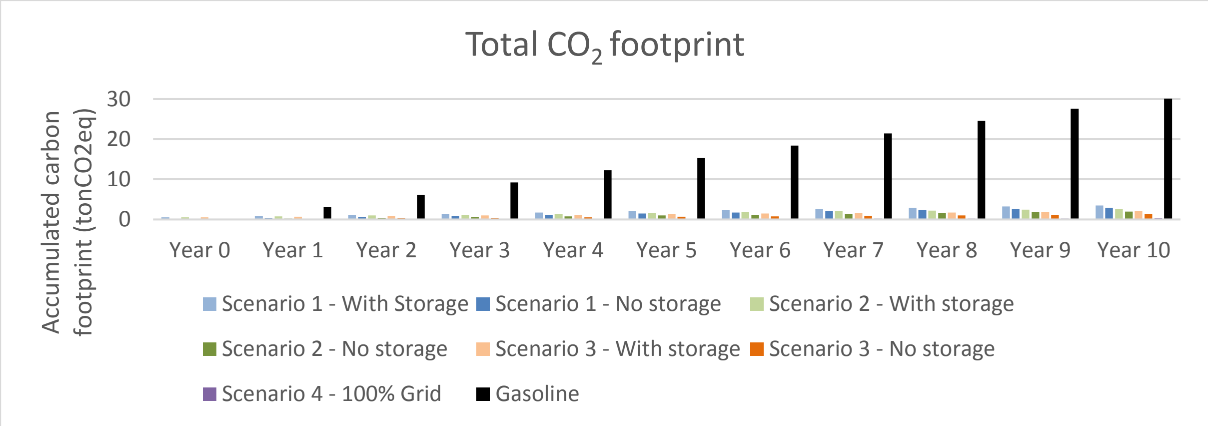


Figure 86 - Accumulated CO_2 footprint of all scenarios over 10 years.
Source: Elaborated by the author

The same trend can be better observed in Figure 87 in which the relative CO_2 footprint per km is compared. Again, the big difference among the gasoline scenario and the others is evidenced. The impact of the storage system is negative, from an environmental perspective, but the difference is not very significant; taking into account that the storage capacity considered in those scenarios was of 5 kWh, bigger storages would mean higher impacts.

The lowest impact is found in the 100% grid scenario in which the electric car using just electricity from the grid would have a relative CO_2 footprint of 1.6 gCO_2eq/km. The scenario 1 would have 17 gCO_2eq/km, while the scenarios 2 and 3 would have 11.5 gCO_2eq/km and 7.5 gCO_2eq/km respectively, all without storage.

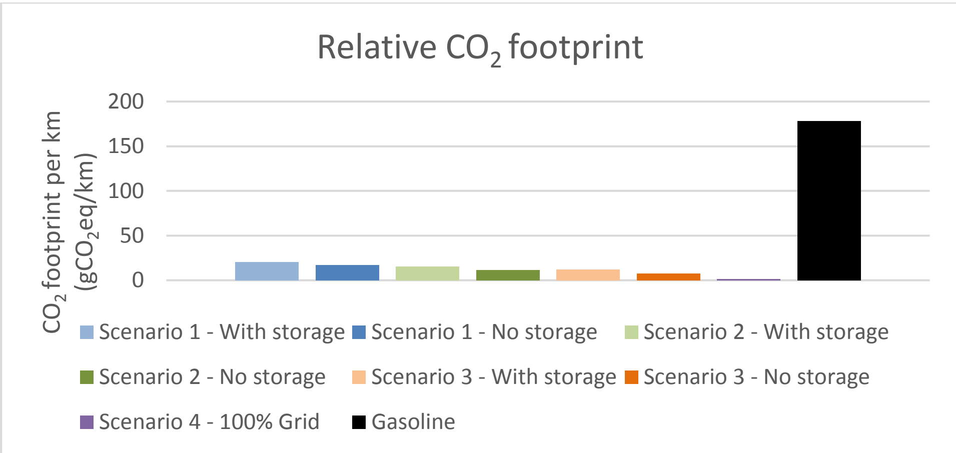


Figure 87 - Relative CO_2 footprint in all scenarios.
Source: Elaborated by the author

Through the proposed comparison among the scenarios results and the CO_2 footprint of an ICEV using gasoline, it is possible to see the amount of CO_2eq emissions saved by using more sustainable energy sources. In this case, the amount of CO_2 that can be saved is similar among the scenarios 1, 2 and 3, because the carbon footprint of the gasoline scenario is much higher than all other scenarios. Over the 10 years simulation, it was possible to save a maximum of 30 $tonCO_2eq$ by substituting one single conventional car by one fully electric car powered by the grid in Norway. The emissions saved can reach 27 $tonCO_2eq$ per car by using an electric car fully powered by a PV system.

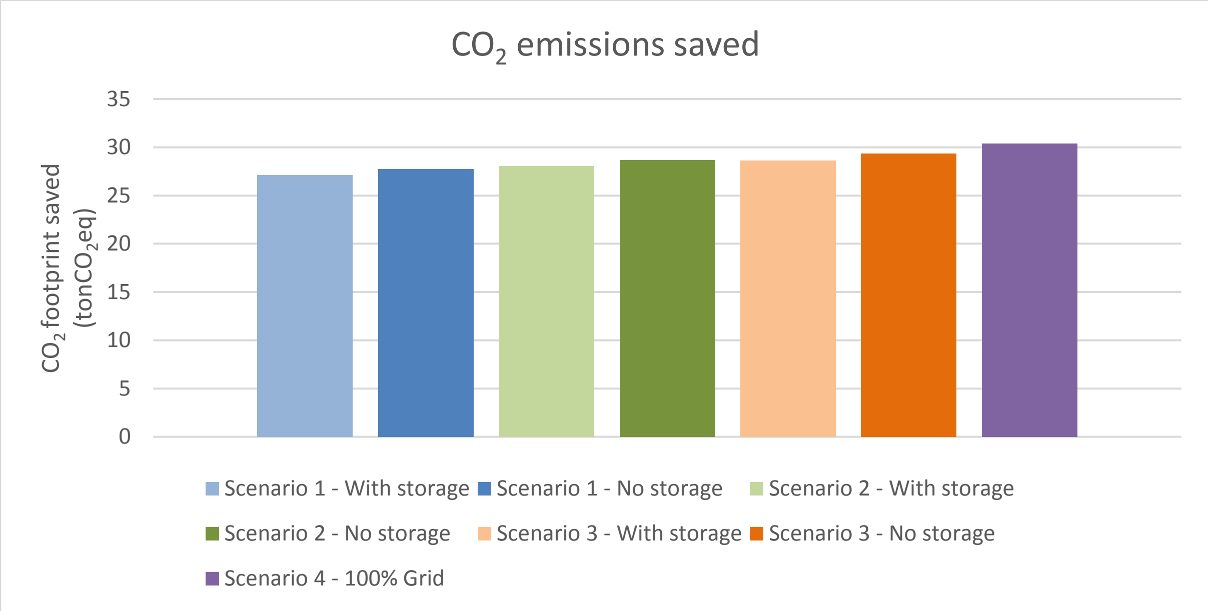


Figure 88 - CO_2eq emissions saved in all scenarios.
Source: Elaborated by the author

4.3.3. Brazil

As already mentioned, in Brazil around 70% of the electricity is produced by hydropower, while the other part is mainly generated by fossil sources such as natural gas and diesel. Through this last section of results analysis regarding the three different countries mix situations proposed, it is possible to say that the CO_2 footprint of the Brazilian mix is more sustainable than the Dutch but way less than the Norwegian one.

In the Figure 89 it is shown (in black) the scenario in which gasoline is used to power the car. Once more, this option is by far the most carbon intense of all scenarios studied. The second most intense scenario is the 100% grid (purple); nevertheless, it still emits almost six times less than gasoline, after 10 years.

All scenarios using the PV system presented low CO_2 footprints decreasing it as the share of solar energy used in the car increases. The storage systems contributed negatively as its CO_2 footprint were always higher in relation to their respective without storage option. The best scenario, from an environmental perspective, was the scenario 1 without storage (dark blue).

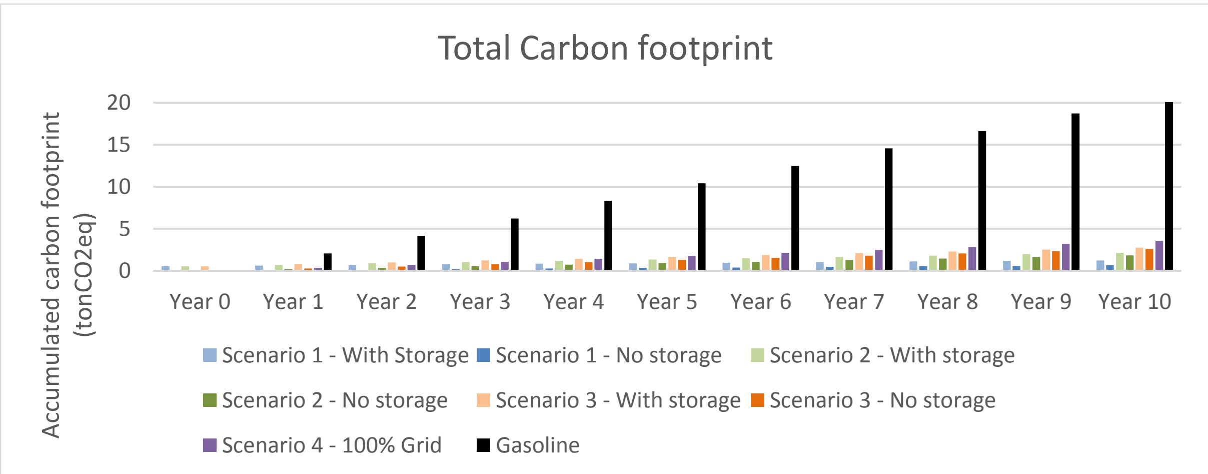


Figure 89 - Accumulated CO_2 footprint of all scenarios over 10 years.
Source: Elaborated by the author

When relative CO_2 footprint in relation to total kilometers travelled are compared, the same trend can be observed. The ICEV has a carbon intensity of 178 gCO_2eq/km, meanwhile, if an electric car is powered only in the grid, its carbon intensity is 30 gCO_2eq/km. This means that the Brazilian electricity mix already demonstrates a great potential to the introduction of electric cars as a solution to decrease the country's transport CO_2 footprint.

By using PV systems this carbon intensity can drop until just 5.6 gCO_2eq/km. However, if relatively big investments cannot be done, a small PV system of just 1.05 kWp (used on scenario 3) can decrease the carbon intensity of the an electric car to 22 gCO_2eq/km, meaning more than eight times less than gasoline.

