Technology Collaboration Programme
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International Energy Agency
**Photovoltaic Power Systems Programme**


Task 17 PV and Transport

PVPS

# PV-Powered Electric Vehicle Charging Stations

## *Preliminary Requirements and Feasibility Conditions*

2021

**Report IEA-PVPS T17-02 : 2021**

# What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of 6 000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The IEA PVPS participants are Australia, Austria, Belgium, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Mexico, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, and the United States of America. The European Commission, Solar Power Europe, the Smart Electric Power Alliance (SEPA), the Solar Energy Industries Association and the Copper Alliance are also members.

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# What is IEA PVPS Task 17?

The objective of Task 17 of the IEA Photovoltaic Power Systems Programme is to deploy PV in the transport, which will contribute to reducing $CO_2$ emissions of the transport and enhancing PV market expansions. The results contribute to clarifying the potential of utilization of PV in transport and to proposal on how to proceed toward realising the concepts.

Task 17's scope includes PV-powered vehicles such as PLDVs (passenger light duty vehicles), LCVs (light commercial vehicles), HDVs (heavy duty vehicles) and other vehicles, as well as PV applications for electric systems and infrastructures, such as charging infrastructure with PV, battery and other power management systems.

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**COVER PICTURE**

PV-powered charging station (experimental platform), Innovation Center of Université de Technologie de Compiègne, France

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INTERNATIONAL ENERGY AGENCY

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

# IEA PVPS
# Task 17
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# TABLE OF CONTENTS

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| AC | Alternating Current |
| BESS | Battery Energy Storage System |
| DC | Direct Current |
| EV | Electric Vehicle |
| GHG | Greenhouse Gas |
| G2V | Grid-to-Vehicle |
| I2H | Infrastructure-To-Home |
| ICDA | Immediate Charge/Discharge Algorithm |
| ICEV | Internal Combustion Engine Vehicle |
| IDT | Innovation Diffusion Theory |
| IIREVs | Intelligent Infrastructure Recharging Electric Vehicles |
| MG | MicroGrid |
| MPPT | Maximum Power Point Tracking |
| NPV | Net Present Value |
| OR | Occupancy Rates |
| PV | PhotoVoltaic |
| PVCS | PV-powered Charging Station |
| SEC | Socio-Economic Classification |
| SOC | State of Charge |
| SPVA | Peak and Valley Searching Algorithm |
| STC | Standard Test Conditions |
| TSO | Transmission System Operator |
| UT | University of Twente |
| UTC | Université de Technologie de Compiègne |
| V2B | Vehicle-to-Building |
| V2G | Vehicle-to-Grid |
| V2H | Vehicle-to-home |
| V2V | Vehicle-to-Vehicle |
| V2X | Vehicle-to-Everything |
| VIPV | Vehicle Integrated Photovoltaic |
| WDO | World Design Organization |

# EXECUTIVE SUMMARY


The advent of electromobility is widely seen as an opportunity to reduce the harmful impacts of the transport sector on the environment and public health. A substantial reduction in $CO_2$ emissions from EV usage can be achieved by the development of solutions based on photovoltaic (PV) systems as a primary energy source. IEA PVPS Task 17 is aiming to clarify the potential of the utilization of PV in transport and to propose how to proceed towards realizing the concepts. Task 17's scope includes PV-powered vehicles as well as PV charging infrastructures.

This report focuses on PV-powered charging stations (PVCS), which can operate for slow charging as well as for fast charging and with / without less dependency on the electricity grid. PVCS can also provide additional services *via* vehicle-to-grid (V2G) and vehicle-to-home (V2H). These may increase the effective use of locally produced solar power. This is the first technical report of subtask 2 of the Task 17. As an interim report, it presents the recent trends in PVCS for passenger cars including system architectures, preliminary requirements and feasibility conditions to increase benefits of PVCS, social acceptance, and proposes steps for realizing PVCS.

**Key recommendations**

- Main requirements and feasibility conditions for increasing PV benefits are:
    - On user behavior/ flexibility:
        - Prefer daily charging over weekly charging;
        - Accept long and slow charging when possible;
        - Limit charging to the number of kWh required for the daily trip, or charge more when PV power is available;
    - On technical aspects:
        - Limit charging power and stationary storage power to about 7 kW;
        - Choose an optimal size for stationary storage;
        - Give priority to charging stationary batteries by PV over charging from the grid.
- Charge / discharge controlling, optimization, PV production forecasting, and communication between the operators and the end-users are necessary to increase PV benefits;
- Technical and economic optimization of PVCS under local meta-conditions (site, weather conditions, user profile, etc.) and over the lifespan are strongly recommended to make full direct use of the PV energy;
- Well-conceived power management strategies with integrated V2G / V2H may reduce the peak pressure on the public grid while meeting the needs of users, and provide an environmental benefit;
- Societal impact and social acceptance, as well as aesthetic design aspects, of PVCS and new services associated have to be considered and undertaken as preliminary studies;
- Design methodologies and tools will be helpful for optimally sizing PVCS.

***A. Recent trends in PV-powered infrastructures for EVs charging for passenger cars***

As PV electricity generation is strongly influenced by the weather, back-up sources (i.e. stationary storage and/or public grid connection) are necessary. PVCS may operate in standalone mode and/or in grid-connected mode. According to an overview of existing projects, most of the small size PV infrastructures are generally equipped with slow charging terminals. An interesting example is the standalone charging station EV ARC™ (4,3 kWp), in San Diego (USA). Considering that this infrastructure is placed in Northern France, in summer, during the best solar irradiation conditions, this installation can provide approximately 23,5 kWh/day. Thus, for a consumption of 15 kWh/100 km, the PV daily production can supply an EV for a trip up to 157 km. Moreover, with the consideration of the stationary storage, the EV ARC™ charging infrastructure can supply an EV for a trip up to 400 km. However, daily charging of 400 km, even for the best solar irradiation conditions, is not possible due to the need, i.e. time duration, of the stationary storage recharging. In contrast, EV charging by ultra-fast charging mode requires a power grid connection. This is the case of the Tesla V3 Supercharger, in Las Vegas (USA), equipped with ultra-

fast charger of 250 kW. This charger significantly reduces the charging time thanks to the 210 kWh stationary batteries storage, which provides a part of the required power. However, the power grid will often complement the available solar power during the charging sessions and will also charge the battery storage system.

To be able to host slow charging and fast charging terminals at a PVCS, the PVCS could be a system based on a microgrid (MG), incorporating stationary storage that is charged exclusively from PV sources, with / without public grid connection, using intelligent power control, optimization system, user application interface, and communication system. Thus, in this context, MG is investigated to become a solution to EV charging allowing the use of the PV energy when, where, and how it is generated, charge controlling, and increasing PV benefits.

### *B. Requirements for expected benefits of PV-powered charging stations for passenger cars*

For charging EVs, the MG power flow control is based on the following priority order: PV sources, stationary storage, and lastly public grid connection. It is assumed that the daily average urban/peri-urban road trip for an EV is 20–40 km, and that a normal drive mode will require 3–6 kWh daily energy consumption. To identify the minimum of the PV energy involved in the EV charging several scenarios are simulated under the worst solar irradiation conditions in Northern France, i.e. 45,5 kWh/m² during December for fixed-angle. In addition, it is assumed that the user may inform the PVCS with the following data: arrival time, state of charge ($SOC_{EV}$) at arrival, desired $SOC_{EV}$ at departure, and park time estimation.

The results presented in these studies show that the preliminary requirements and feasibility conditions to increase PV benefits for PVCS, are:

- In the slow charging mode at 7 kW, the required power can be obtained mainly from PV energy, but the user must then accept that charging is long and slow;
- In the fast charging mode at 22 kW, the charging depends mainly on public grid energy;
- Stationary storage power should be limited at 7 kW for the fast charging mode.

Furthermore, the PV benefits are greatest when EV charging is operated daily rather than weekly, when the slow charging mode is used, and where parking time is known in advance in order to optimize the EV charging during the estimated parking time. A user interface is required to facilitate the interaction between the EV users and the charging station and to take into consideration the EV users' preferences. The public grid can provide energy where required, and / or surplus PV production can be fed into the grid.

### *C. Technical and economic feasibility analysis of PV-powered charging stations for passenger cars*

The PVCS has been analyzed from a technical, economic, and environmental point of view. A three-step methodology, leading to a quantitative evaluation of the PV benefits obtained for PVCS, was designed. A tool has been proposed to adjust the investment cost of the PVCS using four parameters: the type of PV panels, number of PV panels, number of terminals, and the capacity of the stationary storage. The tool can be used to optimally size the PVCS and then, to obtain by simulation the operating modes aiming at increasing the use of PV energy for EV charging.

An economic and environmental evaluation of a PVCS with stationary storage over a period of 10 years and four different locations and scenarios shows that:

- The highest net present value (NPV) is obtained with grid-only charging, which is likely due to the high investment costs of the storage system;
- The emissions per km travelled for each scenario show that:
  - For 100% PV scenario emissions can be as low as 12 to 13 g $CO_2$-eq per km travelled;
  - In all locations the grid-only scenario has the highest $CO_2$ emissions with grid-charged EVs;
  - Scenarios with PV and stationary storage show emissions reductions compared with a gasoline-fueled vehicle.

The results presented in these studies show that with the right combination of the stationary storage and PV array sizes, the use of PVCS can be a feasible EV charging solution from a technical, financial and environmental perspective in comparison not only with a gasoline-fueled vehicle, but with a grid-charged EV as well.

### D. New services associated with PV-powered charging stations

EV batteries can be used as an energy storage system, and deliver energy through V2G and V2H, when there is an opportunity. State of the art research shows that V2G systems are not yet ready for industrial-scale use. However, multiple projects are testing V2G applications. For example, the city of Utrecht in the Netherlands is experimenting at large scale with a smart PV charging bidirectional EV sharing system. PVCS can provide an environmental benefit in the operation of V2G / V2H services.

A successful implementation of V2G / V2H also depends on the development of a management algorithm able to satisfy the charging / discharging demand. To provide ancillary services to the public grid during peak periods, with EV batteries having a dual “load-source” role, a peak and valley searching algorithm (SPVA) able to deal with the intermittency of PV generation, EV charging demand, and V2G has been designed. SPVA defines the optimal charging/discharging start times of EVs, their arrival time, departure time, initial state of charge, and the minimum or maximum state of charge at the time of departure, to achieve peak shaving and valley filling while reducing the costs of energy from the public grid, which is beneficial to the public grid and EV users.

### E. Societal impact and social acceptability of PV-powered charging stations and new services (V2G, V2H)

Studies have been conducted and show that the aesthetic aspects, user experience, and user acceptance of new forms of EV charging are key to the success of PVCS.

A case study in France shows that a large majority socially accepts the PVCS while some imperatives have to be considered. The general trend seems to be favorable to the charging of EVs using PV energy and to the discharge through the V2G/V2H strategies. However, the investment costs to develop, build, install, and maintain, as well as the PVCS’s design and aesthetic aspect are the most important limits.

A survey carried out in The Netherlands showed the specific impact of PV ownership on respondents’ EV experience and their likelihood to adopt (purchase/lease/use) the solar mobility applications. A significant difference in EV ownership was found between respondents with residential PV and respondents without it, indicating a positive relationship between the use of solar energy at home and an interest in electric transport.

An aesthetic design of the PV infrastructure may help user acceptance. One of the main design limitations is the small area available for installing PV systems, particularly for designs for which PV cells are integrated on vehicles. Solar charging infrastructure typically has more space available. Designs for PV-powered charging infrastructure, also show how PV systems can be used for powering a wide range of modes of transportation beyond electric passenger cars. Finally, an important aspect of designing these applications is the use of their visual appearance for communicating to users their function and their focus on sustainability.

### F. Main issues and the way forward to effective implementation and use of PV-powered charging stations

**Main issues for effectively implementation and use of PV-powered charging stations**

- Need for improved understanding of:
  - Pro and cons of slow charging versus fast charging from the stakeholders’ perspectives;
  - Influence of bidirectional charging (V2G / V2H) on the life of EV battery and power electronics;
- Lack of:
  - Proven models for the user experience to make optimal decisions in selecting charging points;
  - Business models and business process implementation and optimization tools to increase PV benefits;
  - Optimal charging strategies in various scenarios, e.g. on-road and covered public parking, residential and office buildings private, in cities public parking, for light and heavy-duty vehicles.

**The way forward**

PVCS may offer significant benefits to drivers and an important contribution to the energy transition. Their massive implementation will require technical and sizing optimization of the system, including stationary storage and grid connection, but also change of the vehicle use and driver behavior. Long parking time for EVs, short driving distance (around 45 km), and slow charging mode allow to maximize the PV benefits of PVCS.

The next steps for the subtask 2 will focus on global cost and carbon impact assessment methodology, human-system interfaces, charging control and power management with demand response, real time power management including optimization algorithm, experimental validation and analyze of experimental results, PV benefits assessment for V2G / V2H, new survey on the social acceptance of PVCS and new services and the analysis compared to the first survey.

# 1 OVERVIEW OF THE CURRENT STATUS OF PV-POWERED INFRASTRUCTURES FOR EV CHARGING

PV solar energy is increasingly being integrated in EV charging systems for three reasons, namely the rapid growth of EV, the need to combat the impact that greenhouse gases (GHG) have on the environment, and the continuing fall in the cost of PV panels. PV-powered charging systems pose their own problems, including the insufficiency of PV production for charging, the continued reliance on the electricity grid, and the lack of a business model to predict the financial profitability and economic benefits of PVCS. All this is examined in the first section of this chapter, which presents an overview and state of the art of infrastructures for EV charging based on PV car parking shades and on building-integrated PV. These infrastructures focus either more narrowly on the charging of EVs, or more broadly on both the consumption and distribution of PV production via the power grid. There are two main operational modes for PVCSs. The first is *grid-connected mode*, where EVs are charged via the power grid partially supplied by PV production or via a microgrid-based system incorporating stationary storage, grid connection, and EV charging from PV power, storage, and grid. The second operational mode is *standalone mode* (also known as *island mode*), where charging is 100% green, but the PV production is insufficient for a full charge, despite the presence of storage, which is limited in capacity.

Studies on the optimization of EV charging infrastructure have attracted the attention of developers and researchers. New challenges are raised by the need for the power grid to be able to support the growing consumption resulting from more EVs and more charging stations. In this context, the second section of this chapter presents a software application for managing and optimizing peak power consumption, developed by the multinational company SAP Labs France at SAP Labs Mougins, as a case study of PV-powered infrastructure for EV charging. This tool features a user communication interface based on state of charge, end of charge, and EV rotation. This case study provides insights into the importance of installing PV panels to reduce consumption peaks generated by charging stations.

## 1.1 Overview and state of the art of PV-powered infrastructures for EV charging

Today, all countries face challenges and problems relating to energy production, demand, operation, management, and also transport. Transport is the main cause of air pollution in cities and is responsible for 56% of GHG emissions in Europe [1]. Most of the energy produced in the world still comes from fossil fuels. Certain sectors of activity, such as the automotive industry, have looked into the problem and now offer a sustainable alternative to internal combustion engines in the shape of the electric motor. Thanks to international efforts and national stimulation policies, sales of EVs have been increasing, with a 43% increase over 2019 [2], and the number of EVs exceeding 10 million globally in 2020.

The explosion in the EV market is leading to an increase in the number of charging points, estimated to be approximately 7,3 million worldwide at the end of 2019 (a 38% increase over the previous year). Most of this increase comes from new private slow charging points, accounting for more than 86% of the 2 million new installations last year [3]. Charging EV batteries from green energy increases the environmental benefits of EVs, and the use of PV power for recharging of EVs is therefore of great interest. As electricity generated by PV systems has low GHG emissions over its lifecycle, charging EVs using PV power during the daytime when PV production is highest complements the benefits of their low GHG emissions on the road.

PV installations for EV charging can be ‘car parking shades’, where the PV panels are installed on dedicated canopies, or they can be on the roofs of buildings. PV-powered charging stations (PVCSs) can operate in grid-connected mode or island mode. As shown in Figure 1.1-1, they usually consist of the following components:

- PV modules – The area station’s main source produces renewable electricity. Fixed arrays with silicon PV modules are usually the chosen technology because they offer the best trade-off between cost and efficiency. Tracking systems or concentrator PV systems are used in some pilots.
- Power balance of system:
  - Power electronics - Either DC-DC (direct current - direct current) converters, including maximum power point tracking (MPPT) or DC-AC (direct current - alternating current) converters are applied.
  - Energy storage system – This system can be used to overcome the mismatch between the time when energy is produced and when it is used. Most charging systems rely on batteries for storing energy. Lithium-ion technology is frequently chosen for this purpose, but lead acid batteries could also be used in principle.
  - Energy management system – This system can use different algorithms to monitor and control the power flows of the PV charging station (particularly if the station includes energy storage) in order to fulfil a specific objective, such as ensuring that an EV is always fully charged, or minimizing the system’s operating cost. Examples of some of these algorithms can be found in Section 1.2.2.
  - Other hardware - Wiring, switches, and mounting structures for the PV array.
- EV supply equipment - This refers to the components necessary to connect the EV to the charging station, such as the connector plug, power supply cable, charging stand and protection components, as well as the charging station’s user interface.

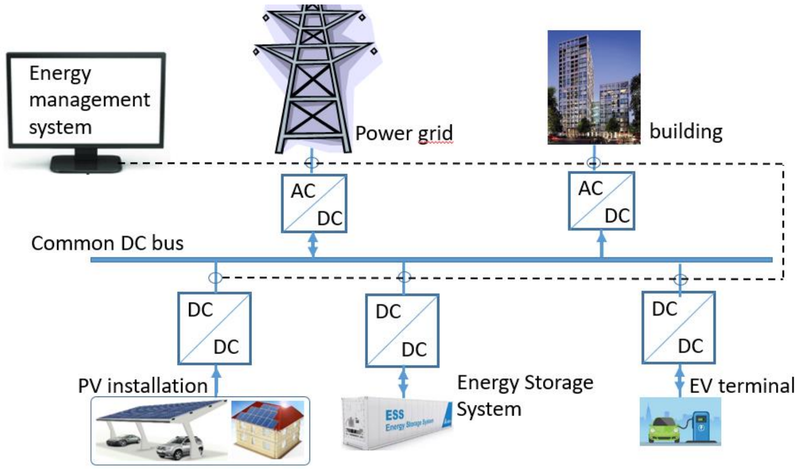


**Figure 1.1-1 PV powered charging stations**

The purpose of this technical chapter is to present an overview of the development of infrastructures powered by PV systems. These PV-powered infrastructures are dedicated either to recharging EVs or to supplying buildings or the power grid. However, in the latter case, it should be noted that EV charging terminals might in some cases easily be incorporated. This chapter presents and discusses various examples of infrastructures that have been installed on car park roofs or on the tops of buildings in several countries.

## 1.1.1 Existing PV-powered infrastructures for EV charging

This section gives an overview of existing PV-powered infrastructures for EV charging. It looks at recent installations in different countries. These cross-disciplinary projects showcase various types of charging solutions that are being tested in real operating conditions.

### *1.1.1.1 EV ARC™ 2020, Beam Global*

Beam Global is working with the city of San Diego (USA) to provide a free public EV charging using the first Beam-branded EV ARC™ 2020 charging unit.

As shown in Figure 1.1-2, EV ARC™ offers a standalone, transportable charging infrastructure, powered entirely by PV energy, to meet the EV charging needs of businesses, government facilities, and municipalities [4]. In contrast to charging infrastructures connected to the power grid, EV ARC™ units can be deployed or relocated in minutes without the need for construction or electrical upgrades. The technology also strengthens its users' energy security and emergency preparedness.

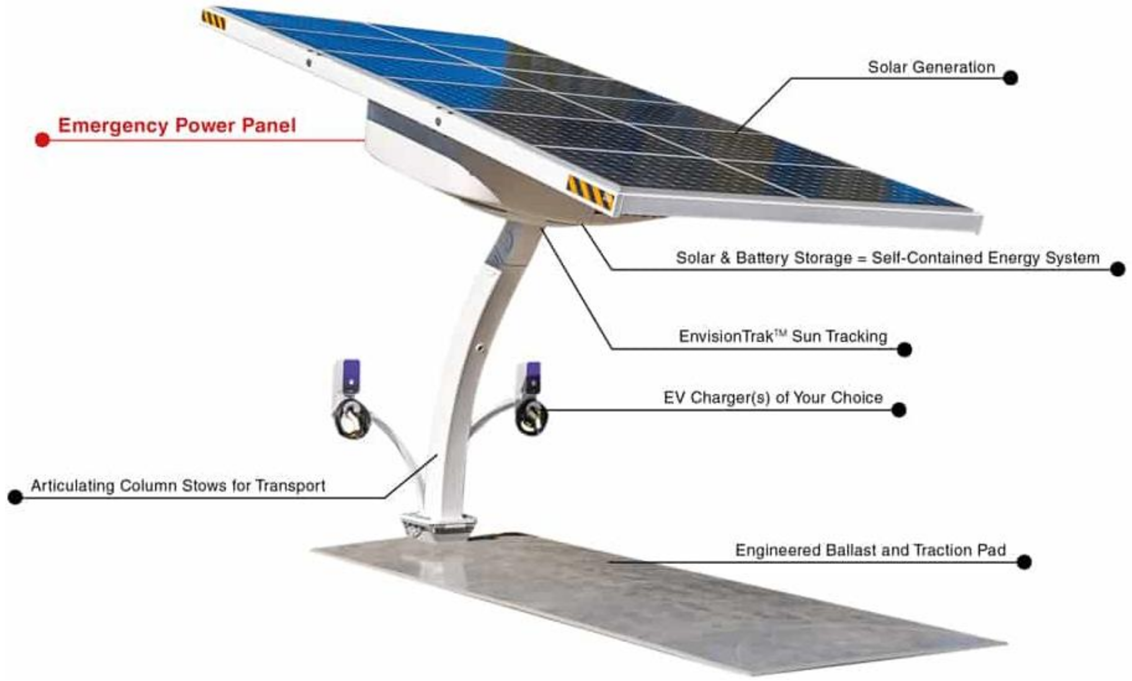


**Figure 1.1-2 EV ARC™ 2020 EV charging unit [4]**

EV ARC™ units come equipped with onboard ARC Technology™ energy storage of capacity up to 40 kWh that enables them to operate at night and in bad weather. It can charge up to six EVs at the same time. EV ARC™ units are independently rated to withstand winds up to 193 km/h and flooding up to 2.74 m and can continue to operate in the event of a blackout or power outage. The principal specifications of the EV ARC™ 2020 are summarized in Table 1.1-1.

**Table 1.1-1 Performance specifications of EV ARC™ 2020**

| EV ARC™ 2020 EV charging unit | Performance specifications |
|---|---|
| Total installed PV power for one unit | 4,3 kWp |
| Possible daily range supplied by PV and storage | Up to 394 km |
| Battery storage options | 24 kWh, 32 kWh, or 40 kWh |
| Terminal output power depends on EV model and charger model | Up to 4,3 kW |
| EV charger type | Any brand: 1-6 plugs |
| Certified wind load | 193 km/h |

Considering that this infrastructure is placed in Northern France, where the average annual irradiation is 1309,36 kWh/m$^2$, the EV ARC™ charging station can deliver roughly 4216 kWh/year. In summer, during the best solar irradiation conditions, this installation can provide approximately 23,5 kWh/day. Thus, for a consumption of 15 kWh/100 km, the PV daily production can supply an EV for a trip up to 157 km. Moreover, with the consideration of the stationary storage, the EV ARC™ charging infrastructure can supply an EV for a trip up to 400 km. However, the question of recharging the stationary storage arises, so daily recharges for 400 km, even for the best solar irradiation conditions, are not possible.

### *1.1.1.2 Other examples of PVCS for private or small parking lots*

Table 1.1-2 gives other examples of existing PVCS for private or small parking lots.

**Table 1.1-2 Examples of existing private PVCS**

| PVCS | PV System | Charging Modes | Energy Storage | Number of charging spots | Operation mode / grid |
|---|---|---|---|---|---|
| Fastned [5]  | 4-8 kWp | 50 kW DC<br>175 kW DC | No | 2 - 4 | Off-grid |
| SEVO Sunstation (Paired Power) [6]  | 16,8 kWp | Variable, up to 16,8 kW DC | No | 6 | Off-grid |
| SECAR E-Port [7]  | 3,78 kWp / 5,67 kWp<br>360° bifacial glass modules | 22 kW | Option | 1 / 2 | On-grid |

### *1.1.1.3 MDT-TEX Solar Carport*

In Germany, MDT-TEX deployed its smart PV Solar Carport car parking shade [8] in 2018. The Solar Carport is available in two different formats, with a symmetric or asymmetric mast. Both formats have a span of 5.3 m, which provides a reasonably generous amount of shading, and 15 PV panels on its surface generate ample energy (Figure 1.1-3). The square 5.3 x 5.3 m structure with a central mast can serve as parking spot for two cars. Given its modular design, several structures can be placed next to each other in a linear or group configuration.

**Figure 1.1-3 MDT-TEX Solar Carport for EV charging [8]**

This smart PV car parking shade is a grid-connected system and can feature chargers for electric bikes or electric cars. This model of PV car parking shade might for example be used in retail hubs, highways, supermarkets, or public parking spaces.

The Solar Carport can be installed with 15 PV panels with total power of 4.05 kWp. Depending on the local infrastructure or particular solution, the Solar Carport can incorporate a battery storage system to increase resilience and use the PV energy to charge EVs. A fully equipped Solar Carport has an installed storage capacity of 4.5 kWh. EV charging is via a 22 kW DC charger terminal. According to the performance specifications, the infrastructure remains dependent on the power grid, i.e. the additional power needed to reach the charging power of 22 kW is taken from the power grid.

The mast is also equipped with drainage pipes to guide rainwater through a filtration system and store it in a covered water tank (an additional green benefit).

#### *1.1.1.4 Tesla: V3 Supercharger with PV and battery*

In Las Vegas, Nevada, in 2019, manufacturer Tesla installed its new "V3 Superchargers" with a charging power of 250 kW [9]. A PV system is installed on the charging infrastructure (Figure 1.1-4) composed of 288 panels directly connected to the power grid. "Powerpack" 210 kWh batteries are also present, but they are charged by the power grid. Since the 288 PV panels are insufficient to supply this V3 supercharger, the power grid is the main supply source.

**Figure 1.1-4 Tesla V3 Supercharger with PV and battery [9]**

#### *1.1.1.5 Car parking shade project, Aix-Marseille-Provence metropolis, France*

The company IRISOLARIS is deploying its PLEXSUN® mixed energy solutions as part of the refurbishment of Gardanne train station, featuring protected parking areas with free charging stations for EVs (Figure 1.1-5). The work started in February 2020 [10].

**Figure 1.1-5 PV-powered infrastructure at Gardanne station [10]**

This project, undertaken by the Aix-Marseille-Provence metropolis in collaboration with the architectural firm Battesti and the delegated project management company SPLA Pays d'Aix Territoires, has two objectives: reducing commuter road traffic by offering protected parking areas, and allowing users to charge their EVs for free. It encourages the use of public transport in the interests of the environment: EV users can park and charge their vehicles when they use public transport.

In total, the car park provides 352 parking spots and is equipped with PV panels with a total area of 950 $m^2$. This grid-connected 130 kWp PV installation supplies 16 EV charging terminals and provides 56 removable battery charging lockers for e-bikes. The PV production is partly self-consumed, the car park providing a large portion of its own energy requirement over and above what is needed for charging EVs. Some of the PV production may be sold to the power grid. A storage system enables energy to be stored where it is not consumed directly, but we have no details regarding this integrated storage system.

#### *1.1.1.6 PV-powered infrastructure for electric bus charging in Queensland, Australia*

In September 2020, public transport operator Transdev announced that it will trial a 39-seater electric bus in South East Queensland powered solely by the sun (Figure 1.1-6).

**Figure 1.1-6 PV-powered electric bus in Queensland [11]**

Transdev will operate the new 39-seat electric bus on TransLink routes in the Brisbane area from 2021 under a two-year partnership with the Queensland State Government. The bus is charged via a purpose-built array of 10 Tesla Powerwall batteries installed at Transdev's Capalaba depot with a 135 kWh storage capacity. The batteries are themselves supplied by 250 PV panels on the depot's roof producing an average of 438 kWh per day [11]. The stored energy will be used to charge the Transdev electric bus, which is built on a BYD chassis and equipped with a 348 kWh battery giving an average range of 250 to 300 km.

The project is laudable, but further improvements are clearly desirable. The capacity of the bus battery is 348 kWh. Given that it consumes 60% of this capacity, meaning about 200 kWh on a given route, while the Tesla Powerwall battery has only a 135 kWh capacity, the bus either has to draw on the power grid for the remaining 65 kWh, or to spend some time at the at Transdev's Capalaba depot during the day for charging.

### *1.1.2 Existing PV-powered infrastructures for energy distribution and building supply*

This section looks at large-scale infrastructures intended mainly for self-consumption and distribution of PV production on the power grid. These are buildings and large parking lots equipped with PV panels, that is to say infrastructures not specifically designed for charging EVs, but charging terminals directly connected to the PV systems may be incorporated in the near future.

#### *1.1.2.1 Self-consumption PV energy: project with second-life battery at a GÉMO store*

The French store GÉMO is running a PV self-consumption pilot project using a car parking shade (Figure 1.1-7) coupled with storage technology based on second-life EV batteries.

This pilot project was inaugurated in Trignac (Loire-Atlantique) in October 2019. With a surface area of 306 m$^2$, the car parking shade comprises 185 PV panels capable of producing around 47 MWh/year, i.e. the equivalent of the annual consumption of 10 households [12]. This installation can cover 33% of the store's electricity needs, rising to 40% thanks to a 40 kWh complementary system of second-life batteries (reused lithium-ion batteries). The remaining 60% of the needs are covered by a contract signed with the alternative energy supplier Enercoop, which will deliver only renewable energy from local sources. Any PV production surplus will be sold to the power grid.


**Figure 1.1-7 PV-powered infrastructure at a GÉMO store [12]**

This PV-powered infrastructure includes an electric charging station under its shade to promote customer involvement. The charging terminal allows two EVs to be connected at the same time. However, the owner of the charging infrastructure did not report data on the PV power and PV energy used to charge EVs.

*1.1.2.2 PV-powered infrastructure at Nouméa-La Tontouta International Airport, New Caledonia*

In February 2020, the government of New Caledonia authorized the commissioning of a PV plant on the public airport domain at La Tontouta. This decision followed the government's call for projects to build and operate innovative PV power generation facilities. The purpose of this installation is not specifically the charging of EVs, and only two EV charging terminals are implanted, meaning that most of the power generated will be injected into the grid.

**Figure 1.1-8 Nouméa-la-Tontouta International Airport, New Caledonia [13]**

This PV-powered installation has a total power of 3 MWp and features two main components [13]:

- PV car parking shades covering 8 000 m² of the airport's public parking lot (i.e. 90% of the parking lot covering 517 spots) (Figure 1.1-8);
- Ground-based plant on unoccupied land (17 000 m²) inside the airport concession.

Overall, 4 654 MWh is expected to be produced annually, equivalent to the annual electricity consumption of 4 390 inhabitants of New Caledonia. Work on the PV plant was scheduled to start in early 2021 for commissioning in the second quarter of 2021. In conclusion, Table 1.1-3 presents key figures for the project.