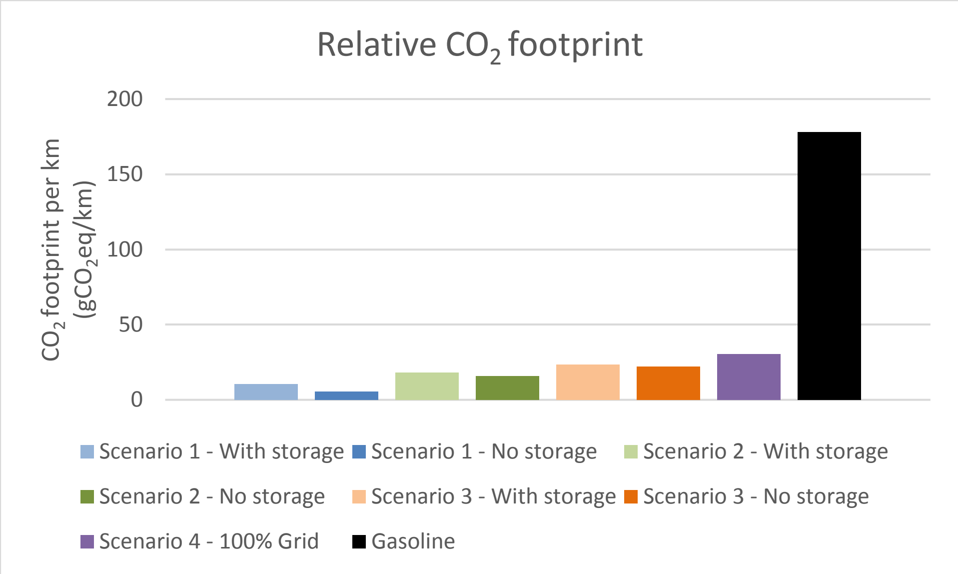


Figure 90 - Relative CO_2 footprint in all scenarios.
Source: Elaborated by the author

Once more, the crossing of the proposed scenarios results with the CO_2 footprint of an ICEV using gasoline evidenced how much CO_2eq emissions were possible to save by using more sustainable energy sources. Over the 10 years simulation, it was saved more than 20 $tonCO_2eq$ by substituting one single conventional car by one fully electric car powered by solar PV. Moreover, by using an electric car fully powered by the grid, which does not require any investment regarding energy generation, the emissions saved can reach 17 $tonCO_2eq$ per car.

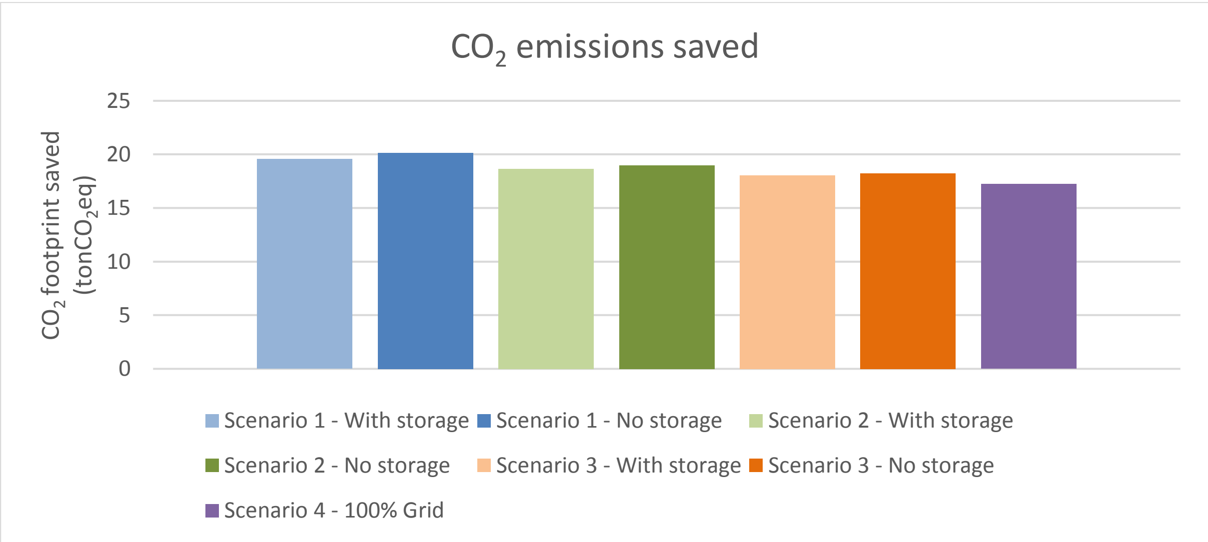


Figure 91 - CO_2eq emissions saved in all scenarios.
Source: Elaborated by the author

Sensitivity Analysis

A sensitivity analysis is carried out in this chapter in order to better understand the relation and importance of some variables in the model. This analysis is important as the model considers and define many variables that can inherently present some uncertainties. Understanding their impact on the results helps assessing the risks on investing on PV powered electric cars.

Two factors to be analyzed in detail are the fuel prices, which include electricity price, gasoline price and PV costs, and the daily distance travelled. However, in the results chapter three different countries were analyzed and their differences on solar irradiation, grid CO_2 footprint and electricity policies already showed how those variables impacted the final results.

For example, the higher solar irradiation in Brazil highly impacted the array size necessary to provide 100% of the energy by PV to the electric car, especially when compared to Norway where the solar irradiation is low. The variability through the year also changes how the storage system impact the array size and how the excess of energy is used. In countries where there is a great variation between the solar irradiation in Summer and Winter (Norway and The Netherlands), the storage system has to be bigger in order to save energy between seasons. Meanwhile, in Brazil, due to its more stable solar irradiation, the storage system is used for a short-term storage, saving energy over the weekend to be used on weekdays.

The low CO_2 footprint in Norway made an electric car fully powered by the grid less carbon intensive than a scenario using 100% energy from PV. Meanwhile, in Brazil and The Netherlands, where the grid has more presence of fossil fuels, PV seemed to be an interesting option to decrease the CO_2 footprint of the electricity used on electric cars.

Economically, the feed-in-tariffs scheme in Norway, where a very low price is paid for electricity injected back to the grid by consumers, made the scenario 1 in which a lot of electricity excess is produced, be the least economically feasible and even more costly than using gasoline. In Brazil and The Netherlands, where a net-mattering system is used, this same scenario presented good economic results mainly because of the revenues due to selling energy back to the grid.

In this chapter all the analysis was made considering a system located in The Netherlands, the country is considered the base case for the model. Therefore, all parameters assumed have the values defined for the Dutch case.

5.1. Fuel prices

There are three type of “fuels”, which influence the simulation in the model: PV cost, electricity price and gasoline price. The PV cost influences the initial costs necessary to install the panels; the electricity price will influence the cost of each scenario according to the amount of grid supply they need and also influences the revenues due to the net-mattering system. Lastly, the gasoline price influences the whole economic model as it is used as reference and all cash flows are calculated based on how much money the scenario would save, or not, in comparison to an ICEV using gasoline.

PV cost

In this section, the costs are adjusted in order to mimic the decrease in costs as shown in Figure 92 in which IRENA projects the historical and the potential future evolution of the global average total installed costs of utility-scale solar PV.

With continued rapid growth in solar PV deployment to between 1 750 and 2 500 GW by 2030, the global average total installed cost of utility-scale PV systems could fall from around USD 1.8/Wp in 2015 to USD 0.8/Wp in 2025, a 57% reduction in 10 years. Taking into account the range of uncertainty around cost drivers, the decrease could be anywhere between 43-

65% from 2015 levels. The majority (about 70%) of the cost reductions are expected to come from lower BoS costs. (IRENA, 2016)

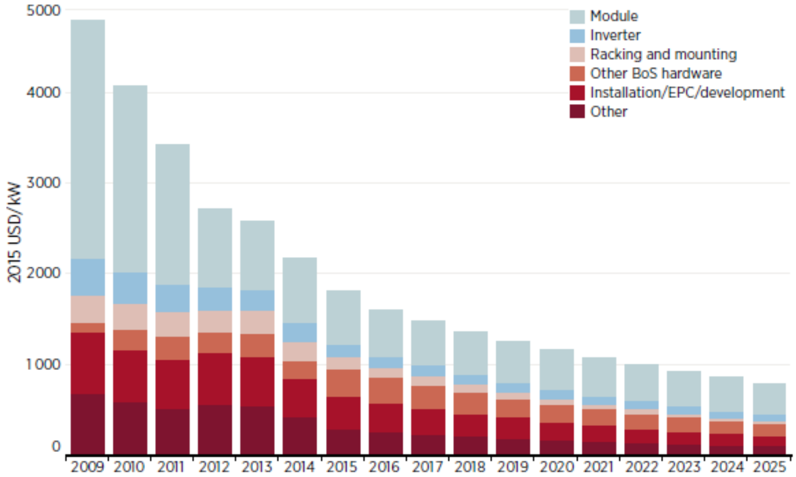


Figure 92 - Global weighted average system costs breakdown of utility-scale solar PV systems, 2009-2025.
Source: (IRENA, 2016)

Based on the aforementioned source, in order to study the impact of the variability of the PV costs in the NPV of each scenario, it was chosen a cost reduction of 5%, 10%, 20%, 30%, 40% and 50%. No costs increase were simulated since this is very unlikely to happen in the next years, as all projections estimate costs reductions for PV systems.

The results are shown in the Figure 93. As expected, the scenario 1 is the most impacted by the cost reduction. In this scenario, the PV provides all the energy required for the system, consequently, it has the biggest array size. Another factor that makes the PV costs more important for this scenario is that there is a lot of electricity being fed to the grid. This means that a lower PV costs will result in a bigger difference between PV and grid leveled cost of electricity (LCOE), increasing its returns from the electricity fed to the grid.