**Table 1.1-3 Key figures for the project**

| | |
|---|---|
| Installed PV power | 3 MWp |
| Theoretical annual PV production | 4 654 MWh |
| Total number of PV panels | 7590 |
| Total surface covered by PV panels | 8 000 m$^2$ of PV shades + 17 000 m$^2$ of ground-mounted PV power plant |

### *1.1.2.3 Car park entirely covered by car parking shades in Saint-Aignan-de-Grandlieu, France*

In February 2020 Urbasolar and the Charles André Group, a company specializing in transport, inaugurated a 9.8 MWp PV power plant covering an entire car park at Saint Aignan de Grandlieu in Loire-Atlantique and providing protection for parked vehicles [14]. The car parking shades (shown in Figure 1.1-9) comprise more than 32 000 PV panels covering a surface area of 53 000 m$^2$, and will produce 10 070 MWh each year. This platform was not specifically designed for charging EVs, and therefore redistributes energy by injection into the power grid.

Drawing on its technical expertise on logistics sites, Urbasolar designed, developed, and built this PV power plant with regard to the constraints of the platform and the site's exposure and with the aim of optimizing performance. The plant will be operated from Urbasolar's monitoring center in Montpellier.

**Figure 1.1-9 Transport Baudron GCA car park, Saint Aignan de Grandlieu [14]**

The car park is unofficially known as the “PV power station”, because it is intended to cover the entire annual consumption (excluding heating) of Saint Aignan de Grandlieu (4 000 inhabitants).

*1.1.2.4 PV rooftop plant for a Robinson shopping mall in the province of Chonburi, Thailand*

Completed in 2018, the Robinson Chonburi PV rooftop plant is the third PV rooftop plant built by ASSYCE Asia for a Robinson shopping mall (Figure 1.1-10). It is located in the province of Chonburi and has an installed PV power of 999.3 kWp [15]. This installation provides only one EV charging terminal for customers, and most of the PV production is used to supply the shopping mall itself. This power plant is expected to generate more than 1 587 MWh/year of PV energy. We do not know whether this project incorporates a storage system.

**Figure 1.1-10 PV rooftop plant for a Robinson shopping mall in Thailand [15]**

*1.1.2.5 PV self-consumption project in Madagascar*

Cap Sud Madagascar, a subsidiary of the Cap Sud Group, financed and commissioned in October 2018 the first PV self-consumption system in Madagascar. The Kube project includes a 410 kWp PV power plant coupled with 1.1 MWh of battery storage [16].

The installation has an intelligent energy management system. It is located in the Galaxy Andraharo business zone in Antananarivo and supplies the Kube A, B, C, and D buildings with PV energy, 2 200 $m^2$ of whose roofs are covered with 1 064 PV panels with 385 Wp unit power, for a production of electricity expected to be around 600 MWh (Figure 1.1-11). All the buildings have 70% energy autonomy. The PV plant with storage (some 700 Lead Gel 2 V 800 Ah batteries) can supply the premises from 7 am to 10 pm and provide an emergency power supply role in the case of power cuts in the public grid.

**Figure 1.1-11 PV self-consumption project in Madagascar [16]**

Madagascar has neither gas nor oil as natural resources, but has a lot of sunshine, which the Cap Sud Group believes could make it energy self-sufficient. This PV infrastructure was not designed to recharge EVs, but it stores and then redistributes energy to buildings and to the power grid.

### *1.1.3 Synopsis of the projects featured above*

Table 1.1-4 provides a brief synopsis of the different infrastructures described above.

**Table 1.1-4 Summary of PV-powered infrastructures and their characteristics**

<table>
<tr><td colspan="5">Infrastructures designed mainly for charging EVs</td></tr>
<tr><td colspan="3"></td><td>Infrastructure</td><td>Comments</td></tr>
<tr><td rowspan="4">On-grid</td><td rowspan="4">With storage</td><td rowspan="4">Car parking shade</td><td>MDT-TEX smart PV shelter (Germany, 2018)</td><td rowspan="4">✓ Possibility of shifting the charging without constraining EV users<br>✓ Reduction of the load on the grid during peak hours<br>x Power grid dependency: the storage systems are charged from the power grid<br>x Installations remain insufficient for full charging</td></tr>
<tr><td>SECAR E-Port (Austria, 2018)</td></tr>
<tr><td>V3 Superchargers (Las Vegas, United States, 2019)</td></tr>
<tr><td>Car parking shade project (Aix-Marseille-Provence, France, 2020)</td></tr>
<tr><td rowspan="4">Off-grid</td><td rowspan="2">With storage</td><td rowspan="2">Car parking shade</td><td>Electric bus charging (Queensland, Australia, 2020)</td><td rowspan="2">✓ Grid independent and 100% sustainable<br>x Low stationary storage capacity compared to the EV battery capacity<br>x Installations remain insufficient for full charging</td></tr>
<tr><td>EV ARC™, Beam Global, San Diego, United States, 2020)</td></tr>
<tr><td rowspan="2">Without storage</td><td rowspan="2">Car parking shade</td><td>SEVO Sunstation (United States, 2019)</td><td>✓ 100% renewable energy<br>✓ No utility bill<br>✓ Real-time energy use analytics</td></tr>
<tr><td>Fastned</td><td>✓ 100% renewable energy<br>✓ Fast charger: Up to 300 km of autonomy in 15 minutes</td></tr>
<tr><td colspan="5">Infrastructures designed mainly for supplying buildings, but EV charging may be developed</td></tr>
<tr><td colspan="3"></td><td>Infrastructure</td><td>Comments</td></tr>
<tr><td rowspan="2">On-grid</td><td rowspan="2">With storage</td><td>Car parking shade</td><td>Self-consumption PV, GÉMO store (Trignac, France, 2019)</td><td rowspan="2">✓ Reduction of the electricity bill<br>✓ Self-consumption<br>✓ Electricity can be sold where PV production is high<br>x Despite the size, low number of charging terminals</td></tr>
<tr><td>Building roof</td><td>PV self-consumption project (Madagascar, 2018)</td></tr>
</table>

| | | | | |
|---|---|---|---|---|
| | Without storage | Car parking shade | PV power plant (Nouméa-La Tontouta International Airport, New Caledonia, 2021) | ✓ Redistribution of energy to power grid<br>✓ Self-consumption<br>x No smart consumption to optimize energy use<br>x Despite the size, low number of charging terminals |
| | | Building roof | PV rooftop plant for a Robinson shopping mall (Thailand, 2018) | |
| Off-grid | Without storage | Car parking shade | PV power plant (Saint Aignan de Grandlieu, France, 2020) | |

It will be remarked that most of these infrastructures, in particular the smaller ones, have slow charging terminals. The V3 Superchargers in Las Vegas and the Fastned installations are equipped with ultra-fast chargers (250 kW and 150 kW, respectively). These ultra-fast chargers significantly reduce charging time but are dependent on the electricity grid, which increases the cost of charging and fails to deliver the full benefits of PV. Where a large number of EVs are charging simultaneously it can also negatively impact the electrical distribution network, possibly causing a consumption peak that exceeds the capacity of the grid.

### *1.1.4 Conclusions*

Our inventory of PV charging stations and parking areas with overhead PV shows that these installations have been in existence for several years. The PV-powered infrastructures presented are generally equipped with charging stations; this is especially the case for smaller infrastructures. So far, however, the larger infrastructures, despite their size, only comprise a few EV charging terminals, and most of the power generated is fed into the grid or consumed by buildings. From our desk research it would appear that these installations are often not coupled to a storage system. Some infrastructures equipped with storage exist, but the storage is often charged by the power grid rather than by the PV system. Consequently, these infrastructures are not necessarily managed by an intelligent energy management algorithm that could optimize the power flow in accordance with the particular constraints of the storage and the grid. At present not many PV installations are able to fully meet the energy needs of EVs, and the charging of EVs in most of the installations listed in this overview is dependent on the public grid.

The deployment of EV charging infrastructures creates new opportunities and attracts (new) actors in mobility, renewable energy and infrastructure. However, the availability of new business models is still too limited to accurately predict the financial profitability and economic benefits for the different actors. In addition, the variability of actors along the EV charging value chain and their adoption of different business models make it very difficult to identify the most suitable business models.

This interim report for ST2 of IEA PVPS Task 17 will therefore focus on the following:

- Requirements, barriers, and solutions for PV-powered infrastructure charging stations;
- Feasibility conditions: technologies, (sub)urban implementation;
- New V2X services linked to PVCS;
- Survey concerning the social acceptance;
- Methodology to compare PV-powered infrastructure and grid-powered infrastructure.

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## 1.2 Case study: PV-powered infrastructure for EV charging at SAP Labs Mougins, France

In this section, a PV-powered charging station based on real data is presented. This case study concerns EV charging at a workplace involving a power management software application and parking time management.

SAP Labs France, a subsidiary of the multinational software company SAP SE, has an interest in electromobility, and has launched a series of policy initiatives to encourage and accelerate the energy transition, particularly in relation to electromobility.

The objectives of the Green Deal commit Europe to becoming the first carbon neutral continent by 2050. A number of funding measures are being put in place for the deployment of cleaner and more affordable private and public transportation. Road traffic, which represents 30%, is one of the main causes of $CO_2$ emissions. The Green Deal roadmap estimates that by 2025 the EU will require more than 1 million public charging stations to service the 13 million EVs expected to be in circulation by then. The challenges are therefore clear: with a significant increase in EVs and charging stations, the public grid will have to be able to support this growing consumption. This is the context in which SAP Labs France is currently developing software to manage and optimize peak power consumption, which has also focused the company's attention on the importance of installing PV panels to generate green energy to help offset its use of the public grid.

As its own fleet of EVs grows in size, SAP Labs plans to increase its PV energy production by installing PV car parking shade devices at the end of 2021. PV panels make a significant contribution to reducing consumption peaks created by charging terminals.

### *1.2.1 Demonstrator site technical description*

The SAP Labs France site is located in the south of France, in Mougins. This region has 2 694 hours of sunshine per year with an average temperature of 16 degrees.

#### *1.2.1.1 Delivery points*

The site is divided into three different zones: *North*, *South*, and *Building*. Each zone has a power delivery point with a specific power meter monitoring consumption by charging stations, heat pumps, and within the building. Energy production comes from PV panels combined with a stationary storage based on electrochemical batteries. Table 1.2-1 and Figure 1.2-1 give an overview of the site's consumption and production capabilities.

**Table 1.2-1 Delivery points**

| Delivery point SAP | | | | |
|---|---|---|---|---|
| Location | Power provider subscription | Connected consumption assets | Power consumption assets | Power production assets |
| North | 200 kVA | 10 charging points at 7 kW each<br><br>Heat pumps 200 kW | 70 kW total charging points<br><br>200 kW | 0 |
| South | 250 kVA | 24 charging points at 22 kW each | 528 kW total charging points | 0 |
| Building | 240 kVA | 2 charging points at 50 kW<br><br>1 charging points at 150 kW with 2 electrical outlets<br><br>Building appliances | 250 kW total charging points<br><br>60 kW (building) | 80 kW PV<br><br>150 kWh Battery |


**Figure 1.2-1 PV-powered demonstrator of SAP Labs France**

It will be remarked that for each zone the power subscription is lower than the theoretical maximum power demand. The power demand is managed through an algorithm that seeks to ensure smart EV charging without incurring additional costs.

*1.2.1.2 EV supply equipment*

Parameters taken into account for the 17 different types of EV being tested include battery capacity, maximum charging current, and whether the EV can receive a one-phase or a three-phase electric charge, the aim being to adapt the charging mode according to their individual characteristics. Moreover, 30 charging terminal devices are in operation in the laboratory and on the site. The objective is to record charging data for different EVs and different terminal devices.

*1.2.1.3 PV system*

The objective of self-consumption involves harnessing any available surface area on the roof or on the ground that receives a significant amount of solar energy every day by installing PV panels (Table 1.2-2). When power is consumed, electricity from the PV panels is always chosen in preference to electricity drawn from the grid, which means that all the production that can be consumed on site will be consumed. Any surplus demand will be met from the grid.

**Table 1.2-2 Technical description of the PV panels**

| Roof | |
|---|---|
| Optimal inclination | 10° |
| Orientation | East-West |
| Total roof area | 768 m² |

| | |
|---|---|
| Total PV area on the roof | 428 m² |
| Panel type | Monocrystalline Voltec |
| Number of panels installed | 252 |
| Peak installed power | 80 kWp |
| Estimated annual production at installation | 78 080 kWh |

The total PV production in 2020 was 57 000 kWh, while SAP Labs' total electricity consumption was 634 082 kWh.

Since the PV panels are connected to the building's delivery point, the assets consuming most electricity, i.e. the "fast charger" charging points, are connected to this delivery point. For 2020, the "fast chargers" consumed 49 442 kWh, which represents 10.42% of the total energy consumption by the building, and 86,73% of the PV energy produced on site (Figure 1.2-2). It should be noted, however, that because of the pandemic, consumption both by the building and through EV charging was lower in 2020 than in "normal" years.

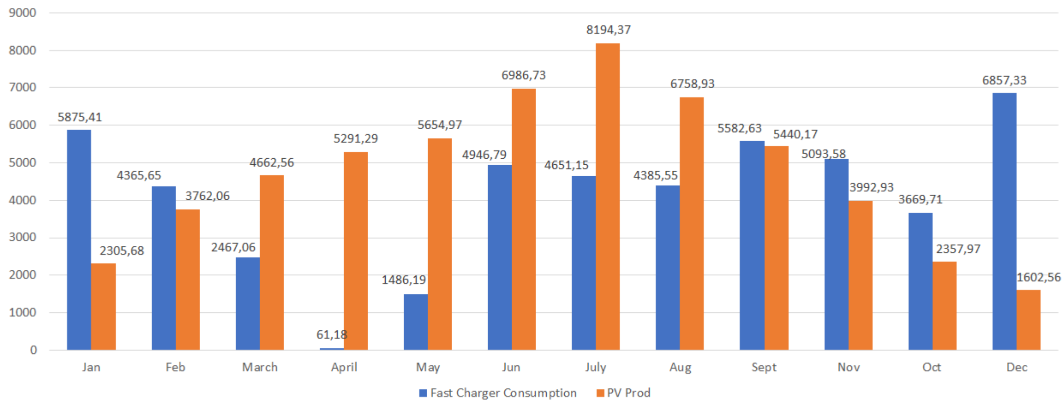


**Figure 1.2-2 SAP Labs France fast chargers' consumption and PV production for 2020**

*1.2.1.4 PV car parking shades*

As part of the move towards carbon neutrality by 2025 the objective is to continue to increase PV production. Therefore, it was decided to install PV car parking shades for real-time self-consumption, as presented in Table 1.2-3.

**Table 1.2-3 Technical characteristics of the car parking shades**

| Car parking shades | Power | PV panels |
|---|---|---|
| 4 parking spots: 50 m² | 9,3 kWp | 30 PV panels monocrystalline Voltec |
| 8 parking spots: 100 m² | 18,6 kWp | 60 PV panels monocrystalline Voltec |

The PV installation energy management system is able to limit the PV production when required. By restricting the PV production in real time, according to consumption as well to the storage capacity, there is no injection into the public grid, in compliance with the objective of energy self-consumption.

#### *1.2.1.5 Battery storage*

SAP Labs France installed a 150 kWh stationary storage (second-life batteries) to meet four different scenarios detailed above:

1. PV production at weekends: Since the offices of SAP Labs France are not open during the weekend, the electricity consumption at the point of delivery is greatly reduced. The goal is therefore to store the energy produced by the PV panels during the weekends and use it during the peak energy demand on Monday mornings.
2. Charging peak shaving: given the peaks in energy demand for charging being between 8:00 am and 9:00 am on Mondays and 4:00 pm and 5:00 pm on Fridays, a solution was required to smooth these peaks while allowing a sufficiently rapid charge.
3. Public grid peak hours / off peak hours: The e-Mobility smart grid solution can also take account of off-peak hours / peak hours determined by the electricity supplier: e-Mobility can schedule charging times according to the availability of off-peak hours, helping to optimize available grid capacity.
4. Energy provider flexibility: SAP Labs France is currently testing the flexibility that the stationary storage can bring to the grid, and the electricity provider is actively participating in this process.

### *1.2.2 e-Mobility*

e-Mobility is a software package that provides supervision of charging infrastructures for EVs. It allows a better management and a better distribution of the charging infrastructures. Its smart charging algorithm is designed to optimize energy costs and power demand by the charging terminals, and to ensure an equitable distribution. e-Mobility is also available as a smartphone app, which provides real-time monitoring with email and text alerts, and it is fully compatible the SAP environment (SAP Hybris Billing, Stripe) and other roaming platforms.

#### *1.2.2.1 Push Notifications*

The e-Mobility software gives EV fleet managers and charging station managers an overview of how charging stations are being used, and it facilitates the management of the infrastructure. Via the application the end user can start the charge, receive information about the remaining charge time, and receive notifications when charging is complete. Notifications are a real asset when seeking to optimize the turnaround time of EV charging and to free up the terminals more quickly. Administrators can track the idle time per user directly on the interface, applying filters to check the most inactive users. e-Mobility supervision also allows the EV fleet manager to centralize data and to access some functions directly from the tool. Managers therefore have information on the different charging profiles, enabling them to remotely restart terminals, stop the charging of certain terminals, etc.

#### *1.2.2.2 Integration with third parties*

One advantage of the e-Mobility software is that it can be integrated with software applications commonly used in the business world, not only with SAP products, but also with a number of non-SAP applications, in order to cater to a variety of customers (Figure 1.2-3).

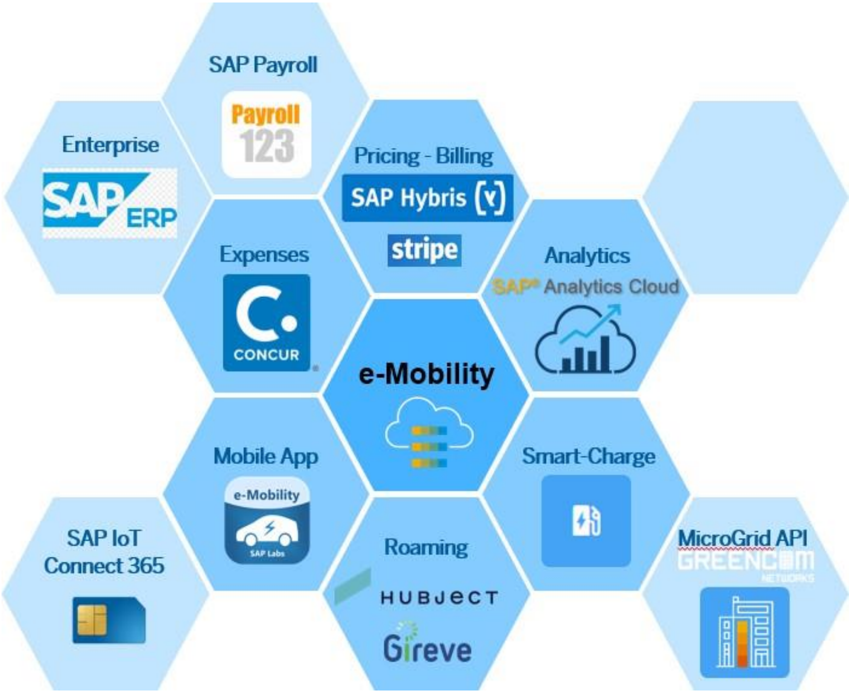


**Figure 1.2-3 Stakeholders linked to e-Mobility**

Legend:

- SAP Payroll: payroll software;
- Enterprise: software for business resource scheduling;
- Expenses: software that allows employees to submit their expense reports;
- Pricing & Billing: e-commerce management software provider;
- Analytics: data visualization software (business intelligence);
- Smart-Charge: algorithm allowing 4 different scenarios;
- Smart-Grid: Building energy management system for monitoring multiple assets;
- Roaming: marketplace that connects e-Mobility service providers and charging point operators.

#### *1.2.2.3 Smart Charging*

The growing number of EVs poses a major challenge for an undersized electricity network that lacks infrastructure for charging EVs. Where demand cannot be met adequately, the quality and stability of the network may suffer, network outages may occur as well as transmission losses due to overheating, and neighboring networks may also be adversely affected. The imperative to handle increasing charging demand calls for innovative solutions. SAP has chosen to focus on smart charging as a mitigating strategy. Four objective function components are employed [1] (Figure 1.2-4):

- minimizing energy costs according to intraday market prices;
- minimizing peak demand through system usage fees determined by the highest consumption peak;
- minimizing load imbalance by addressing unbalanced electricity consumption between the three phases;
- maximizing a *fair share* component addressing inequalities between the final state of charge (SOC) of individual EVs.

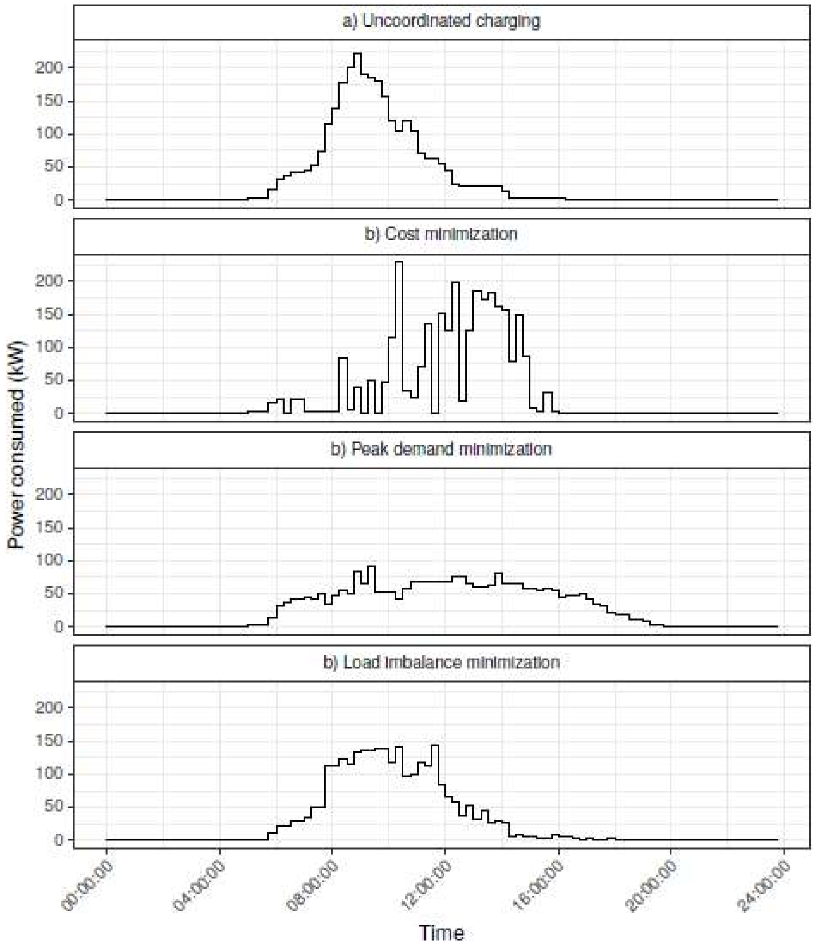


**Figure 1.2-4 Power consumed [1]**

Figure 1.2-4 shows that the peak activity time is shortly after 8 a.m., i.e. when employees are arriving at the office. This period is therefore the most precarious for the electricity network, and it is this period that will have to be optimized as a priority by the algorithm.

To develop the algorithm, peaks of charge during the week were first measured, confirming an initial hypothesis that these peaks would occur on Monday mornings at 8:00 am (weekend return) and Friday evenings (start of the weekend) were confirmed. The local recording of the total of transactions highlights that Mondays represent 21.17% of the total weekly consumption of the charging terminals, and Fridays 25.19%.

#### *1.2.2.4 Cost minimization component*

This concerns the minimization of energy cost in relation to the electricity tariff. In France, this optimization is easier to implement because the provider determines in advance the off-peak and peak hour rates. If users wish to adjust the use of a charging terminal according to the electricity tariff, they can simply enter the data provided by the provider in the software and the algorithm will establish a load plan for the automatic management of the terminal. On the SAP Labs site, the objective is to link the use of stationary storage to the provider's electricity price and to reinject stored PV production during peak hours.

#### *1.2.2.5 Peak shaving component*

This concerns the optimization of peaks according to the total power of the network available on site. The maximum power allocated to the site is known, and corresponds to an amount stipulated in the contract drawn up with the electricity provider; this is an input in the software, allowing the algorithm to intelligently manage the load on each load point according to the remaining available power. The contracted maximum power is therefore never exceeded.

#### *1.2.2.6 Load imbalance component*

The power network operators who run flexible AC transmission systems for the long-distance transport of electricity generally seek to minimize load imbalance. Whenever there is significant imbalance between the three phases of AC power, the operators must take measures, such as via unified power flow controllers, to reduce this imbalance in order to prevent damage to power transformers. Operators require consumers to help reduce load imbalance. On the consumers' side, imbalance between the three phases is caused, for example, by EVs that do not charge evenly on three phases. Plug-in hybrid EVs often charge using 16 A (3.7 kW) on a single phase. A large number of plug-in hybrid EVs charging on a single phase can thus lead to a large load imbalance.

#### *1.2.2.7 Fair share component*

"Fair Share" refers to the distribution of consumption between cars. The idea in e-Mobility is to divide the electricity consumed by charging vehicles in an equitable manner, and this means taking into account the number of cars connected to the different charging terminals. The fewer cars connected to a terminal, the faster they can be charged without worrying about the effect of a potential consumption peak on the infrastructure. We will use the example of a 150 kW DC fast-charging station to illustrate how e-Mobility can optimize power peaks in relation to EV state of charge (SOC), the electric power allocated by the station, and the network power limit.

Figure 1.2-5 presents the example of an EV (user 1) connected to the 150 kW charging point; as illustrated, the charging point's power is limited by the network power. Because of this limit, when a second EV (user 2) connects to the same charging point the algorithm decreases the power in order to avoid consumption peaks. The red curve shows that at the start user 1 is charging at 150 kW, then at 5:50 p.m., the available power decreases to 75 kW and the allocated power (blue curve) follows this power decrease call because user 2 has connected to the second electric outlet of the charging point.

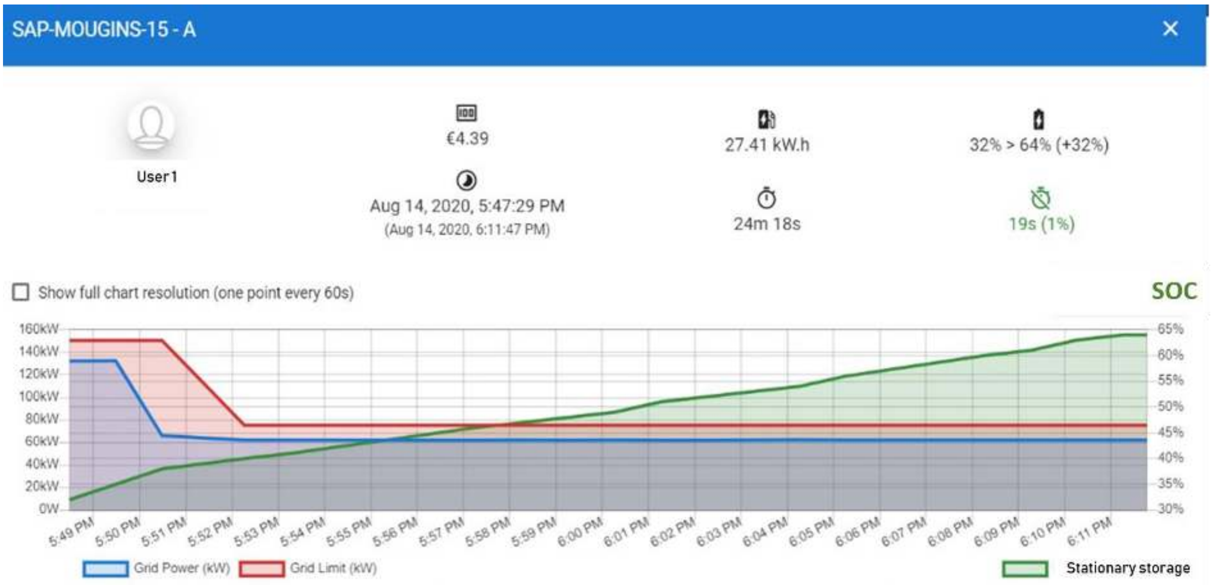


**Figure 1.2-5 User 1 - peak load optimization**

Figure 1.2-6 shows how user 2 is immediately limited to a charging power of 75 kW. This is mainly to protect the electricity network. Without this protection it would be necessary to invest in additional electricity infrastructure.

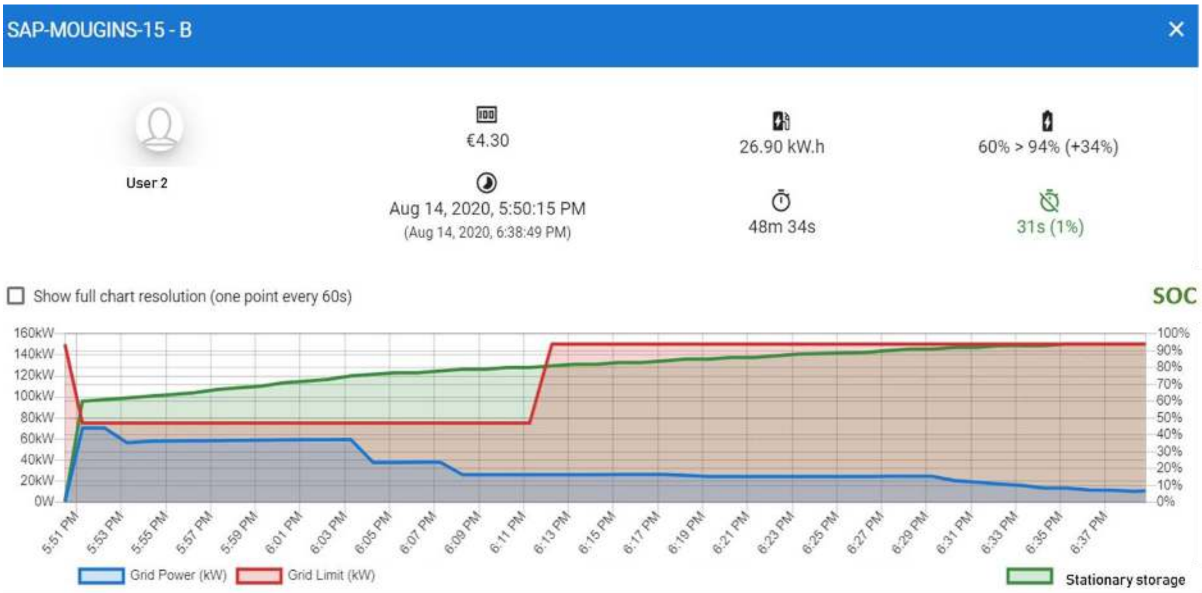


**Figure 1.2-6 User 2 - peak load optimization**

e-Mobility focuses on the energy management and in particular, on the optimized management of PV production. The software will be improved and enhanced over time.

*1.2.2.8 Vehicle-To-Grid*

The operation of public grid flexibility may be based on demand responses, or on strategies such as vehicle-to-grid (V2G), building-to-grid, and vehicle-to-infrastructure. Harnessing public grid flexibility necessarily involves the Internet of Things, which is why it is so important to bring together all the partners involved in the development of solutions.

The next steps in the development of e-Mobility will focus on V2G, using EV batteries as a means of storing renewable energy. Some of this energy may be wasted when it is not used. For example, energy produced at weekends by PV sources on tertiary buildings is often lost because of low electricity consumption at weekends. The e-Mobility software therefore includes the option of storing electricity in the batteries of the EV fleet and reinjecting it into the public grid to support the network when demand is high, or using it in a timely manner according to peaks. The same principle of bi-directionality between the terminal, the EV and the network can be used to reduce the cost of charging by storing energy in the battery during off-peak hours (at night) when demand for energy is low and reinjecting energy into the network when demand is higher during the day.