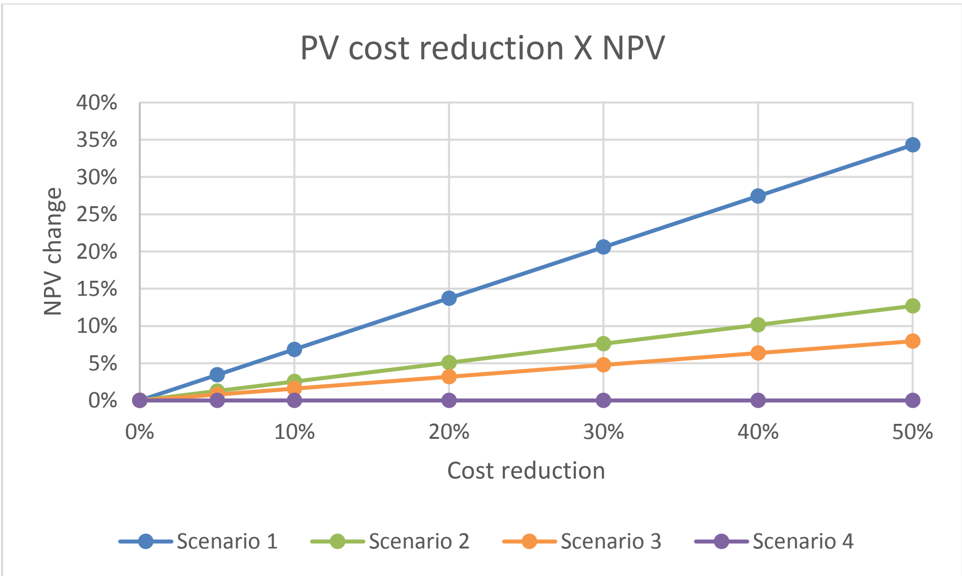


Figure 93 - Sensitivity analysis of the PV cost.
Source: Elaborated by the author

For the other scenarios in which the PV contribution share is lower, the cost reduction is less impactful despite still increasing their NPV. In other words, reducing the PV costs favors systems using this technology proportionally to its share on the system. The scenario 4 in which all energy is provided by the grid, as expected, presented no change due to the reduction of PV costs. Therefore, the scenario 4 is independent from PV prices.

Electricity Price

According to a report of the European Union on energy and greenhouse gases, electricity prices are expected to continue rising until 2020. The developments in the EU28 power sector have significant impacts on energy costs and electricity prices, in particular in the short term. Power generation costs will significantly increase by 2020 relative to 2010, mainly as a consequence of higher investments due to the need for significant capital replacement and higher fuel costs (Capros, et al., 2014).

Beyond 2020, average electricity prices remain broadly stable up to 2035 and then are projected to moderately decrease up to 2050 (Figure 94), as the benefits, in terms of fuel cost savings, resulting from the enormous restructuring investments in electricity supply come increasingly to the fore. In addition, lower technology costs from technology progress and learning over time help contain electricity prices together with deceleration of gas price increase. Over time, the structure of costs slightly changes; capital intensive investments (renewable energy systems (RES) and carbon capture systems (CCS)) and increasing grid costs bring a decrease of the share of variable cost components and a corresponding increase in the capital cost components.

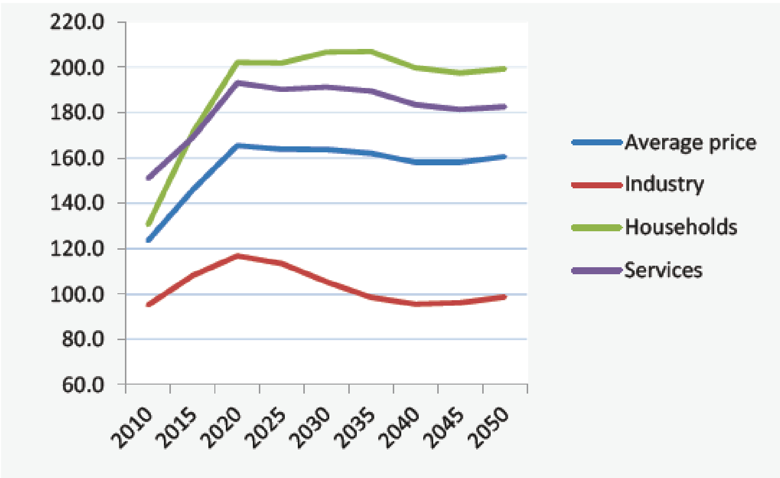


Figure 94 - Electricity price (pre-tax) by sector.
Source: (Capros, et al., 2014)

Based on electricity prices stabilization trends in the next years, it was defined a variation of 10%, 5%, 2%, -2%, -5% and -10% over 10 years. This means that after the 10 years simulation the electricity price will increase or decrease linearly the rate defined.

The results are shown on Figure 95. Scenario 3 and 4 followed a logical change, as with the increase in the electricity price its NPV decreased and vice-versa. This is expected as both scenarios have high participation of the grid in the energy necessary to power the car: 100% for scenario 4 and 50% for scenario 3. Therefore, it is normal that by increasing electricity price rates those scenarios become less attractive and by decreasing the electricity price they become more attractive.

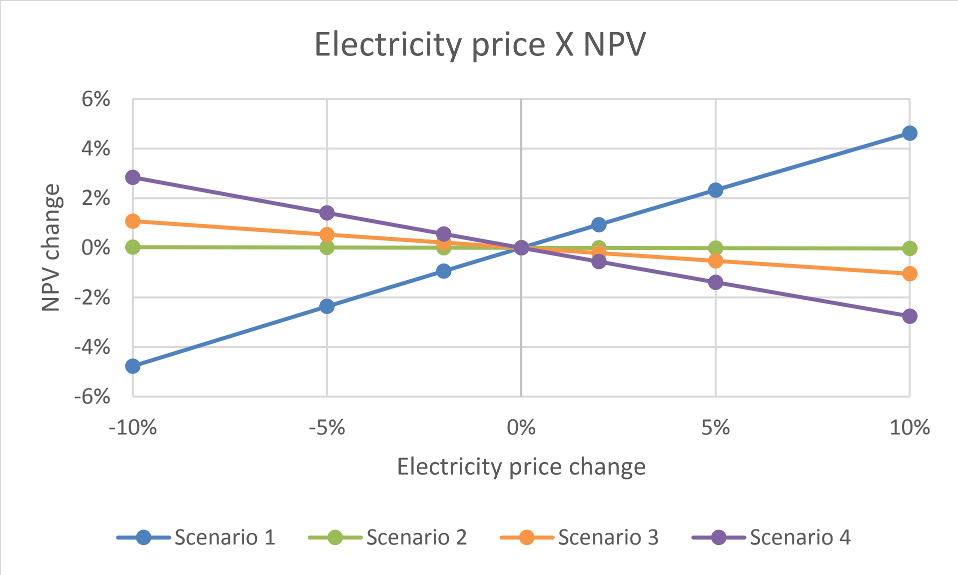


Figure 95 - Sensitivity analysis of the electricity price.
Source: Elaborated by the author

However, the scenario 1 presented an inverted trend, increasing its NPV as the electricity price is increased and vice-versa. At first sight, this can cause strangeness as in this scenario there is no grid supply, so why the results are impacted that much? Because of the Dutch net-mattering system the electricity price defines the revenues from the electricity fed into the grid. In scenario 1 there is a great amount of electricity fed into the grid, as seen in the technical model results; therefore, by increasing the electricity price the revenues from the net-mattering system are increased. That is why an increase in the NPV, with the increase in the electricity price, appears in this scenario.

On the other hand, the scenario 2 presented almost no change. Differently from scenario 4 in the previous case (PV cost), this time the change is not absolute zero. There is a very small change which is imperceptible on the graph. In this scenario both "forces" are in action, a significant amount of electricity fed into the grid and also the grid supply participation in the energy necessary to the car. Therefore, these both drivers compensate each other, giving the impression of no change in relation to the electricity price.

Gasoline Price

As already mentioned, the last fuel that influences the economic analysis is the gasoline price. Even though, the electric cars considered in the study are BEV's and make no use of gasoline. The economic analysis is based on the costs saved by not using an ICEV and using an electric car.

For gasoline, in line with the assumptions in the sensitivity analysis of the electricity price, it was also assumed a change in the gasoline price of 10%, 5%, 2%, -2%, -5% and -10% over 10 years. The results are shown in the Figure 96.

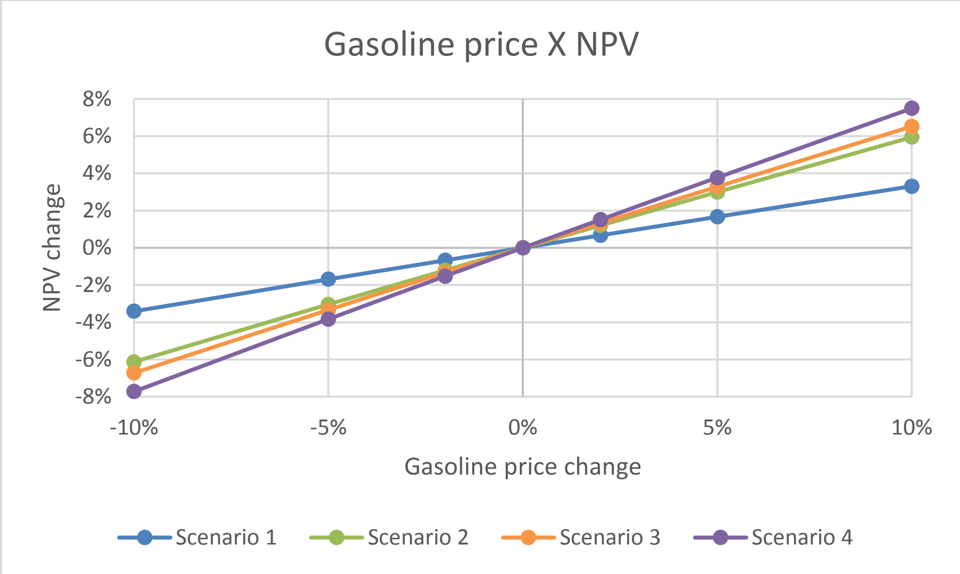


Figure 96 - Sensitivity analysis of the gasoline price.
Source: Elaborated by the author

The increase in the gasoline price caused returns increase to all scenarios, evidenced by their NPV. The difference among scenarios is related to how much the gasoline price influenced their economic results. Scenario 1 was the least impacted and scenario 4 the most. This shows that the higher the PV production is and consequently its share in the system, the less impactful the gasoline price will be. This happens because the systems have, basically, two sources of returns. One is the difference between the costs of gasoline and the electricity used on the electric car which will be a combination of electricity from the grid and PV. The other source of return is the amount of electricity being fed to the grid. This last one has no direct relation with the gasoline price and, therefore, is independent from it. Furthermore, scenarios in which this second source of return is more significant are less impacted by the gasoline price. No surprise, the scenario 4 where there no electricity fed to the grid is the most impacted, followed by the scenario 3 and the scenario 2.

5.2. Daily distance travelled

Many variables could be tested in the sensitivity analysis in the technical model. However, most of them are defined by the electric car such as car efficiency, depth of discharge and battery capacity. It would be too complex to test different cars and draw trends about it, as many variables would change at once. Maybe a separate study can compare different car models.

Nevertheless, other variables have many uncertainties as they depend on the human behavior; despite trends and averages can be estimated, everyone has different routines. For example, the driving pattern and the daily distance travelled is highly influenced by each individual, depending on where the work or the residence are located or if there are additional places where each person has to go before or after work; what each family does on weekends etc. In order to see how the model behaves, the average daily distance travelled was changed on +15, +10, +5, -5, -10 and -15 kilometers. It seems to be a small change, but it is important to remind that it is a daily distance, so the change is applied over every day in the 10 years of simulations.