Charge controlling remains necessary for energy management on the SAP Labs Mougins site. Without this piloting, the total power demand would be higher than the power capacity of the site. PV panels contribute up to 10% of the site's needs. Over time, this share could be increased by increasing the PV surface area by a factor of 3.5. Battery storage of residual energy generated will contribute to the return on investment.

The objective is to create a complete smart grid on the Mougins site, including all the assets that will help to optimize it. When combining all the assets (chargers, battery storage, PV) the return on investment is potentially interesting. Considering each asset alone does not make economic sense. If all the assets are combined, an acceptable return on investment may be obtained. The software allows for intelligent communication between the site and the electricity provider, making battery storage available to the provider for flexibility, and using V2G and frequency regulation.

### *1.2.3 Conclusions*

Charge controlling remains necessary for energy management at the Mougins site. Indeed, without piloting, the total power demand would be higher than the power capacity of the site. PV panels contribute up to 10% of SAP Labs needs. SAP Labs strives to create a complete smart grid at the Mougins site. The software allows for intelligent communication between the operators and the end-users.

## *[References]*

[1] O. Frendo, N. Gaertner and H. Stuckenschmidt, "Real-Time Smart Charging Based on Precomputed Schedules," in IEEE Transactions on Smart Grid, vol. 10, no. 6, pp. 6921-6932, Nov. 2019

# 2 REQUIREMENTS, BARRIERS AND SOLUTIONS FOR PV-POWERED INFRASTRUCTURE FOR EV CHARGING

Combining EV charging stations and PV power is one possible path to sustainable development in today's EV market. EV use worldwide has recently been rising sharply, but the infrastructure of charging stations is still very limited and mostly supplied from the public grid. In this chapter, the requirements, barriers, and solutions for PV-powered infrastructure for EV charging are analysed, from both a technical and an economic perspective, under different conditions of solar irradiance.

The first section presents a technical, financial, and environmental feasibility analysis for PV charging stations for EV with local battery storage in China and in the United States, based on the use of silicon PV modules and a storage capacity of 5 kWh. A model featuring different scenarios over ten years was developed to compute the interactions between PV, storage system, public grid, and EVs in the two countries. The aim was to determine the technical, financial, and environmental consequences of a PV-powered infrastructure for EV charging, by comparing the PV-powered scenario with other scenarios, namely a scenario where EVs are charged exclusively from the grid, and a scenario where vehicles are gasoline-fueled. It was found that the right combination of storage system and PV could provide a feasible EV charging solution as regards electricity balance, $CO_2$ emissions, and economic considerations.

The second section presents the preliminary requirements and feasibility conditions for a PV-powered EV charging station based on a DC microgrid, where the aim is to harness the benefits of PV under two alternative charging modes. In the slow charging mode with power up to 7 kW, charging uses PV energy and stationary storage that is charged exclusively from PV sources. The charge is therefore obtained mainly from PV energy, but the user must accept that charging is long and slow. In the fast charging mode with power from 7 kW to 22 kW, charging uses public grid energy. The advantage of this mode is the reduced charging time, but the user must accept higher charging costs. The benefits obtainable from PV are shown to be greatest where charging is daily rather than weekly, where the slow charging mode is used, and where parking time is known in advance.

The third section assesses the potential role and benefits of better energy management in PV-powered EV charging infrastructures. The proposed management methodology is based on a techno-economic tool for managing and sizing the charging infrastructure. Improved charging station sizing and operating modes can help optimize PV benefits. The proposed methodology can also improve charging station performance through balancing energy use between PV and the public grid according to different weather conditions and charging scenarios. The slow charging mode improves the PV benefits, allowing EVs to be charged mainly with PV energy, reducing the impact on the power grid, and having a lower cost for the user.

## 2.1 Technical, financial, and environmental feasibility analysis of PV-powered infrastructure for EV charging

This chapter[1] assesses the feasibility of PV charging stations with local battery storage for EVs located in the United States and China using a simulation model, which estimates the system's energy balance, yearly energy costs and cumulative $CO_2$ emissions in different scenarios based on the system's PV energy share, assuming silicon PV modules and 5 kWh of storage capacity. Results show that systems located in commercial or office parking lots and used for charging EVs during working hours can be a feasible solution in all locations from a technical, financial and environmental perspective in comparison with not only gasoline-fueled vehicles but also with grid-only charging. PV shares of 50% and 75% are achievable in all locations with PV array sizes in the order of 1 to 1,5 kWp while a 100% PV share is possible but might result in high system costs. Scenarios with PV charging and local storage show emissions reductions of 60%-93% in the USA and 28%-93% in China compared to a gasoline-fueled vehicle.

### *2.1.1 Introduction*

The transport sector is currently responsible for almost a quarter of global energy-related $CO_2$ emissions [1], and there are high hopes on reducing these emissions using EVs, which represent a low-$CO_2$ alternative to internal combustion engine vehicles (ICEVs). Depending on the location, EV use could potentially further reduce $CO_2$ emissions by charging with a renewable energy source such as PV. This could also have added benefits such as reducing risk of local grid overloading, providing self-sufficiency and increasing energy self-consumption [2], [3]. Adding BESS (battery energy storage system) to these charging stations will increase the share of solar energy supplied to EVs while increasing the grid's resilience to the intrinsic intermittency of PV power [4], [5].

While there exist several studies in literature analyzing the performance of PV-powered vehicle charging stations [3], [6], [7], few of them have assessed the financial and environmental impact that these systems could have in practice. This is particularly important considering the influence a given location has on aspects such as irradiance, electricity prices and $CO_2$ emissions per kWh generated by the local energy mix, which can be decisive in determining the feasibility of installing a PV charging station.

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[1] This chapter is based on the following publication: Sierra, A., Gercek, C., Geurs, K. and Reinders, A.H.M.E., "Technical, Financial, and Environmental Feasibility Analysis of Photovoltaic EV Charging Stations with Energy Storage in China and the United States," in IEEE Journal of Photovoltaics, vol. 10, no. 6, pp. 1892-1899, Nov. 2020, doi:10.1109/JPHOTOV.2020.3019955.

To this end, a model was developed to analyze these aspects in an interdisciplinary manner; this model has been published in the Progress in Photovoltaic journal [8]. In our previous work we analyzed the feasibility of PV charged EVs in two locations in Europe (Norway and the Netherlands) as well as in Brazil and Australia. This study will add to these results by exploring the potential of stationary PV charging of EVs in two locations in the United States (San Francisco and Chicago) and two in China (Guangzhou and Xi'an). With 1,1 and 2,3 million units respectively, these two countries had the largest numbers of EVs in 2018, which represented over 60% of the global EV stock [9], making them interesting locations for the deployment of PV charging stations. Due to their geographic dimensions and the expected variability in conditions such as irradiance and system costs, two different cities in each country are studied to give a clear representation of the feasibility of these systems. Table 2.1-1 shows the horizontal and in-plane irradiance at each of the selected locations.

**Table 2.1-1 Locations selected for the present study [10]**

| Location | Coordinates | GHI [kWh/m$^2$] | Optimal Tilt [°] | In-plane irradiance* [kWh/m$^2$] |
|---|---|---|---|---|
| San Francisco | 37,78 -122,42 | 1 810 | 35° | 2 110 |
| Chicago | 41,88 -87,62 | 1 440 | 35° | 1 640 |
| Guangzhou | 23,13 -113,26 | 1 430 | 21° | 1 490 |
| Xi'an | 34,35 -108,94 | 1 410 | 33° | 1 580 |

## 2.1.2 Method

### *2.1.2.1 EV feasibility model*

A feasibility model has previously been developed by the authors to analyse the interactions between a PV system, an EV and the local grid (with the possibility of adding a local battery storage system) in order to determine the system's global energy balance, yearly cash flows and cumulative emissions within a specific time frame (Figure 2.1-1). In addition to the PV vehicle charging system, a grid-charged EV and a gasoline-fuelled ICEV are also modelled as a reference [8].

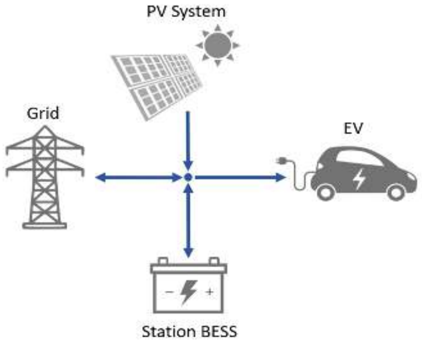


**Figure 2.1-1 System configuration for a PV-powered EV charging station with local energy storage**

The model assumes EV properties similar to those of a Nissan Leaf, which is used for commuting during weekdays, travelling a given distance during a fixed time span. In order to match the times at which PV production takes place, the charging system is assumed to be a silicon PV system installed in commercial or office parking lots where users park and charge their vehicle during working hours (9:00 am – 5:00 pm). The charging point operates at 6.6 kW (see Table 2.1-2) corresponding to a Level 2 charger.

**Table 2.1-2 Feasibility model input data**

| Location: | San Francisco, US | Chicago, US | Guangzhou, China | Xi'an, China |
|---|---|---|---|---|
| Technical Submodel | | | | |
| EV Battery Capacity (kWh) [11] | 30 | | | |
| EV Charging Power (kW) [11] | 6,6 | | | |
| EV Energy Consumption (kWh/km) [11] | 0,174 | | | |
| ICEV Efficiency (L/km) [12] | 0,072 | | | |
| Average driving distance (km/day) [13][14] | 26 | 32 | 28 | 26 |
| Average in-plane irradiance (kWh/$m^2$.year) [10] | 2 110 | 1 640 | 1 490 | 1 580 |
| Yearly PV Degradation Rate [15] | 0,5% | | | |
| Economic Submodel | | | | |
| Base Fuel Price (USD/L) [16][17] | 0,99 | 0,82 | 1,03 | 1,03 |
| Electricity Price (USD/kWh) [18]-[19] | 0,26 | 0,05 | 0,07 | 0,07 |
| Sellback Rate* (USD/kWh) [20]-[21] | 0,03 | 0 | 0.03 | 0,03 |
| PV Cost (USD/kWp) [22]-[23] | 1 280 | 1 280 | 1 010 | 1 010 |
| Storage Cost (USD/kWh) [24] | 990 | 990 | 990 | 990 |
| Discount Rate | 5% | | | |
| Environmental Submodel | | | | |
| Grid Footprint (g $CO_2$-eq/kWh) [25]-[26] | 239 | 577 | 910 | 1 180 |
| PV Footprint (g $CO_2$-eq/kWh) [27] | 21 | 26 | 26 | 26 |
| WTW Gasoline Footprint (g $CO_2$-eq/km) [28] | 178 | | | |
| Storage Footprint (g $CO_2$-eq/Wh) [29] | 110 | | | |
| Project Lifetime (years) | 10 | | | |

PV Geographical Information System (PVGIS) software datasets with hourly solar irradiance values for a period of one year are used as the main input for estimating PV production, followed by an estimation of the hourly SOC for the EV and the BESS as well as the system's expected exchange with the grid. Regarding the station's charging operation, electricity is stored in the charging station's stationary battery (BESS) whenever the PV system produces electricity and no EV is plugged in or the car's battery is fully charged (Figure 2.1-2). Grid charging only occurs if the stationary battery is depleted, and the car's battery has reached a depth of discharge of 80%. A mathematical description of this charging algorithm is presented in full detail in our previous work [8]. A charging efficiency of 90% is assumed for both the BESS and the EV battery; grid charging efficiency is also estimated at 90%.

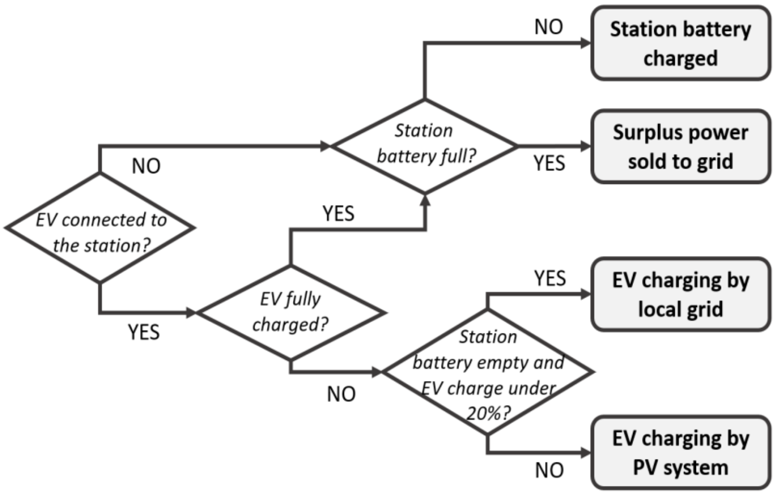


**Figure 2.1-2 Charging algorithm flowchart used in the EV feasibility model**

Economic and environmental indicators are calculated based on this energy balance. The economic analysis calculates an annual cash flow based on investment costs for the PV array and the station's BESS, grid electricity purchases and revenue from electricity sales to the grid. Avoided fuel costs from an equivalent ICEV are also considered a revenue stream in this model; a linear fuel price increase of 6% per year is forecasted in line with historical trends in crude oil prices [30]. The environmental analysis, on the other hand, takes into account the lifetime emissions of the storage system based on its total capacity while the PV and grid emissions are estimated on a kWh basis.

The outputs for the economic and environmental feasibility analysis are also combined to calculate the system's greenhouse gas (GHG) mitigation cost. This indicator is frequently used to compare different strategies for GHG emissions reduction [31] [32], and is defined as the net cost of an emissions reduction measure divided by the amount of emissions avoided (units: USD/ton $CO_2$-eq).

*2.1.2.2 Input Data*

Table 2.1-2 shows the main inputs used by the feasibility model in each of the four selected locations. Four different scenarios are modelled to evaluate the feasibility of a PV charging system at each location, based on different PV/grid energy shares over a year. These scenarios are:

- 100% PV: all generated electricity originates from the PV system.
- 75% PV + 25% Grid: 75% of the generated electricity is produced by the PV system and 25% is supplied by the grid.
- 50% PV + 50% Grid: 50% of the generated electricity is produced by the PV system and 50% from the grid.
- 100% Grid: the EV is only powered by electricity from the grid.

## 2.1.3 Results

Figure 2.1-3 shows the hourly EV charge and grid supply (in kWh) in all four scenarios for a system located in San Francisco. It can be observed that a lower PV share correlates with an increased number of batteries charging cycles, particularly cycles involving deep discharging; this is expected to decrease EV batteries lifetime, showing an additional benefit of EV charging in high-share solar power scenarios. Additionally, it is possible to see how the number of grid charging events (corresponding to peaks in the grid supply curve) decreases as the PV share increases, with the 50% and 75% PV scenarios drawing power from the grid only 14 and 26 times respectively as opposed to the 43 grid charging events required in the grid-only charging scenario. This decrease follows a seasonal pattern as well, as the density of charging events in the summer months is slightly lower than that of the winter months.