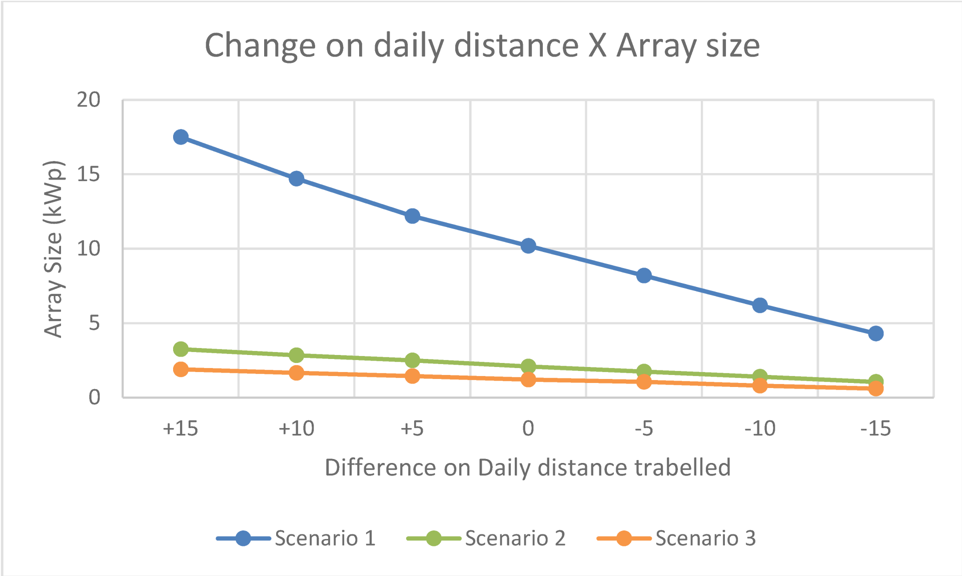


Figure 97 - Sensitivity analysis of the daily distance travelled, on absolute values.
Source: Elaborated by the author

The Figure 97 shows a big impact on the necessary array size in the scenario 1. The same trend can be observed in the scenarios 2 and 3, but with apparent lower magnitudes. A bigger daily distance means more energy being spent by the car. Therefore, in order to compensate this demand increase, the system has also to increase its energy generation by a bigger array size, as solar conditions are kept the same.

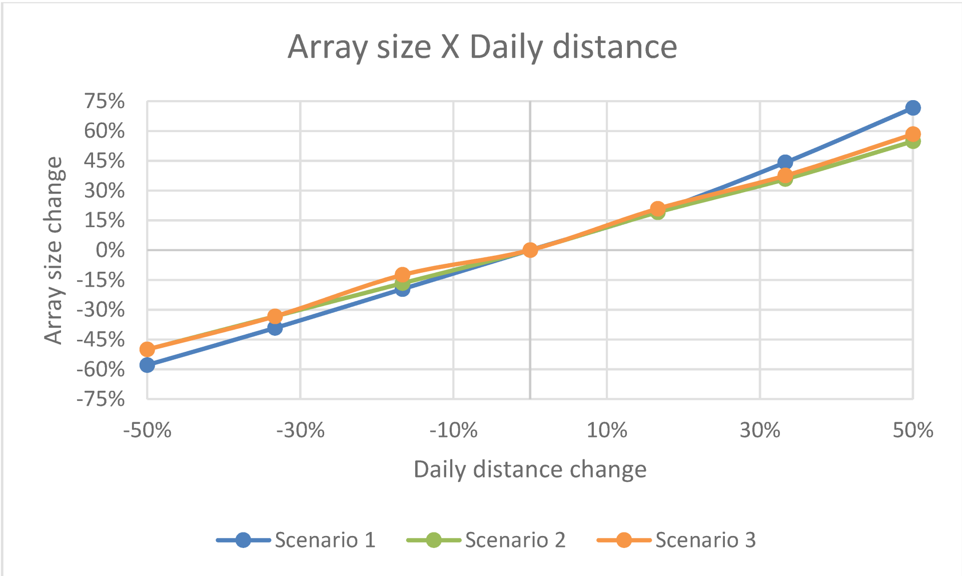


Figure 98 - Sensitivity analysis of the daily distance travelled, on relative values.
Source: Elaborated by the author

When looking to Figure 98 it is possible to see the relative change on the array size. It is observed that the change in the daily distance were almost the same in all scenarios, especially when the distance varied less than 33%. When 50% of the distance travelled changed, the scenario 1 started to have bigger impacts. In conclusion, the daily distance will highly affect the array size, but the magnitude of impact is independent of the PV participation share in the system.

Discussion

Four different scenarios were tested in three different countries in the simulation carried in the results chapter; three of those scenarios had a storage option. In total, there were 24 different situations in which alternative ways to power an electric car were simulated. All those results allow to analyze a number of factors that impact design and performance of such systems. In this chapter, the parameters that most affect the system are dissected and better explained in order to clarify how the previous results can serve as reference on analyzing similar situations, but in different realities.

6.1. Solar Radiation

The first and probably the most important factor that influences a PV system is the local solar irradiation. For more obvious that can appear to be, the current analyses simulated the same system in three different locations. First, in The Netherlands, a temperate country with high variability between Summer and Winter radiations. Second, in Norway, a country further north than The Netherlands, with even more variability and lower solar radiations. Lastly, in Brazil, a tropical country with a much more stable solar irradiation throughout the year and higher solar radiation overall.

As shown in the methodology section, in the Figure 14 there is a comparison between the three solar irradiations patterns in 2016. Without question Brazil has much more solar irradiation; except between May and August, during the period that corresponds to the Brazilian Winter and European Summer, the Norwegian and Dutch irradiations are slightly bigger. However, the most important difference that impacts the most PV systems is the very very low irradiations during the European Winter. This happens due to the very short days and the low incidence angle of the solar rays in regions situated at relatively high latitudes.

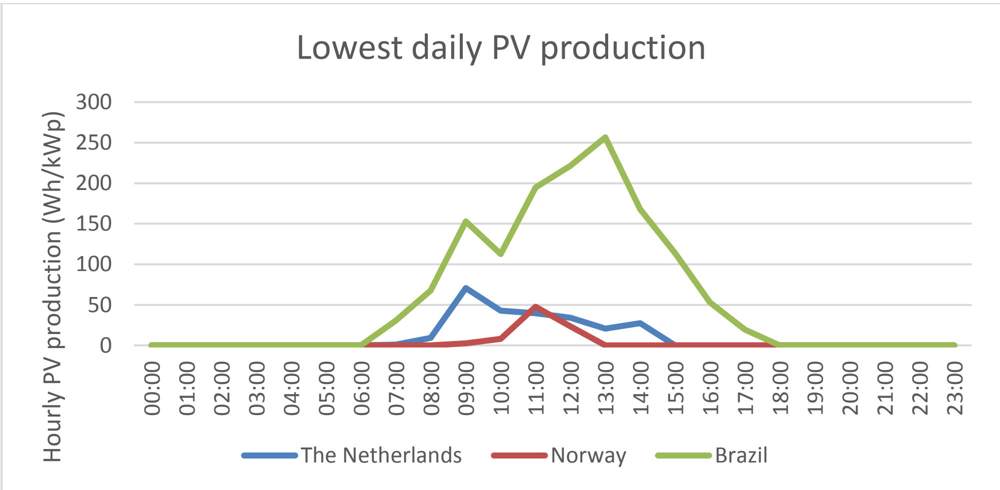


Figure 99 - Lowest daily PV production in The Netherlands, Norway and Brazil.
Source: Elaborated by the author

Figure 99, also showed in the methodology Chapter, presents a comparison among the three countries worse day in the year. The worse day is considered the day in which the PV produces less electricity. Clearly Brazil, even in its worse day, produces way more electricity than Norway and The Netherlands; meanwhile, the Dutch situation, even though not much, still produces a bit more electricity than in Norway. Not just the magnitude is bigger, but also the tropical country has more daylight hours.

These very low irradiations brings a lot of difficulties when designing solar systems, especially when developing independent ones, as foreseen in the scenario 1 in which all energy provided to the car had to come from PV. In these cases, as there is no backup system, the PV has to provide all the energy needed in the worse days; because of that, the system becomes unnecessarily big in order to compensate the low irradiations. This is evidenced by comparing the array size of scenario 1: The Netherlands 10.2 kWp, Norway 79 kWp and Brazil 4 kWp.

It can be observed that the array size grows exponentially, as the difference between the solar irradiation in The Netherlands and Norway is not that big, notwithstanding their significantly big differences in the array size. And despite the bigger difference between Brazil and The Netherlands (when comparing The Netherlands and Norway), the array size difference is way lower. As expected, Brazil had the lowest array size as it has, by far, the highest solar irradiation among the studied countries.

In addition, when a backup system is provided and the PV system does not necessarily need to provide all the energy in the worse days, the necessary array size decreases significantly. This is exemplified by the scenario 2 results in which a small grid participation of 25% is allowed. In Norway the needed array size decreased from 79 kWp to 4 kWp, meanwhile in Brazil the change was from 4 kWp to 1.9 kWp. Moreover, any type of backup system are very effective in countries with low solar irradiations and high seasonality.

6.2. Storage system

Another option for waiving the effect of the low solar irradiations mentioned above is implementing a storage system where stored electricity could provide additional energy to the system without the need to produce on demand, consequently decreasing the necessary array size.

The results Chapter showed the impact a storage system had on the array size. In all cases, the storage system was able to reduce the array size. However, those reductions were not very significant; only very big storage capacities would be enough to reduce significantly the array size. The only exception was the scenario 1 in Norway where the array size was reduced in 11 kWp just with 5 kWh capacity. Nevertheless, this is an exception where the array size is way bigger than any other configuration tested.

In addition, it could be observed that the storage system can work in two ways: the first is a 'long-term' storage, where the system stores excess of electricity produced in Summer to be used in Winter when the solar irradiation is low and the PV production is not enough to fulfill the demand. The second way is a 'short-term' storage where the system stores the electricity excess produced during the hours the car is not connected to the grid, including the weekends, to be used in the same day or in the next week in order to keep the car battery always at the highest state of charge. There is no control on how the storage system will work in the developed model. It is strictly defined by the intrinsic conditions of the system determined by solar irradiation, driving patterns, total distance travelled, car efficiency, etc.

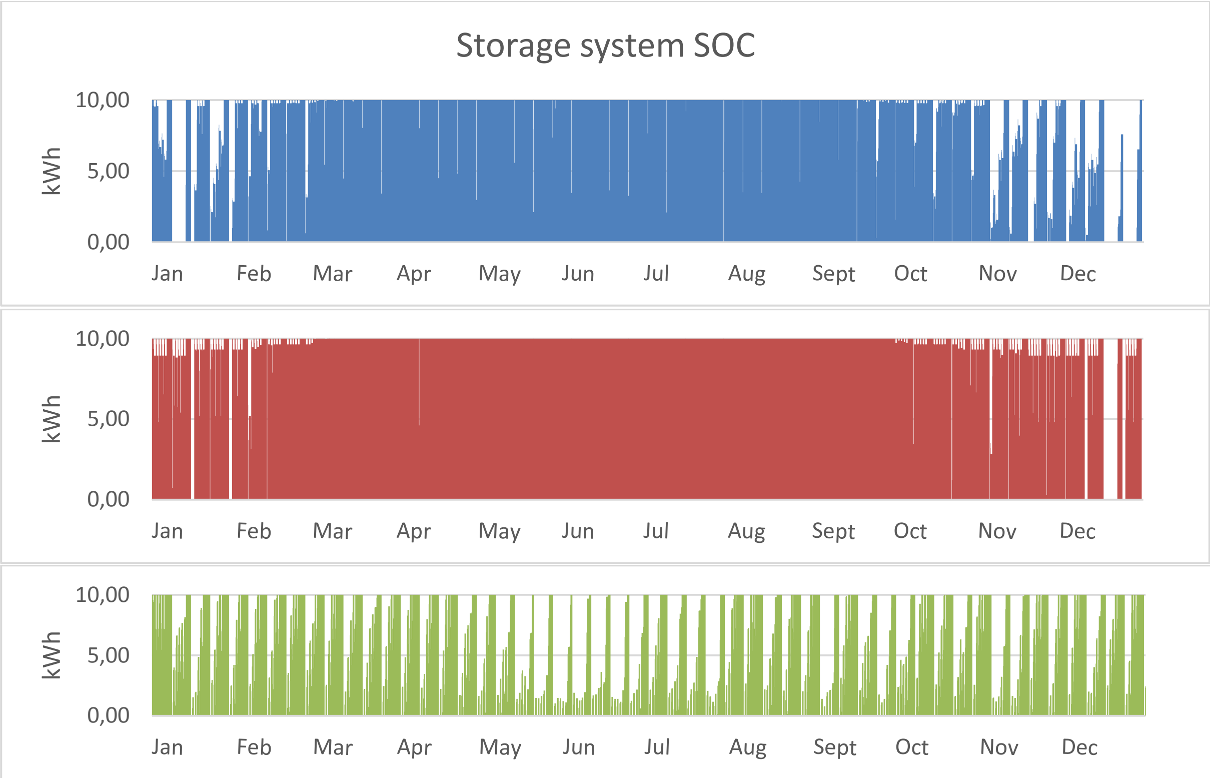


Figure 100 - Storage SOC variation in the first year in The Netherlands (blue), Norway (red) and Brazil (green).
Source: Elaborated by the author

In the Figure 100 it can be depicted how the storage is working on scenario 1 with a storage of 10 kWh capacity in the three countries. In Norway and The Netherlands the storage system is working in the ‘long-term’ way, as during Summer the state of charge of the storage battery is always 100% (full) and just in the colder months this energy is used. In The Netherlands the energy is used spread during Winter with the storage battery being charged and discharged several times, while in Norway the energy in the battery is used in just a few moments. These moments correspond exactly to the worse days as explained in the previous section. Furthermore, in Brazil the storage battery are being charged and discharged several times during the whole year indicating that the system is working in the ‘short term’ way. What changes between Summer and Winter is just the frequency as in Summer the need of energy is lower and, consequently, a complete battery discharge takes more time than in the Winter.

A storage system is indeed a good way to cope with the variability of solar radiation and, consequently, the variability of electricity production of a PV system. However, in countries at high latitudes it is advisable to seek for a storage system which can hold the energy for long time as in these places there is excess of energy being produced in Summer and lack of energy in Winter. In countries at low latitudes, where the solar irradiation is much more stable through the year, it is advisable to use systems that have a bigger ‘fatigue’ resistance, as it will be charged and discharged several times, independently of the time of the year.

6.3. Scenarios’ sustainability

When mentioning the sustainability concept here, the author means the balance between environment, economics and social benefits. As seen in the results Chapter, indicators to measure environmental and economic feasibilities were approached by calculation, but when it comes to social benefits it is very hard to use these kind of procedures, especially for a simulation which does not include any experimental data; for this reason the social feasibility of the scenarios tested are neglected in this analysis.

Firstly the scenarios in each country will be analyzed and then a comparison of all scenarios and configurations tested will be depicted. It is always important to highlight that the purpose of this analysis is investigating how the variables impact the systems without necessarily judging which scenario is 'better' or 'worse'. In the following figures the circle means a configuration without storage and the diamond means a configuration with a storage of 5 kWh capacity.

The Figure 101 shows the results of all scenarios in The Netherlands regarding the NPV (horizontal axis) and emissions saved (vertical axis). Therefore, the closer to the upper right corner, more sustainable is the scenario. The scenario 1 clearly has the best results either economically or environmentally. The other scenarios have more similar results, but more PV share means a higher NPV and more emissions saved, showing attractive results in the adoption of PV system in The Netherlands.

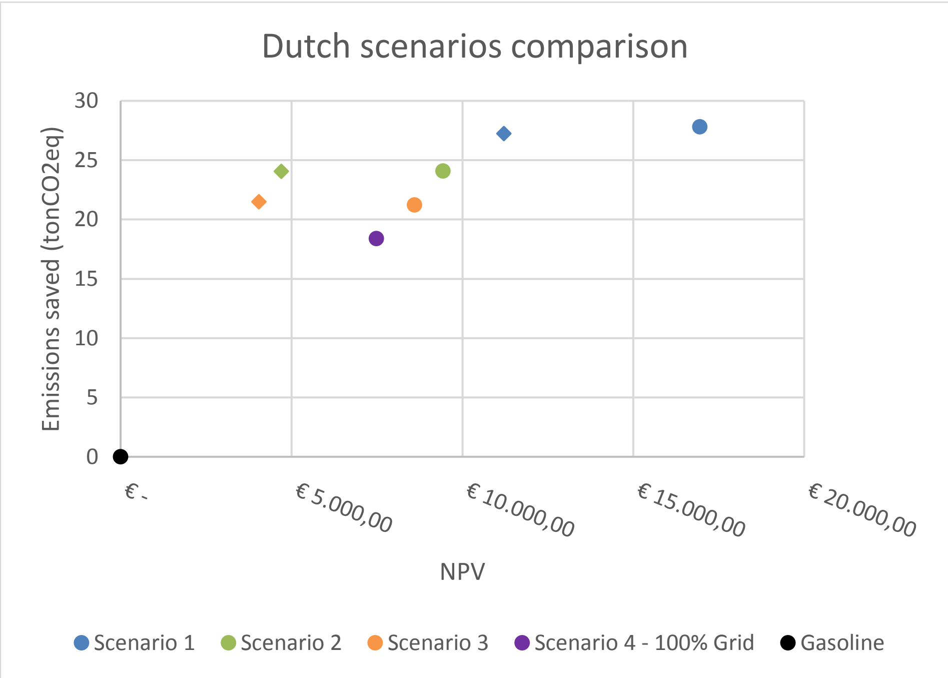


Figure 101 - Dutch scenarios without storage (circle) and with storage (diamond) comparison.
Source: Elaborated by the author

Regarding the adoption of a storage system, all scenarios presented worse economic and environmental results than their respective scenarios without storage. The difference in the total emissions saved was not very big and the real impact of those systems was in the NPV. This means that the extra CO_2 footprint related to the production of the batteries is more or less compensated by the reduction of the array size; however, the costs of the batteries still does not compensate the cost reduction by the decrease of the necessary array size. Nevertheless, these costs have been dropping over the last years and probably will continue to do it, as storage systems and lithium batteries are becoming more popular and necessary to cope with the variability of renewable sources of energy.

It became clear that adopting a PV system to charge cars is feasible and profitable in The Netherlands and bigger systems means bigger savings of money and emissions. The generous net-mattering system, to which the user can sell electricity by the same retail price, is the main responsible for the big attractiveness of the PV systems. However, as mentioned in the results Chapter, because of the way this system was implemented, the user has to consume all the electricity fed into the grid later on. Regarding the emissions saved, obviously, PV systems have a much lower carbon intensity than gasoline, but what calls the attention on the Dutch case is that the scenario 4, in which all energy comes from the grid, presents the lowest amount of emissions saved among the scenarios simulated. This is because the grid carbon intensity is higher than PV systems which makes their adoption a more sustainable choice. However, even the scenario 4 has way better results than using gasoline which shows, despite the fossil based Dutch grid, a great potential for electric cars.

As can be seen in the Figure 102, the opposite of The Netherlands happens in Norway, where the scenario 1 presented by far the worse economical result. As discussed in the first section of this chapter, in the Norwegian scenario 1 the necessary array size is absurdly big and differently from The Netherlands, in Norway the price paid for the electricity injected back to the grid is much lower than the retail price, making this source of revenues almost negligible. It could be said that the great "advantage" of a big array size is producing a lot of electricity excess to sell it back to the grid. So, this configuration is much more costly than gasoline or any other scenario. The interesting thing here is just that the implementation of a storage system improved the NPV, but not enough to make it even close to feasible.