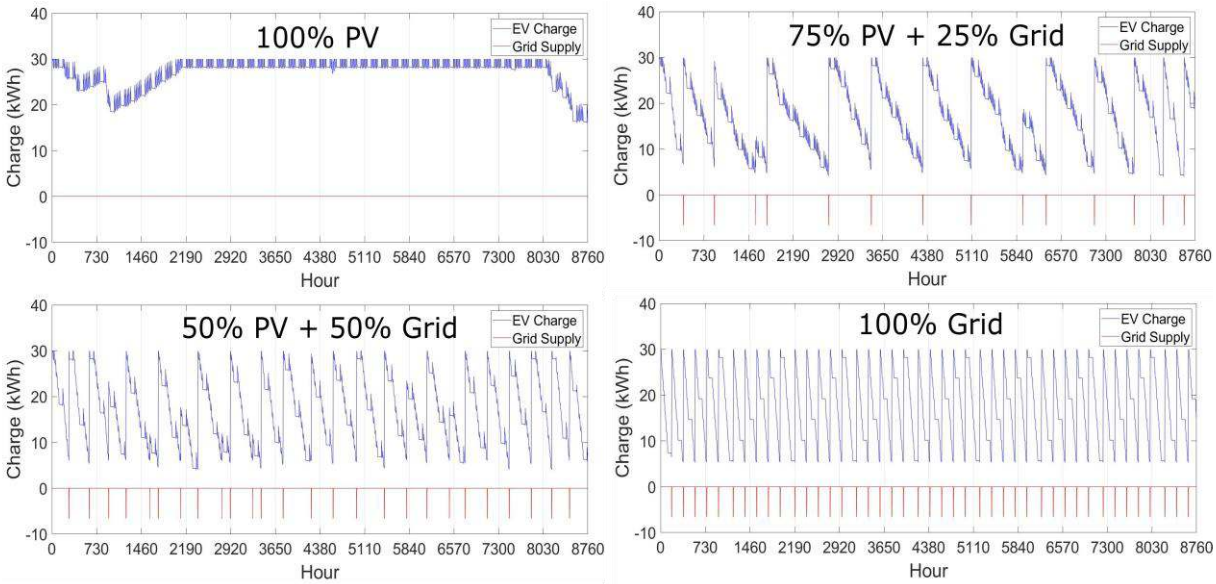


**Figure 2.1-3 Hourly EV charge and grid supply (in kWh) during a 1-year period in San Francisco for each modelled scenario (5kWh BESS)**

This analysis was done in all four locations to show the system's various interactions with the grid depending on each scenario. The required grid charging events for all four locations are shown in Table 2.1-3.

**Table 2.1-3 Number of grid charging events**

| Location | 100% PV | 75% PV + 25% Grid | 50% PV + 50% Grid | 100% Grid |
|---|---|---|---|---|
| San Francisco | 0 | 14 | 26 | 43 |
| Chicago | 0 | 16 | 32 | 52 |
| Guangzhou | 0 | 17 | 28 | 57 |
| Xi'an | 0 | 17 | 25 | 43 |

### *2.1.3.1 Technical feasibility*

The PV array size required to meet the share of PV electricity set by each scenario is shown in Figure 2.1-4. It can be seen that for the set BESS capacity (5 kWh), a 100% PV share can be achieved in all locations with less than 5 $kW_p$ of PV capacity. The required capacity roughly correlates with in-plane irradiance at each location, with Chicago requiring the largest system (4,3 $kW_p$) and San Francisco the smallest (2,2 $kW_p$). The difference in array size becomes significantly smaller for lower PV shares with three locations requiring virtually the same PV capacity for the 75% and 50% PV scenarios.

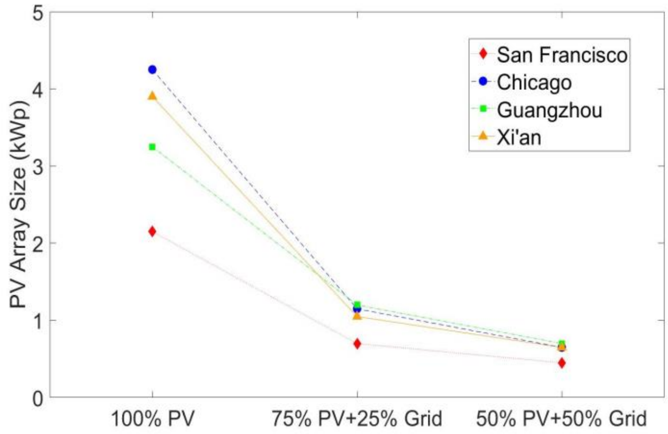


**Figure 2.1-4 Array size required to meet the PV share set by each scenario for a system with a 5 kWh BESS**

Figure 2.1-5 shows the results for charging systems in Chicago and Xi'an as a function of PV and BESS size where in both cases installing just 1 $kW_p$ of PV capacity yields shares higher than 50% regardless of which BESS size is used; storage capacity only has a significant impact for achieving PV shares larger than 75%.

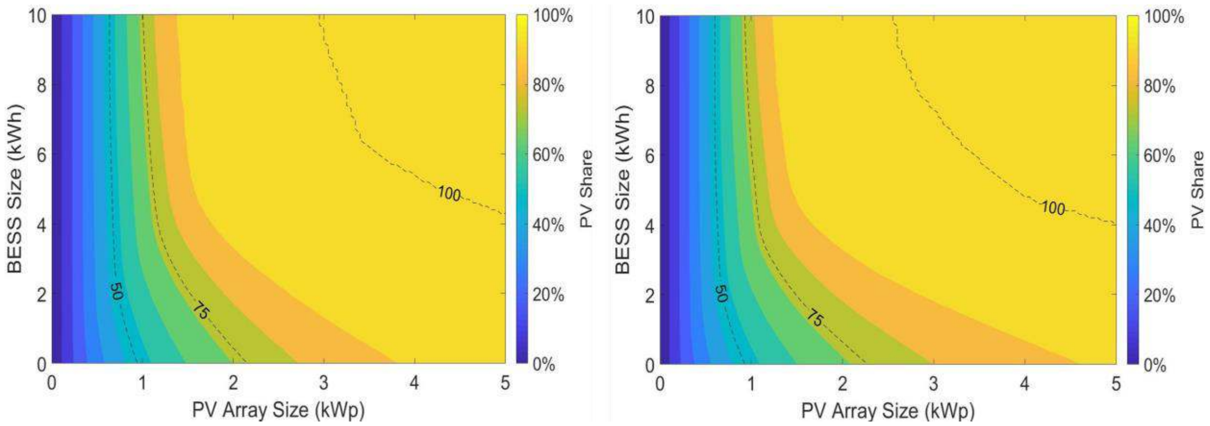


**Figure 2.1-5 Technical evaluation: Contour plots of a charging system located in Chicago (left) and Xi'an (right) showing dotted lines with a constant PV share of 50%, 75% and 100%**

*2.1.3.2 Economic feasibility*

Figure 2.1-6 shows the results of the economic evaluation of a PV charging system with 5 kWh storage at each location over a period of 10 years. In all locations, the highest net present value (NPV) is obtained with grid-only charging, which is likely due to the high investment costs of the storage system. This is clearly seen in systems with no storage (indicated by icons) which have a higher NPV for the 50% and 75% PV scenarios. For instance, a charging station in Chicago with a 5 kWh BESS has a present value of -1 233 USD in a 50% PV + 50% Grid scenario which increases to 3 549 USD if the storage system is removed while maintaining the same PV energy share.

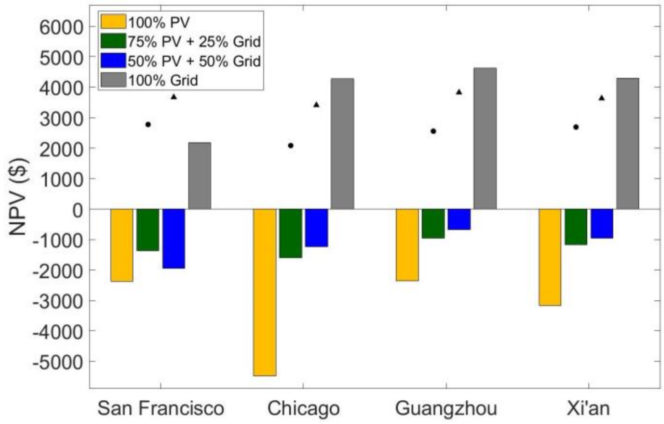


**Figure 2.1-6 NPV after 10 years for a system with a 5 kWh BESS located in each of the four analyzed locations; icons denote results for a system with the same PV energy share and no storage**

The contour plot for a system located in San Francisco presented in Figure 2.1-7 shows that the NPV of a system at this location depends strongly on the BESS capacity. Additionally, PV system size reaches an optimum around 0,8 $kW_p$, which corresponds to the point at which grid imports and exports are equal and maximum revenue is earned according to the net metering scheme used at this location. However, results from a system in Guangzhou (Figure 2.1-7, right) show this is not always the case as the NPV only decreases when the PV system size is increased; this trend was observed in the other two locations as well. Storage costs still have the largest impact on financial attractiveness at this location, with a break-even point reached only at BESS capacities lower than 5 kWh.

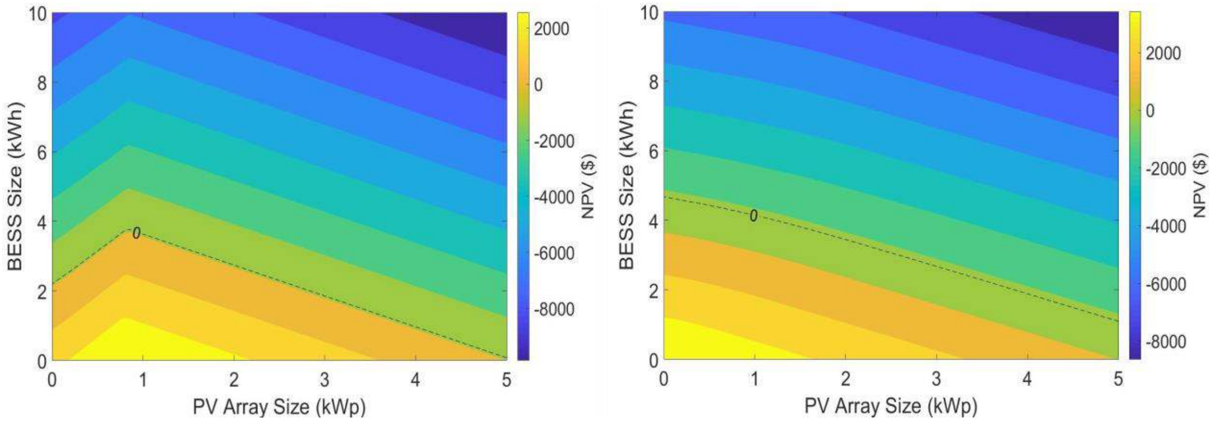


**Figure 2.1-7 Economic evaluation: Contour plots of a charging system located in San Francisco (left) and Guangzhou (right) showing the break-even point (NPV = 0) as a dotted line**

### *2.1.3.3 Environmental feasibility*

The emissions per km travelled for each scenario seen on Figure 2.1-8 show that for 100% PV scenarios emissions can be as low as 12 to 13 g $CO_2$-eq per km travelled. Results also show that in all locations the grid-only scenario has the highest $CO_2$ emissions with grid-charged EVs in Guangzhou (175 g $CO_2$-eq/km) and Xi'an (228 g $CO_2$-eq/km) potentially emitting an equal or higher amount of $CO_2$ than an ICEV (178 g $CO_2$-eq/km). Figure 2.2-9 reinforces this point further, showing that a system in Xi'an requires a PV array of at least 0,5 $kW_p$ to have a lower environmental impact than an ICEV while a system in San Francisco (which has a significantly less $CO_2$-intensive grid) will emit less than 50 g $CO_2$-eq/km in almost all cases. In addition to the impact of the grid mix at each location, it can be seen that despite increasing total system costs, the use of local energy storage reduces total emissions for systems with 50% and 75% PV shares (see Figure 2.1-8); this can be attributed to the avoided emissions from reduced grid purchases being greater than the life cycle emissions from the added storage system.

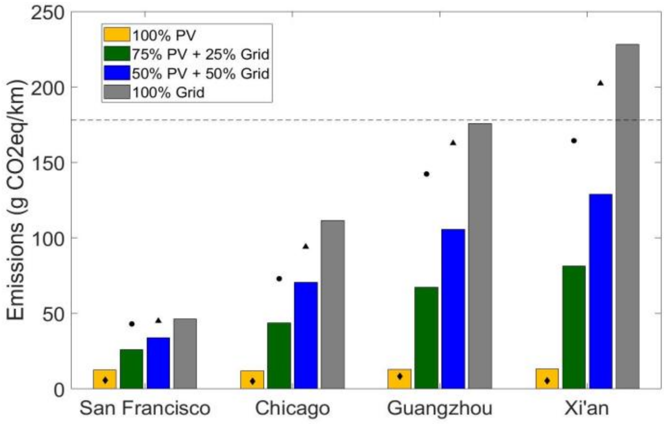


**Figure 2.1-8 $CO_2$-eq emissions per km travelled for a system with a 5 kWh BESS located in each of the four analysed locations; icons denote results for a system with the same PV share and no storage while the dotted line indicates the emissions per km travelled of a gasoline ICEV (178g $CO_2$-eq/km)**

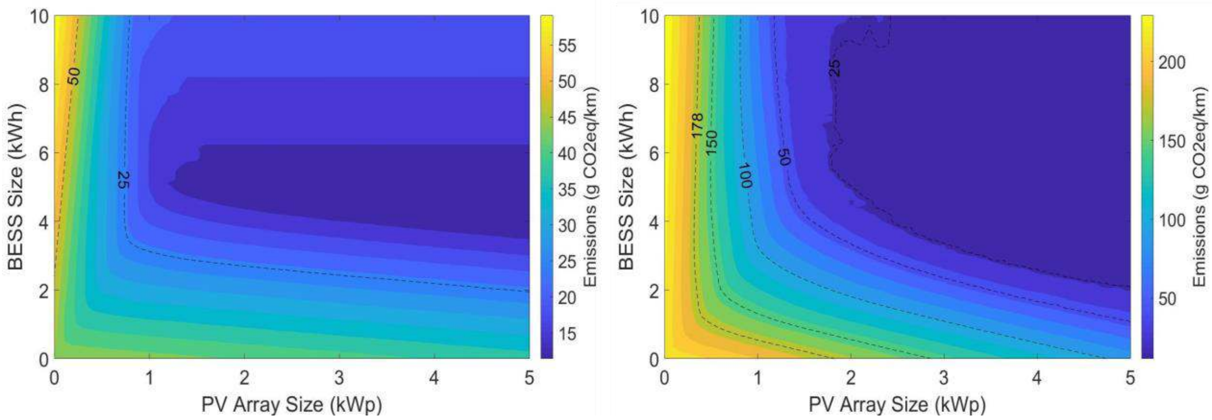


**Figure 2.1-9 Environmental evaluation: Contour plots of a charging system located in San Francisco (left) and Xi'an (right) showing dotted lines with constant emissions of 25, 50, 100 and 150 g $CO_2$-eq/km as well as the average emissions of an equivalent ICEV (178 g $CO_2$-eq/km)**

### *2.1.3.4 GHG mitigation costs*

Table 2.1-4 shows the GHG mitigation costs in each scenario for systems with and without local energy storage; as was the case before an equivalent ICEV is used as a reference for calculating the emissions reduction. It is important to mention that mitigation costs could not be calculated for all scenarios as in some cases PV-powered charging was found to be less feasible while in others a reduction in emissions was not observed.

**Table 2.1-4 System GHG Mitigation Costs (USD/ton $CO_2$-eq)**

| Scenario: | | San Francisco, US | Chicago, US | Guangzhou, China | Xi'an, China |
|---|---|---|---|---|---|
| 5 kWh Storage | 100% PV | 212 | 396 | 196 | 284 |
| | 75% PV + 25% Grid | 131 | 142 | 118 | 179 |
| | 50% PV + 50% Grid | 199 | 134 | 126 | 288 |

| | | | | | |
|---|---|---|---|---|---|
| | 100% Grid | -243 | -771 | * | * |
| No Storage | 100% PV | - | - | - | - |
| | 75% PV + 25% Grid | -303 | -236 | -980 | -3 170 |
| | 50% PV + 50% Grid | -407 | -506 | -3 418 | * |
| | 100% Grid | -243 | -771 | * | * |

- These scenarios required more than 20 kWp PV capacity and were thus considered technically unfeasible.

* GHG mitigation costs cannot be calculated for these scenarios since there was not a reduction in driving $CO_2$ emissions compared to an ICEV.

Overall, PV charging scenarios with local storage have mitigation costs in the order of 120 – 400 USD/ton $CO_2$-eq while grid-only charging scenarios have negative mitigation costs. All systems without local storage have negative mitigation costs as well, meaning that they are “no-regret” options where it is possible to achieve a net reduction in both $CO_2$ emissions and system costs at the same time.