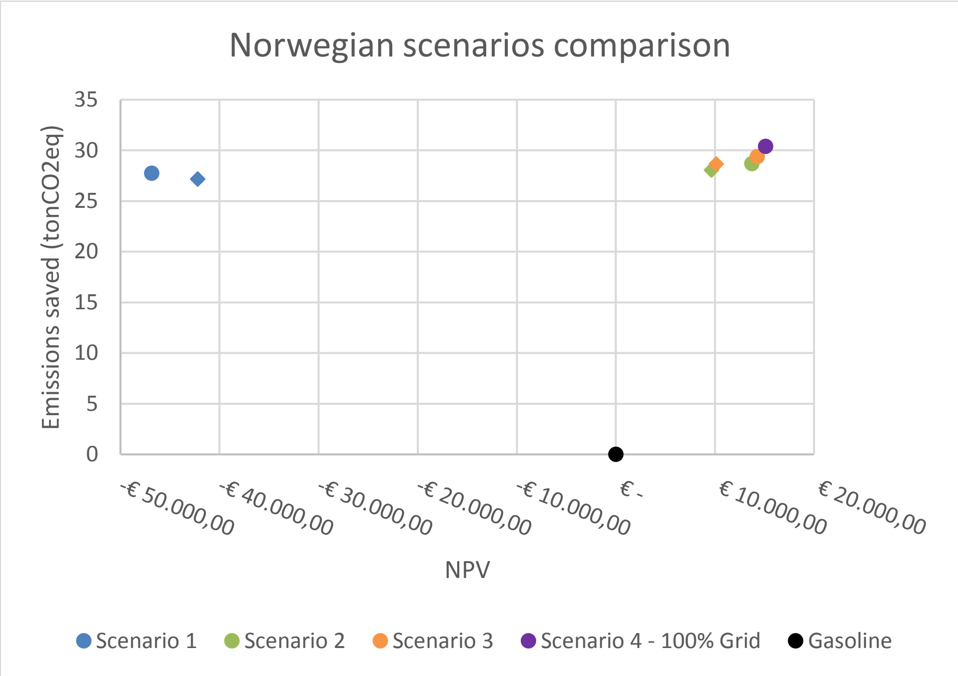


Figure 102 - Norwegian scenarios without storage (circle) and with storage (diamond) comparison.
Source: Elaborated by the author

Environmentally speaking, it can be seen that all scenarios have very close results. This is due to the similarity between the Norwegian grid and its PV systems CO_2 footprint (when compared to gasoline), so that a decrease in the share of PV does not affect significantly the amount of emissions saved. In fact, the grid CO_2 footprint is even lower than PV systems footprint in Norway, what makes the scenario using 100% of the energy from the grid the most sustainable in this country. Additionally, because of the electricity scheme in force in Norway, this same scenario is also the most attractive in economic terms.

The Norwegian case shows how PV systems can be less attractive than charging an electric car always in the grid. Because of their not advantageous feed-in-tariffs scheme and their electricity generation heavily based on hydropower, neither feeding electricity back to the grid nor using solar PV power are more sustainable. However, this does not mean that PV systems in Norway are not feasible. Medium and small systems (represented by scenario 2 and 3) did show better results when compared to gasoline, meaning these system can be less attractive than using the grid, but much better than using gasoline.

In the Brazilian case, the first thing to highlight is how economically bad all configurations with storage resulted (Figure 103). The high costs of Li-Ion batteries for stationary storage in Brazil can explain that. Additionally, like in the other countries' cases, the storage system is not effective on decreasing the necessary investment costs of PV systems. As explained in the previous sections in this Chapter, Brazil has a relatively stable solar irradiation through the year and the array size does not need to be very big to compensate low irradiations in Winter; consequently, the PV system does not produce much electricity excess in Summer. Therefore, all scenarios tested do not have a significant income from this surplus of electricity fed back to the grid, in spite of Brazil having a net-mattering scheme very similar to the Dutch one.

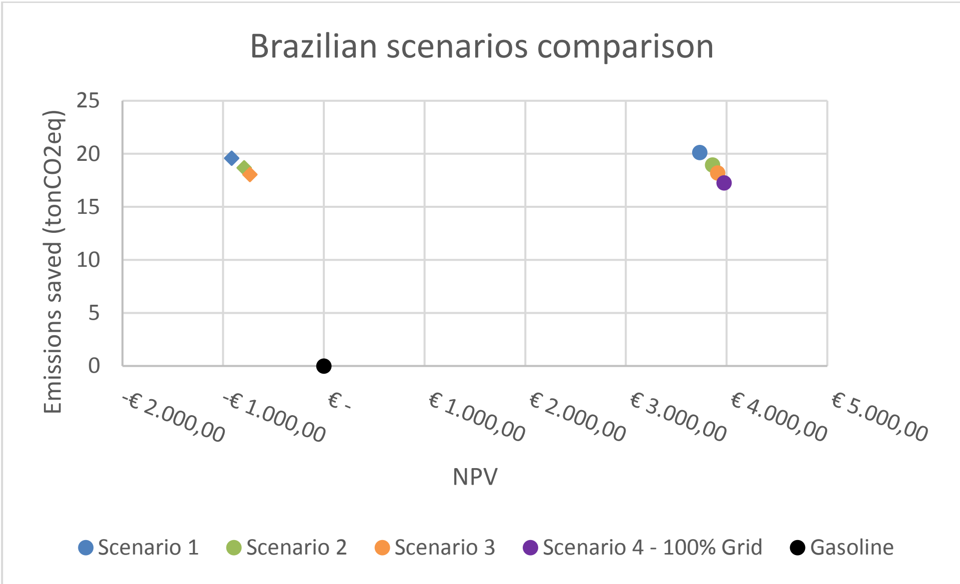


Figure 103 - Brazilian scenarios without storage (circle) and with storage (diamond) comparison.
Source: Elaborated by the author

A different trend can also be observed in Brazil: as the share of PV increases the NPV decreases. This is due to Brazilian PV systems which are more expensive than in Europe; this condition increases the necessary initial investment and the electricity rate is relatively cheap (cheaper than the other two European countries analyzed). Additionally, Brazil suffers with relatively high inflation rates; therefore, as those scenarios assumed that the electricity rate stays the same through the years, when the values are corrected by inflation (result of calculating the NPV), the electricity rate becomes cheaper in present values over the years. The same phenomenon does not affect PV systems as they require an initial investment on year 0; so there is no devaluation through the years. Given the assumptions, the result indicates that using electricity from the grid is economically more attractive than investing on PV systems in Brazil. On the other hand, regarding the emissions saved, the opposite happens. The Brazilian grid is also mainly based on hydropower but a significant part is still fossil fuel dependent what makes the Brazilian grid carbon intensity higher than PV systems. That is why less emissions are saved with lower PV shares.

Therefore, the Brazilian case shows that cheap electricity can make PV systems not as profitable as just using electricity from the grid. In addition, even having a generous net-mattering system, with the price for electricity fed back to the grid being the same as retail price, was good enough to turn PV systems economically more attractive than the grid. Moreover, PV systems are cleaner than grid, but when compared to gasoline the grid still presents great results. Overall, Brazil shows a great potential for electric cars, but this has not been a priority yet in the country's government mobility policies, as evidenced by the almost insignificant share of electric car in its fleet.

In the next analysis, all scenarios in the three countries were compared. In this simulation, the indicators used previously were changed in order to give an equal perspective. Both indicators are given per km so that the interference of local conditions, such as the car use intensity, is normalized. In the Figure 104, a total of 21 scenarios (7 per country) are shown in relation to the emissions per km and euros per km. In this case, the most sustainable scenarios are pointing to the bottom right corner, as they present the lower emissions and higher financial savings.

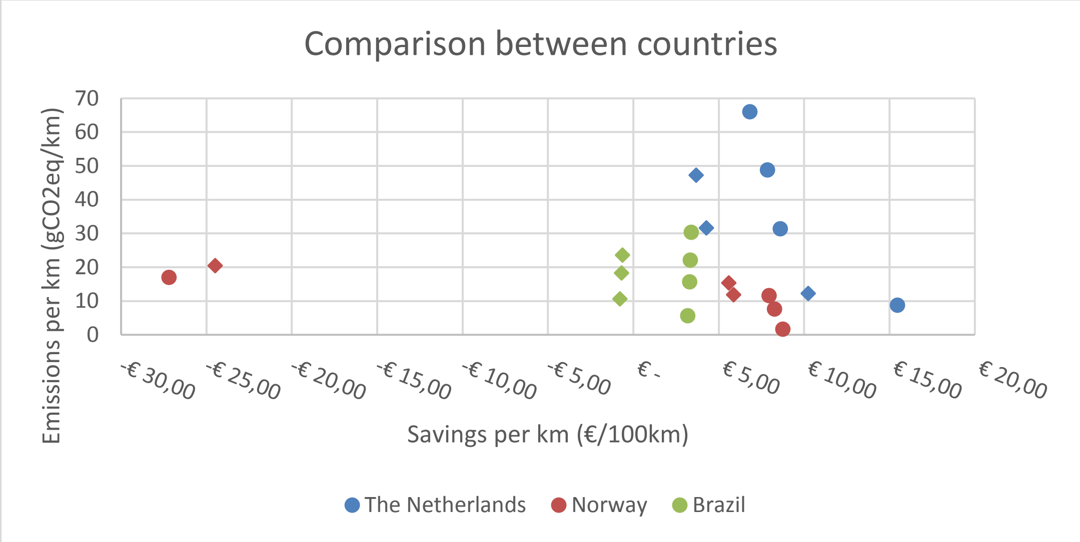


Figure 104 - Comparison between the 21 scenarios in The Netherlands, Norway and Brazil - Without storage (circle) and with storage (diamond).
Source: Elaborated by the author

Figure 104 shows that The Netherlands clearly is the country which presents the worse results from an environmental point of view; except in the 100% PV scenario, when they have results comparable to the best scenarios in Norway and Brazil. On the other hand, all the Norwegian scenarios presented good environmental results, being a very attractive country to adopt electric cars independently of having PV or not. Economically, The Netherlands and Norway have an advantage when compared to Brazil; except the scenario 1 in Norway, all others have better financial results than the Brazilian ones. This can be explained by the relatively low electricity and gasoline price in the tropical country as well as the higher costs related to PV and storage systems. Another important fact already mentioned is the higher inflation rate in Brazil, which depreciate prices and revenues over the years.

In summary, Norway is by far the most suitable country for electric cars due to its very sustainable grid. However, PV systems are not the best choice, also because of its hydro based mix and its geographical location where there is low solar irradiation overall and way too much variability between seasons. Anyway, when compared to gasoline, any small or medium PV system will still be feasible and profitable. In the Dutch case, the adoption of electric cars will not increase the transport CO_2 footprint. Nevertheless, in order to have a significant impact, EV users should seek more renewable ways to charge their cars until the country does not change the electricity mix profile. Despite the low solar irradiation, PV can be a good solution for it, but because of the solar irradiation variability between seasons a generous scheme between users and utility companies is crucial to make those systems feasible. Brazil also seems to be a suitable country for electric cars and PV systems. Especially because of its high solar irradiation during the whole year and its relatively sustainable electricity mix, using an electric car is feasible and sustainable. However, in order to give a boost to its adoption, measurements regarding fossil fuel prices should be taken so that people would be keener to change their choice in transport energy source matters.

Solar Car

In the previous chapters, it was possible to see how solar PV can help electric cars decrease its carbon footprint and be profitable at the same time. However, all scenarios assumed a very important premise that users had to connect their car to the charging station (equipped with the PV system) every day what is quite a great habit change, as nowadays people are used to go to a gas station to refill their car just once a week.

Additionally, today, only 1.1% of newly sold cars in Europe are electric. Research shows the biggest restrictions to an electric car purchase are the limited reach and the high purchase price (Bessenbach & Wallrapp, 2013). The underlying fear cause about the reach is the uncertainty about whether the car can be charged when the battery is empty; in other words, whether there will be charging infrastructure in the vicinity. The US Environmental Authority EPA sees the electric cars currently on the market as interesting for only 2-4% of the population (Kodjak, 2012). The same research shows that there is a big gap between the expectations and actual performance of electric cars also indicating the car's charging time and range as the biggest restrictions. Furthermore, charging points are still a major issue, especially for the 70% of Dutch people who do not own a driveway (Natuur en Milieu, 2016) and are, therefore, reliant on public charging infrastructure. It is expected that approximately 53,000 additional charging stations will be needed in the Netherlands by 2020; the cost of these charging stations is estimated at around 25 million euros, almost €500 per station (Autoweek, 2016). Considering The Netherlands have one of the best charging infrastructure in the world, the challenges for the other countries, especially the developing economies, are way bigger.

Therefore, an obvious solution for rolling out an infrastructure is the development of a vehicle requiring as few modifications as possible in the infrastructure. The idea of a vehicle which can power itself has been intriguing scientists for many years. For a long time the development of such a vehicle was unfeasible. However, recent technical progress and cost reductions in PV systems might have changed this perspective. In this Chapter, the possibility of installing solar cells on cars in order to charge themselves will be analyzed, based on the proposed technical model.

Examples of solar cars were given in the literature review chapter. Furthermore, no project intends to develop a car completely independent from the grid, despite some very ambitious claims. However, in the simulation carried below, the objective was to estimate how many solar panels are needed so that an electric car could be independent of any charging station in ten years and also how far the current state of art is from achieving this condition. The assumptions regarding car efficiency and battery capacity will be the same as in the previous chapters, where specs about Nissan Leaf were used. The car will run on Brazilian conditions regarding solar irradiation and driving patterns. The same data from PVGIS regarding the PV production will be used acknowledging that in real conditions the panels would not have an optimal incidence angle and losses by shading would be way higher. Therefore, the results presented should be analyzed carefully given their limitations.

According to the conditions defined in the model, the minimum array size needed in the car to be fully independent of the grid in ten years is 2.04 kWp. In the Figure 105 it can be seen the car battery SOC variation. As already seen in the technical model section, the biggest barrier to develop an independent solar system is designing it for the worst day in the year, as in the rest the year it produces more than enough energy.

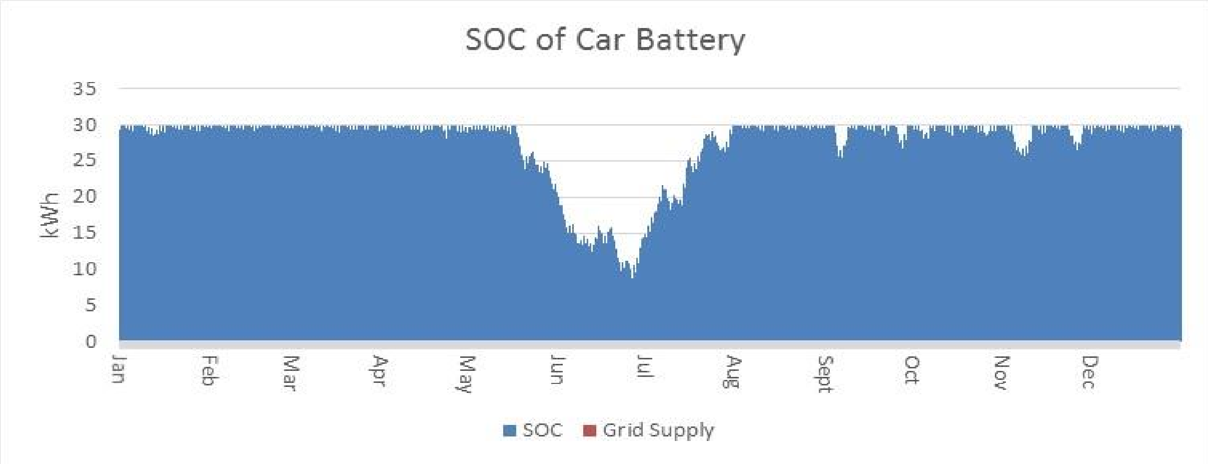


Figure 105 - Solar Car Battery State of Charge variation in the 10th year.
Source: Elaborated by the author

The size of 2.04 kWp would require about 3.5 m^2, assuming current efficiencies. A car usually has between 4 to 6 m^2, what can give the impression that developing a solar car is feasible. However, great part of this surface area are in the doors and other faces which are more or less 90^0 in relation to the ground. This condition decreases a lot the solar irradiance on them and, consequently, the electricity on their solar cells. In addition, it should not be forgotten that according to studies (reference literature review) a car is estimated to receive 42% less solar radiation than rooftop systems.

Nevertheless, with the increase of electric cars adoption, more development will follow. For example, fuel engines have been around for almost 100 years and were transformed from that inefficient and dirty braking engine to the powerful, economical, quiet and relatively clean fuel today's engine. Among all possible improvements, the increase in the efficiency and in the battery capacity are the ones that can most impact the electric car desired ‘independence’. By changing both variables, separately, their impact in the reduction of the necessary array size can be observed (Figure 106).

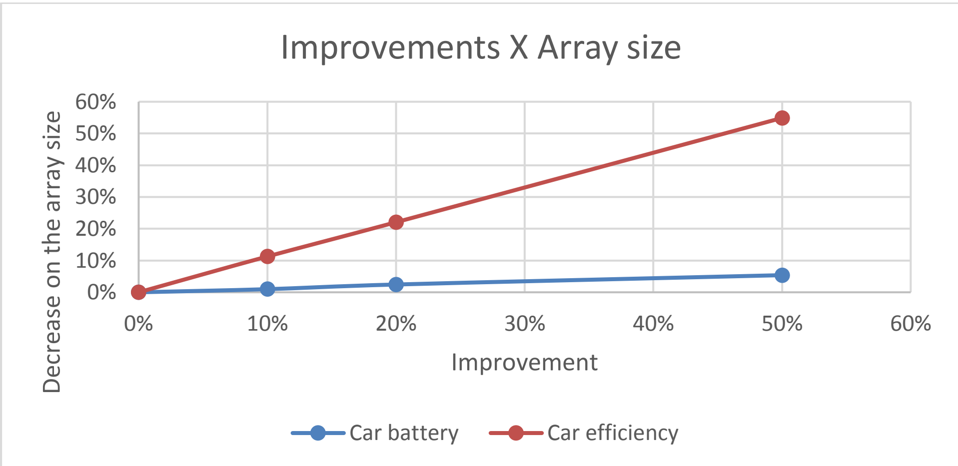


Figure 106 - Impact of car efficiency and battery improvements on the solar array size.
Source: Elaborated by the author

The car efficiency, defined as 0.174 kWh/km, was improved on 10%, 20% and 50% when reached 0.87 kWh/km. It is very interesting that this impact is higher than the change occurred, for example, by improving the car efficiency in 20% when the array size was reduced in 22%. This shows the great importance of this variable. Improvements on the car efficiency includes: decreasing the rolling resistance, aerodynamic drag, vehicle weight and the auxiliary power usage. Regarding the battery capacity, there is a way lower impact on the array size. By improving in 50% its capacity, reaching 45 kWh, the necessary array size would decrease just

5%. The major efforts, nowadays, regarding electric car batteries are not only to increase its capacity in order to cover higher ranges, but also looking for lighter materials, as the battery is one of the heaviest component in the electric car. As already mentioned, reducing weight can increase the car efficiency, what has a great impact on the electric overall performance.

Hypothetically assuming that a 50% improvement on both car efficiency and battery capacity are achieved, the necessary array size for the car to be totally independent from the grid, in São Paulo, Brazil, according to the model defined before, is 0.88 kWp. In the Figure 107 it can be seen the SOC variation in the tenth year.

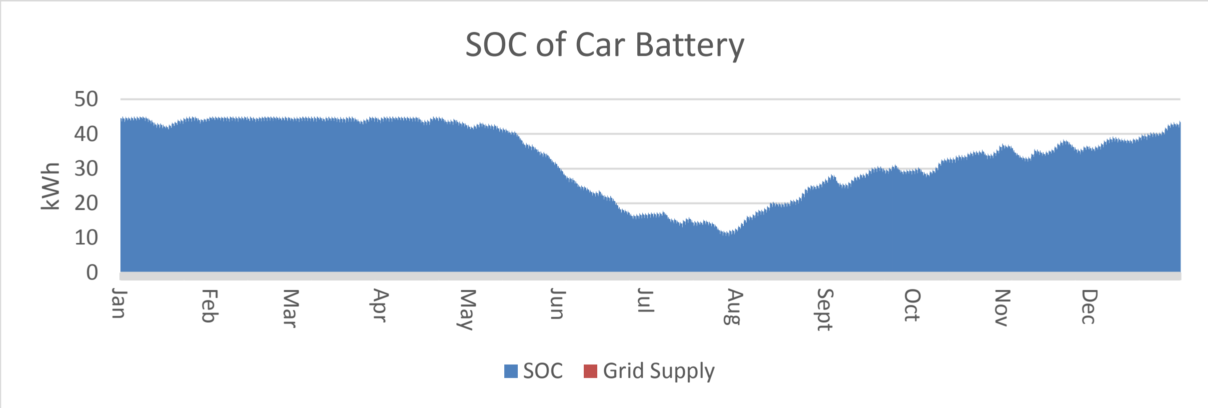


Figure 107 - Solar Car Battery State of Charge variation in the 10th year after 50% improvements.
Source: Elaborated by the author

Differently from Figure 105, the energy produced this time is better distributed throughout the year decreasing the excess of electricity being wasted. A higher battery capacity gives the electric car more energy to be spent during Winter when the solar production is not enough to match the car electric demand. Furthermore, the increase in the car efficiency makes the SOC decreasing slope less steep, as it was observed between May and August.

An array size of 0.88 kWp requires about 1.5 m^2. As it can be seen on the Figure 108, the area covered by the panels can be fitted in the car top surface. However, as already mentioned, this estimation has a lot of limitations regarding the real efficiency of those cells built-in on the car. It is also true that solar cells are becoming each day more efficient, as nowadays some solar cells can have efficiencies higher than 40% in laboratory.