### *2.1.4 Discussion*

The presented results show the importance of an interdisciplinary analysis of emerging technologies like PV charging stations since there are instances for which an improvement in one aspect of the system is detrimental to another one, setting up a trade-off between both aspects, which needs to be resolved. In general, it was found that PV charging of EVs could be a feasible solution in all four locations by achieving significant $CO_2$ emissions reductions at a relatively low-cost using systems with modest PV and storage capacities. The charging stations modelled in four Chinese and American cities had comparable sizes and costs, although there was a more significant difference in environmental performance due to the grid energy mix at each location.

The technical sub-model results show that 50 and 75% PV shares are achievable in all locations with PV array sizes in the order of 1-1,5 $kW_p$ while the 100% PV condition is harder to meet but still possible; this is consistent with our findings for similar systems in the Netherlands, Brazil and Australia [8]. The 100% PV scenario was found to be unfeasible in systems without any local storage, showing that the presence of a BESS is required for fully PV-powered EV charging stations. Additionally, results were found to be sensitive to driving distance, which is the main factor determining total EV demand; for a sensitivity analysis on the model’s response to this and other factors such as the EV battery size and yearly solar irradiance please refer to our previous publication [8]. The assumed driving distances are in some cases based on the Euclidean (“as the crow flies”) distance rather than on the actual network distance which is higher by definition and can vary depending on the location [33].

Despite the observed reduction in system emissions, the financial analysis on most PV charging cases yielded a negative NPV at the end of a 10-year period; this was particularly the case for systems relying entirely on PV electricity since they sell a significant amount of surplus energy to the local grid but only receive a small compensation for it. Storage costs represent a significant share of the total system costs but, while decreasing the size of the BESS or removing it altogether can reduce investment costs, it results in a lower PV share and an increase in total emissions creating a tradeoff between sustainability and cost effectiveness. A possible solution to this tradeoff is installing only a small storage capacity (< 5 kWh) so that a sufficiently high PV share is achieved while keeping investment costs reasonably low. Furthermore, it is worth mentioning that lithium-ion cost figures from 2017 were considered for the current analysis but are expected to decrease further as this technology continues to mature, increasing the financial attractiveness of this type of systems.

The environmental assessment for the grid-only scenario in both Chinese locations highlights the need for coupling EVs with PV in locations with $CO_2$-intensive electricity production, where EV implementation on its own could result in a net increase in generated emissions. With the exception of these cases, PV charging resulted in emissions reductions of 60 – 93% in the US and 28 – 93% in China compared to an equivalent ICEV. These intervals are similar to those previously estimated for similar systems in the Netherlands (38 – 91%), Brazil (83 – 92%) and Australia (18 – 93%) [8].

In order to assess how changes in the carbon footprint of PV systems would impact the results of our model, we carried out a sensitivity analysis comparing the $CO_2$ emission values from Table 2.1-5 (21 – 26 g $CO_2$–eq/kWh) to an additional value quoted from literature, namely 57 g $CO_2$–eq/kWh [34]. Results from this analysis indicate that a 170% higher carbon footprint for PV systems mainly has an effect on the emissions of EVs for scenarios with a high share of PV charging such as 75% and 100% PV charging. For scenarios with 25% PV charging these effects are minor, while for those with 0% PV charging logically no effect is observed. In the worst-case scenarios, for instance in San Francisco, this results in a relative change of 60% corresponding to an increase of only 7 g $CO_2$–eq/km for an EV at 100% PV charging. For $CO_2$ emissions in other locations, this increase is at most 6 g $CO_2$–eq/km. The reason for this comparatively small change is that the $CO_2$ emissions of the total 'PV charging of EVs' system are mainly determined by the $CO_2$ emissions of grid electricity and batteries rather than those of PV systems themselves.

**Table 2.1-5 Overview of feasibility analysis results**

| | | 5 kWh storage | | | No storage | | |
|---|---|---|---|---|---|---|---|
| Location: | Scenario | PV Capacity (kWp) | NPV (USD) | Emissions (g $CO_2$-eq/km) | PV Capacity (kWp) | NPV (USD) | Emissions (g $CO_2$-eq/km) |
| San Francisco, US | 100% PV | 2,2 | -2 380 | 13 | - | - | - |
| | 75% PV + 25% Grid | 0,7 | -1 365 | 26 | 2 | 2 778 | 43 |
| | 50% PV + 50% Grid | 0,5 | -1 948 | 34 | 0.7 | 3 673 | 45 |
| | 100% Grid | 0 | 2 177 | 46 | 0 | 2 177 | 46 |
| Chicago, US | 100% PV | 4,3 | -5 487 | 12 | - | - | - |
| | 75% PV + 25% Grid | 1,2 | -1 590 | 44 | 2.2 | 2 087 | 73 |
| | 50% PV + 50% Grid | 0,7 | -1 233 | 71 | 1 | 3 549 | 94 |
| | 100% Grid | 0 | 4 280 | 112 | 0 | 4 280 | 112 |
| Guangzhou, China | 100% PV | 3,3 | -2 366 | 13 | - | - | - |
| | 75% PV + 25% Grid | 1,2 | -955 | 67 | 2.9 | 2 558 | 142 |
| | 50% PV + 50% Grid | 0,7 | -669 | 106 | 1.1 | 3 828 | 163 |
| | 100% Grid | 0 | 4 626 | 176 | 0 | 4 626 | 176 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Xi'an, China | 100% PV | 3,9 | -3 171 | 13 | - | - | - |
| | 75% PV + 25% Grid | 1,1 | -1 174 | 81 | 2.3 | 2 694 | 164 |
| | 50% PV + 50% Grid | 0,7 | -958 | 129 | 1 | 3 634 | 202 |
| | 100% Grid | 0 | 4 295 | 228 | 0 | 4 295 | 228 |

It is important to note that the $CO_2$ emissions from grid electricity cover direct emissions only while those for PV systems and gasoline are life cycle values. It is also worth considering that, while grid emissions figures from 2014-2015 were used in this study, average grid $CO_2$ emissions per kWh are expected to decrease in the future as large-scale renewable sources are increasingly added to the energy mix. Furthermore, this evaluation does not consider the EV's production and end-of-life phases. Estimating the impact of these phases on the system's generated emissions through an adequate life cycle analysis would further improve the accuracy of the modelled results.

Regarding the presented GHG mitigation costs, it is important to consider that due to the inherent uncertainty in estimating system costs and emissions, mitigation costs should only be compared based on their order of magnitude [32]. Based on this criterion, it can be concluded that systems with PV charging and energy storage in all locations have roughly equivalent mitigation costs while grid-only charging and systems without local storage invariably result in a negative mitigation cost. Other studies have cited GHG mitigation costs for electric mobility in the range of 300 – 1 100 USD/ton $CO_2$-eq [33] and 1 900 – 4 500 €/ton $CO_2$-eq [35] but their focus is on the EVs themselves rather than on charging stations.

### *2.1.5 Conclusions*

The results presented in this study show that with the right combination of BESS and PV array sizes, the use of PV systems in all four analysed locations can be a feasible EV charging solution from a technical, financial and environmental perspective in comparison not only with a gasoline-fueled ICEV, but with a grid-charged EV as well.

- Yearly PV electricity shares of 50% and 75% are achievable in all four locations requiring PV array sizes in the order of 1 to 1,5 kWp. Systems with a 100% PV share would require a larger PV system ranging from 2,2 to 4,3 kWp depending on the location. The use of local storage was found to have a significant impact only for achieving PV shares larger than 75%.
- Grid-only charging scenarios had the highest NPV in a period of 10 years since no investment in a PV system or local storage was needed. In all other cases, the storage cost was observed to have a significantly larger impact than PV costs in the system's economic feasibility. While removing the BESS from the system significantly increases NPV, this comes at the expense of lower self-consumption and an increase in $CO_2$ emissions.
- PV charging stations can reduce the $CO_2$ emissions produced by an EV by 60-93% in the US and 28-93% in China compared to a gasoline-fueled vehicle. This translates to $CO_2$ footprints as low as 12 to 13 g $CO_2$-eq per km travelled in 100% PV scenarios. Grid-only charging in the two Chinese cities on the other hand was found to potentially emit an equal or higher amount of $CO_2$ than an ICEV due to the $CO_2$ intensive grid energy mix at these locations.
- Systems with PV charging and local storage have GHG mitigation costs in the order of 120 – 400 USD/ton $CO_2$-eq while grid-only charging scenarios and systems without local storage have a negative mitigation cost, meaning they are "no-regret" options where it is possible to achieve both a reduction in $CO_2$ emissions and a net financial benefit.

Due to the present scarcity of solar PV charging EV systems, validating these results against real measurements has not been possible; conducting this validation in the future is recommended in order to further support these findings.

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## 2.2 Preliminary requirements for increasing PV benefits for PV-powered EV charging stations

The environmental benefits lie in halting direct air pollution and reducing GHG emissions. In contrast to internal combustion engine vehicles, EVs have zero tailpipe emissions, but their contribution to reducing global air pollution is highly dependent on the source of the energy that they have been charged with. The energy system described in this chapter is a PV-powered EV charging station based on a DC microgrid (MG), and includes stationary storage and a public grid connection as power source backups. The objective is to identify the preliminary requirements and feasibility conditions for PV-powered EV charging stations that can increase the benefits of PV[2]. Simulation results for different scenarios indicate that slow charging with long parking times can increase PV benefits for EVs and may reduce charging costs. For these benefits to materialise, EV users need to be willing to spend more time at the charging station.

### *2.2.1 Introduction*

The environmental and public health impact of EVs is less than that of ICE vehicles, and as such their potential cannot be ignored. The EV market is dominated by China, the United States and Europe [1]. The growth in the number of EVs in circulation requires installing charging stations to respond to the rising charging demand. In 2019, 7,3 million chargers were deployed worldwide, where 90% of these chargers were private chargers, according to the International Energy Agency [1]. The charging of EVs could over time increase the burden on the public grid, as they may increase the peak load, as shown in Figure 2.2-1 left. However, EVs are considered flexible loads. Therefore, the charging of EVs can be controlled and shifted to other times to alleviate peaks. An example is overnight charging, as shown in Figure 2.2-1 right.

[2] This chapter is based on the following publication: S. Cheikh-Mohamad, M. Sechilariu, F. Locment, Y. Krim, “PV-Powered Electric Vehicle Charging Stations: Preliminary Requirements and Feasibility Conditions”, Applied Sciences, vol. 11, no.4, pp 1770, 2021, https://doi.org/10.3390/app11041770.

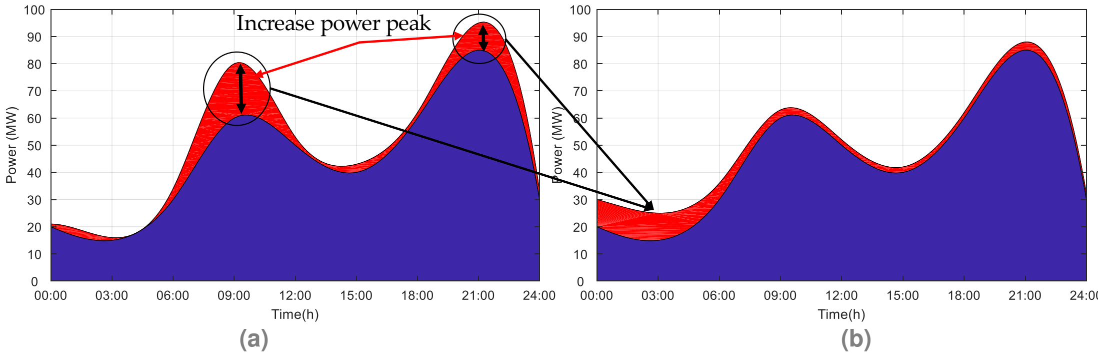



**Figure 2.2-1 (a) EV charging and peak load and (b) Shifted EV charging by overnight charging**

To overcome this grid constraint, the EVs can charge with PV energy which is a reliable and an effective option to reduce the burden on the public grid [2]. Charging EVs with green energy [3,4] may also help the market adoption of EVs since it will help to reduce the impact of transportation on the environment [3,5,6].

Different charging/discharging strategies for EVs exist [7]:

(1) Uncontrolled charging: the EV starts charging immediately until its battery is fully charged or the EV user unplugs the vehicle [8,9,10]. In this case, there is not any interaction between the EV users and the grid. This is the worst scenario since it charges the EV with the maximum power to be fully charged in the shortest time possibly imposing difficulties on the grid [11].

(2) Delayed charging: when the park time (time duration for an EV parked in a station) is longer than the actual required time of charging, therefore, the EV charging can be delayed taking into account the time of use price and can be charged during low-cost periods and off-peak [8,9].

(3) Average charging: the EV is charged at constant power depending on the park time in which the EV is able to meet the requested SOC or full SOC, where it is not necessary to charge with full power [9,11].

(4) Smart charging: the EV user provides the charging station with information regarding the park time and the requested charge that must be supplied before leaving the station. Therefore, the renewable energies are used first to supply the load, then the public grid will control and shape the EV charging profiles and minimize the charging costs [8].

(5) Smart discharging: known as V2G, the EV acts as a stationary storage allowing to discharge power back to the public grid [8]. This will improve the electrical grid efficiency and reliability.

Delayed charging can be considered as smart charging, since it changes the charging start time, charging end time and charging power, while making sure to recharge the EV to the requested level. Also, the average charging can be considered as uncoordinated charging strategy, since it starts charging immediately when the EV is plugged-in but with limited power [11]. The delayed charging profile is similar to the uncontrolled charging profile but the peak load is shifted to overnight/dawn (around 5:00 am and 9:00 am). Whereas, in average charging, the profile is flattened instead of having a peak [9].

Uncoordinated charging of EVs may increase the peak load, imposing heavy burden on the public grid leading to efficiency losses on the grid. In contrast, through smart charging or coordinated charging, EVs can be an asset for the grid by helping to increase penetration of renewable energies, balancing the energy system and improving the efficiency of the system while satisfying EV user demands [12]. Coordinated charging is classified into two types, time coordinated charging and power coordinated charging [13]. In time coordinated charging, the number of EVs that can charge is controlled to insure the total load demand is within the power available for EV charging. Whereas, in power coordinated charging, the power of EV charging is controlled to insure that total load demand is within the power available for EV charging.

The most important parameters in EV modelling are charging/discharging rate, initial SOC, battery capacity, charge depleting distance and user behavior, which are hard to predict in advance. In addition, the arrival time at the charging station, the departure time and the driving distance of the EV are variables, depending on user habits.

But, they can be assumed and they follow probability distribution functions [10,14]. For this purpose, probability distribution functions are generated to determine the arrival time at the charging station, the departure time and the driving distance of the EV. Then, the energy needed to fully charge the EV is calculated and the total charging time of the EV is the energy needed to fully charge the EV over the charging rate [10,14,15].

### *2.2.2 Literature review*

Since the EV market is growing fast, many research studies are expanding in this field, especially on the charging processes for EVs. A home-scale EV charging station based on natural gas has been proposed in [16]. The environmental and financial aspects were compared to a conventional fossil fuel-based vehicle, having the same characteristics and with an EV charged directly from the public grid. It was shown that the EV charged with natural gas has zero carbon emissions coming from the vehicle and that an EV charged by natural gas or electricity is cheaper than oil/petrol over the year.

In [17], the minimum size and cost of charging station for EV fleets has been studied in two urban areas in Europe as well as the impact of the charging station on the grid in terms of power and energy requests. In [18], the authors have proposed an EV charging control scheme from the grid operator's perspective rather than the EV user's. They have proposed a method to change indirectly the route of the EV using dynamic pricing to improve the system operation, keep the voltage stable and meet the charging demands. The optimal operation of a DC-based microgrid EV charging station using a mixed-integer linear programming has been studied in [19]. The operation aimed to optimize the daily operating cost, based on PV production forecast and EV needs. In [20], the authors have studied a bi-level planning model of charging stations, by establishing a travel pattern model based on Monte Carlo simulation and driving data of EVs. They aimed at satisfying the needs of EV users and minimizing the total social cost.