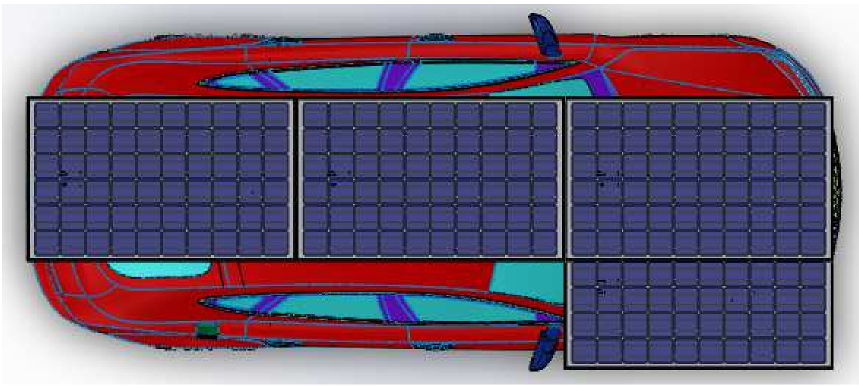


Figure 108 - Array size (0.88 kWp) and conventional car top view comparison.
Source: Elaborated by the author

In summary, with the current technology regarding electric cars, batteries and solar PV, a total independent car it is very unlikely to happen. However, those same technologies are evolving fast and those improvements could make possible the dream of driving a car without needing to stop to refill or charge it in a near future.

Conclusions and recommendations

3.1 Conclusions

The impacts of climate change had already urged the decrease in the world emissions and the transport sector plays a main role on this issue. In the short term, it will be possible to make the cars more fuel-efficient and in the medium-long term electric cars seems to be the most suitable solution. However, these cars must be charged by renewable sources of energy, otherwise, if the electricity continues to be generated by fossil sources, transport CO_2 footprint will remain one of the main climate change drivers globally. Solar PV can be a great match for electric cars as their installation can be decentralized either on rooftops or on parking lots. The variability of solar radiation couples well with driving patterns where commuters leave in the morning and let their cars parked during the whole afternoon, the higher solar irradiation period.

The developed model in this study showed a way to estimate how an electric car would perform in many different conditions, including the use of solar PV to charge it. The methodology took into account different technical, economic and environmental aspects which have relations with each other. Because of these complex links among all considered variables, the results obtained through this study brought some intrinsic uncertainties that should always be considered when analyzing them. However, some technical aspects such as the performance decay of the solar cells, batteries efficiencies of charge/discharge, battery capacity, car efficiency and storage capacity have more reliability than social and economic aspects, which can significantly change depending on the context. Therefore, more important than the specific values found for each studied scenario, the main contribution of the present study should be the traced variables trends found in the analyses.

The daily total distance, for example, changes greatly from person to person and highly relies on local conditions. Everyone has his/her own daily routines, so defining one pattern means a great but necessary simplification in the analysis. The sensitivity analysis led to a conclusion that depending on the daily distance travelled the necessary array size changes greatly and it does not depend on the share of PV in the system. Despite that, average data from local studies used in this study require the results should be treated carefully as differences on these routines can affect the final result. The daily total distance travelled and the driving patterns are some of the most important variables that should be adjusted in order to evaluate each specific case.

Another solar systems intrinsic variable is the solar irradiation. Measuring and estimating it is also challenging as the solar irradiation can be divided in many forms (direct, diffuse, reflected, circumsolar etc.). However, nowadays with satellite measuring methods, there are very reliable solar data available. Based on that the analysis simulated the same system on three different locations and concluded that countries located at high latitudes, where the solar irradiation is low and where there is a high discrepancy between Summer and Winter irradiations, are subject to a great impact in the necessary array size of PV systems. But, in this case the share of PV is very important as high shares are more impacted by it. Additionally, this impact grows exponentially with the decrease of the average irradiation of the worse day in the year. For instance, the analysis of the scenario 1 (100% PV) results in Norway and in The Netherlands evidenced that. In Norway the daily average irradiation is three times lower than in The Netherlands, nevertheless the necessary array size is eight times bigger. Meanwhile, the Brazilian worse average daily irradiation is almost 6 times higher than the Dutch one, but the array size is only 2.5 times smaller.

Financially, some fuel prices were evaluated. The PV costs have a direct influence on the system returns and, as expected, higher shares of PV are more affected. However, the proportion of this impact is less than one to one, even in the 100% PV scenario which means that despite the great importance of this factor, other variables are influencing the economic result as well. The same analysis found that gasoline prices have a fair impact on the financial results, as they are the reference of all economic results. The only revenue source that does not depend on this reference is the return regarding the electricity sold back to the grid. For this reason, the scenarios in which more electricity is sold are less affected by the change of gasoline prices. Additionally, gasoline prices are so impactful that Brazil, despite having by far the higher solar irradiation among the three countries analyzed, presented the worse economic results in general. The low gasoline prices in Brazil brought all the financial indicators down as they are calculated based on how much each scenario would save by not using gasoline to power the car. Therefore, if gasoline does not cost that much, the related savings are also low.

The next parameter tested was the electricity rate which has even less impact than the PV cost. On opposite of PV costs, higher shares of PV means less impact of the electricity rate, but even in the 100% grid scenario the impact is not that big. Furthermore, there are another aspect that greatly impacts how the electricity price affects the system which is the electricity scheme regarding the electricity being fed back to the grid by the user. In The Netherlands, where the utility company pays the same price as the retail, the decrease of the electricity price meant a decrease on the financial results in scenario 1 (81% of all electricity produced is injected into the grid). On the other hand, in Norway, where the utility company pays way less than the retail price, big systems producing a lot of electricity excess are totally worthless, being much more costly than an ICEV.

When renewable energy are considerate, storage systems always come as a solution to cope with their electricity generation intermittent condition. The addition of storage systems indeed helped and decreased the necessary array size of every scenario. In addition, those systems also decreased the share of electricity being fed to the grid which demonstrates that they help to better distribute the electricity generated by the PV to where it matters most, the electric car. More specifically, in countries at high latitudes, such as Norway and The Netherlands it is advisable to seek for a storage system that can hold the energy for long time, as there is excess of energy being produced during Summer and lack of energy during Winter. On other hand, in countries at low latitudes, where the solar irradiation is much more stable through the year, it is advisable to use systems with high 'fatigue' resistance, as the car will be charged and discharged several times, independently of the year period. Environmentally, storage systems were not worth it in any scenario. The reduction of the emissions regarding the PV production, due to the decrease of array size and better distribution of the energy generated, consequence of the storage systems, did not compensate the increase of emissions due to the manufacturing of the them. Therefore, based on this study's assumptions, using a storage system does not reduce the overall emissions of PV systems used to charge electric cars. Financially, the same trend was observed. The reduction of investment costs, due to the reduction of array size, did not compensate the extra costs to install a storage system. Just on the Norwegian scenario 1 the costs were compensated; however, this was, by far, the worse scenario, economically speaking, as the necessary array size was absurdly big with and without storage. In summary, storage systems did not show to be a sustainable option for the situations simulated in this study. Maybe more technology development regarding more sustainable materials and manufacturing methods, as well as more costs reductions, can turn those systems feasible and sustainable in the future.

The electricity CO_2 footprint from where the car is charged is the main variable that impacts the environment electric car performance. As mentioned, the way electricity is produced defines if electric cars are an environmental hero or a fraud. Unsurprisingly, the higher are the shares of PV, the lower are its impact, and in a 100% PV scenario there is no impact of the local electricity mix CO_2 footprint. Moreover, the mix CO_2 footprint can be an environment boost or an environment hindrance to invest on PV systems. In Norway, as the mix is greener than PV systems, the adoption of those systems means releasing more emissions than charging entirely in the grid. In Brazil, and especially in The Netherlands, PV systems are greener what means adopting those systems helps to decrease the CO_2 footprint of EVs.

As already mentioned, Norway is by far the most suitable country for electric cars due to its very sustainable grid. However, because of this PV systems are not the most profitable choice. Anyway, when compared to gasoline any small or medium PV system still will be feasible and profitable. In the Dutch case, the adoption of electric cars will not increase the transport CO_2 footprint, even when charging it entirely in the grid. Nevertheless, in order to have a significant impact on the country's emissions reduction, EV users should seek more renewable ways to charge their cars until the country makes the transition to a more sustainable electricity mix profile. Despite the Dutch low solar irradiation, PV could be good solution for it. However, in order to compensate the solar radiation variability between seasons, a generous scheme between users and utility companies is crucial to make those systems feasible and profitable. Brazil also seems to be a suitable country for electric cars and PV systems. Using an electric car is feasible and sustainable in this country, especially because of its high solar irradiation during the whole year and its relatively sustainable electricity mix.

Almost all the systems tested in Norway, The Netherlands and Brazil can be considered feasible. Only the scenario 1 (100% PV) in Norway and all scenarios with storage in Brazil appeared to be more costly than using gasoline. All other scenarios resulted to be feasible, profitable and, therefore, sustainable. In addition, the scenario 4 (100% grid) in The Netherlands showed the highest CO_2 footprint; however, it still is significantly lower than an ICEV and, therefore, considered a sustainable and feasible option in this study.

In order to find the most sustainable scenario, according to these study assumptions, two scenarios stood out. First, the Norwegian scenario 4 (100% grid), the one with the lowest CO_2 footprint of all and the third best financial return, and secondly, the Dutch scenario 1 (100% PV) without storage, the one with the highest financial returns and the fourth lowest CO_2 footprint. However, the Dutch one has most of its revenues coming from injecting electricity back to the grid which is not the main objective of the envisaged systems. Therefore, the most sustainable scenario simulated in this study is using an electric car in Norway and charging it completely in the grid.

As to the possibility of having a solar car with built-in solar panels providing all the necessary electricity to the vehicle, it still is very unlikely with the current technology regarding electric cars, batteries and solar PV. Nevertheless, these same technologies are being developed faster and the analysis concluded that by increasing the car efficiency a greater impact on the solar car feasibility is achieved. On the other hand, the increase in the battery capacity does not have a significant impact on the same issue. Moreover, the desired improvements could make possible the dream of driving a car not needing to stop to refill or charge in a near future.

3.2 Recommendations

With the results obtained in the accomplishment of this work, as well as the knowledge acquired in the development of the study, it is possible to recommend the following subjects to be embraced in future studies.

- Validate the developed model with real world data obtained in experimental trials. By tracking an electric car and all energy produced by a PV system the model could be validated and the extrapolation of its results would have more reliability.
- Expand the model in order to estimate the PV production by supplying solar irradiation data. Until this moment, the model used directly the amount of electricity produced by a PV system, provided by PVGIS. By estimating the PV production inside the model variables, the solar PV system performance could be controlled and adjusted in order to give more precise results.
- Estimate different driving patterns, such as charging the at home instead of charging at the workplace. Also consider the possibility of using the electricity stored in the battery of the car to power the house, vehicle to grid (V2G) technology.

- Incorporate costs and emissions estimation of manufacturing and acquiring the vehicle (electric or conventional car) in the model as well as its end of life. By introducing both processes, a complete life cycle analysis (LCA) and life cycle cost analysis (LCCA) can be calculated.
- The transition to an electric vehicle fleet will need a behavioral change. For that reason is recommended to analyze social aspects involved in the adoption of electric cars and charging systems.

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