The authors of [21] have designed the aspects and presented the practical implementation of solar-assisted EV charging stations. A smart charging strategy has been presented in [22] for plug-in EV networks that provide different charging options, battery swapping facilities at charging station, AC level 2 charging and DC fast charging. The strategy aimed at finding the optimal charging station considering the minimum driving time, charging cost and charging time. In [23], the authors have evaluated the factors affecting the EV charging demand and predicted the charging demand of various EVs under different circumstances, such factors are driver behavior, electricity pricing, location of charging stations, social characteristics of EV user and economic elements. Their results contribute in identifying optimal locations for charging stations to maximize their utilization.

The authors of [24] have analyzed competitive interactions for different EV charging stations with renewable energy sources using a game theoretical analysis. The objective is to maximize the revenue of each EV charging station, subject to physical constraints. Their results have shown that EV charging stations equipped with renewable energy sources lower the electricity price and increase the revenue of the EV charging station. An EV charging station based on PV sources, stationary storage, diesel generator and public grid connection has been implemented in [25] so it can operates in three modes: grid-connected, islanded operation and diesel generator set connected. Their test results have proved the capability of the EV charging station under different conditions.

In [26] A real-time rule-based algorithm has been proposed for the operation of a DC-based microgrid EV charging station with imposing charging power limit depending on power availability. They have focused on the management strategy for the EV charging station, highlighting the interaction with EV users. Their results have proved the feasibility of the intelligent management proposed, including EV shedding and EV restoration priority, and its efficiency in considering user choices.

In [27], the authors have proposed an optimization problem to reduce the stress on the grid and to reduce the cost of consumed energy. They have proposed a predictive model to forecast EVs' power demand. They have proposed to charge the EVs by PV, storage and grid instead of directly feed the EVs from the grid. In [28], the authors have investigated peak load reduction using PV, storage and V2G strategy for EVs. They have focused on increasing the capacity of the storage to decrease the grid dependency. The authors of [29] have investigated the charging of

EVs using PV energy in the workplace. They have studied the optimal sizing of storage to make the charging station grid independent. However, these articles did not propose different charging modes for the EVs; they have focused on reducing peak load demand or reducing the cost of energy consumed by the grid rather than increasing the PV benefits for the EV users. Moreover, energy distribution system and energy distribution for each EV are not depicted in these papers.

However, to the extent of our knowledge, the previously cited references have not discussed the preliminary requirements and feasibility conditions for an EV charging station, while satisfying EV user needs and the factors that can influence their choice to increase PV benefits and lower their charging cost from the public grid. In previous studies, home charging represents 75% of EV charging time, the longest duration of vehicle dwelling time and workplace charging represents 14% of EV charging time. These two locations have the largest opportunity for charging [9]. EV users tend to charge their EV based on their convenient time and place rather than what the public grid operators prefer and when the electricity price is low to prevent negative impact on the public grid [11].

In this chapter, the goal is to define the preliminary requirements and feasibility conditions for PV-powered EV charging stations in an urban area and to emphasize the importance of a business model that can influence the EV users' behavior. The main contributions of this work are:

(1) A PV-powered EV charging station model is proposed, which consists of PV sources, stationary storage system, public grid connection and EVs. This model satisfies the EV user demands while improving PV-benefits for EVs.

(2) A proper power flow management is proposed for the PV-powered EV charging station. The priority order is PV sources, stationary storage and lastly public grid connection for charging EVs. In addition, PV sources inject power first to stationary storage then to the public grid, in case of PV excess energy.

(3) An EVs energy distribution method is proposed to calculate the portion of consumed energy for each EV from each power source. In addition, energy system distribution is calculated to specify the portion of energy charged/injected into the power source and energy discharged/supplied from the power source.

This chapter is organized as follows, Section 2.2.3 describes the charging infrastructures for EVs, Section 2.2.4 presents the driving characteristics and charging load profiles, Sections 2.2.5 depicts PV-powered EV charging stations power flow management, Sections 2.2.6 presents the PV-powered EV charging stations simulation results and discussion and Section 2.2.7 concludes this chapter with perspectives.

### 2.2.3 Charging infrastructures for EV

The charging infrastructures rely on the relations between driving needs, charging equipment usage, EV stock and technical capabilities. Population density, driving range, and charging behavior are specific factors that have direct implications on the geographical location of the EV supply equipment and on the charging rates, for electric low-duty vehicles. Two charging modes, slow and fast charging [30,31], are presented in this chapter, which denote the charging rate for an EV.

Slow charging is mostly rated at 3 kW, but in reality, it is between 1,8 kW and 6 kW. Charging time depends on the charging rate and the EV's energy capacity, thus, a full charge takes 6-12 hours at 3 kW, with the power decreasing when the battery is almost fully charged. Slow chargers are common for most EVs, they can be found everywhere, e.g. at home, at the workplace, and in public places. EV users tend to charge at home overnight for long charging.

Fast charging is typically rated from 7 kW up to 22 kW (single or three phase 32 A). Charging an EV with a 40 kWh capacity battery takes 4-6 hours with 7 kW and 1-2 hours with 22 kW. The majority of fast chargers provide AC charging. However, some infrastructures are equipped with 25 kW DC chargers with CHAdeMO connectors. Fast chargers can be found in public places, as shopping centers, car parks, workplace, supermarkets, train stations, and airport parkings.

The sizing and characteristics of PV-powered EV charging stations depend on the PV installation (parking shade or building-integrated PV), solar irradiance potential, stationary storage, and the adopted business model. The viability of well-designed PV-powered EV charging stations depends on social acceptance, PV benefits and business model.

Private chargers stand for 90% of global EV chargers in 2019, as profitability, convenience and various supports and incentives are the main motivations of the universality of private chargers [32]. The preferred locations are homes and private workplaces to charge the EV. The infrastructure for home charging is a compatible electric socket and charger plug, which already exists in homes. Nearly 60% of EV users have access to private chargers in China based on The China EV charging Infrastructure Promotion Agency report in 2019 [31]. The EVs consume approximately 75% of energy from private charging at homes and at the workplace, in the United States, United Kingdom and the European Union [33].

### 2.2.4 Driving characteristics and charging profiles

People have different attitudes and living styles, and therefore, they differ in their driving patterns, which significantly affect the spatial-temporal distribution of the charging load. However, the EV charging load profiles vary and depend mainly on the type of charging preferences, EV user habits, and energy consumption rates. In [34] the driving data for different users are analyzed in time and space dimensions to understand driving patterns of different populations, grouped by age as a demographic attributes. The daily driving distance is the factor to compare the behavior of different EV users. The U.S. National Household Travel Survey dataset, as in [34], shows the daily driving distance and where the elderly drive for a short distance. Based on these data, the daily average urban/peri-urban trip can be deduced as 20–40 km. Considering two driving modes, a normal drive mode with 15 kWh/100 km and an eco-drive mode with 10 kWh/100 km, the daily energy consumption rate is 3–6 kWh for a normal drive and 2–4 kWh for an eco-drive. Considering the above and an average EV battery, e.g. 50 kWh, Figure 2.2-2 shows the required time for 80% charging (green lines) and 10% charging (orange lines) depending on power delivered by the terminal and accepted by the EV battery.

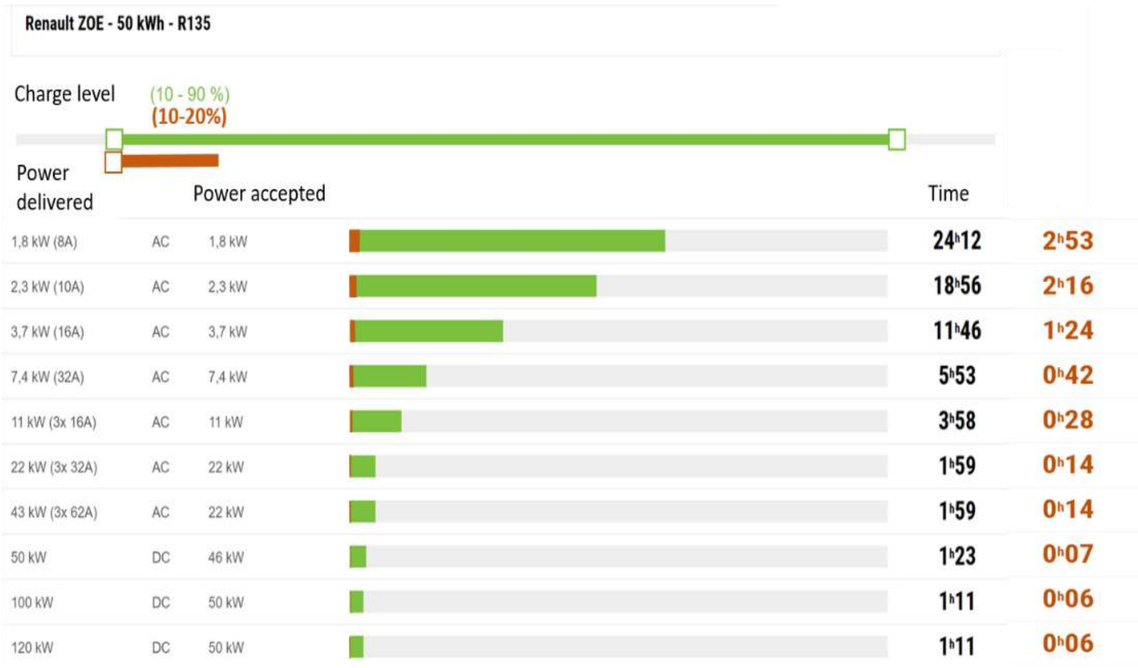



**Figure 2.2-2 Required time for EV charging based on demand charge and delivered/accepted power**

For delivered and accepted power of 1,8 kW, the time required is more than 24 h to charge 80% and around 3 h to charge 10% of the EV's battery capacity. On the other hand, the time required is around 1 h to charge 80% and around 6 min to charge 10% of EV battery capacity, for delivered power of 100 kW and accepted power of 50 kW. Thus, a 10% increase of charge, e.g. 5 kWh, is possible with reasonable charging time depending on delivered/accepted power. A suitable EV charging load profile allows increasing PV benefits for PV-powered EV charging stations.

## *2.2.5 PV-powered EV charging stations power flow management*

The EV charging station considered in this chapter is PV-powered including stationary storage and public grid connection. It has been modeled using MATLAB/Simulink as illustrated in Figure 2.2-3.

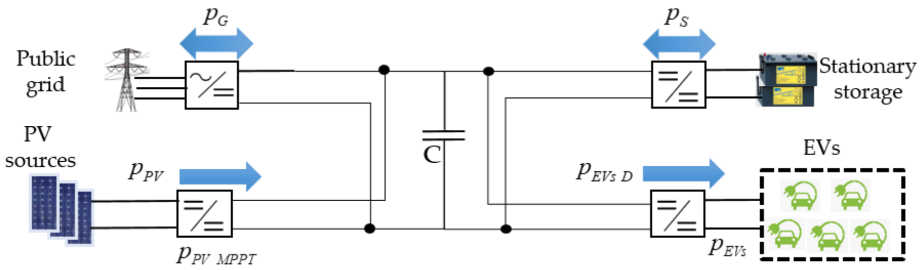



**Figure 2.2-3 PV-powered EV charging station scheme**

where $p_{PV\ MPPT}$ is the PV power in MPPT mode, $p_{PV}$ is the PV power, $p_G$ is the public grid power, $p_S$ is the stationary storage power, $p_{EVs\ D}$ the EVs total demand power, and $p_{EVs}$ is the total EVs power. The public grid can absorb or supply power. The DC bus is represented by the capacitor C, where the components are coupled to the DC bus through their dedicated converters. PV sources are connected to the DC bus through DC/DC converter to extract the MPPT power. The Stationary storage is needed to construct the DC MG and it is connected through DC/DC converter. The DC load, represented by the EVs batteries, is connected through DC/DC converter. The public grid connection is required to ensure power at all time and mitigate the power difference between the power production and the load demand; it is connected through three-phase bidirectional AC/DC converter. The stationary storage is charged by PV sources only and can discharge power in DC common bus.

The energy management strategy, as shown in Figure 2.2-4, functions on the following order of priorities: PV is the first energy source to charge EVs, then stationary storage is the second energy source, and finally the public grid is the last energy source to charge EVs. Stationary storage is charged with excess energy produced by PV sources and the public grid by excess energy from PV sources when the stationary storage reaches its maximum limits (power or SOC).

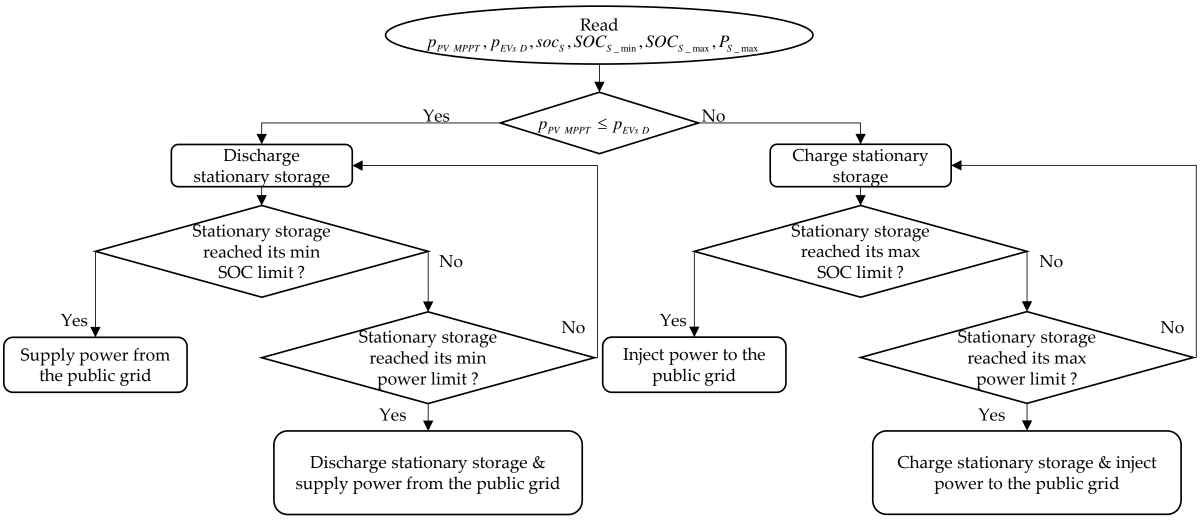



**Figure 2.2-4 Flowchart for the power flow management of the PV-powered EV charging station**

The design of the PV-powered charging station is based on DC microgrid, as shown in Figure 2.2-3. Therefore, it is required to keep the power balance [35] given by (2.2-1):

$$p_{PV}(t_i) = p_{EVs}(t_i) + p_S(t_i) + p_G(t_i), \ with\ t_i = \{t_0, t_0 + \Delta t, t_0 + 2\Delta t, ..., t_F\}, \tag{2.2-1}$$

where $t_i$, $t_0$, $\Delta t$, and $t_F$ are continuous time, initial time instant, time interval between two samples, and time instant at the end of time operation respectively.

The PV power is calculated in MPPT mode, $p_{PV\ MPPT}$, [36] as given by (2.2-2) and ((2.2-3):

$$p_{PV\ MPPT}(t_i) = P_{PV\_STC} \cdot \frac{g(t_i)}{1000} \cdot [1 + \gamma \cdot (T_{PV}(t_i) - 25)] \cdot N_{PV}, \tag{2.2-2}$$

$$T_{PV}(t_i) = T_{amb}(t_i) + g(t_i) \cdot \frac{NOCT - T_{air-test}}{G_{test}}, \tag{2.2-3}$$

where $P_{PV\_STC}$ is the PV power under standard test conditions (STC), $g$ is the solar irradiance, $\gamma = -0.29\% / ^\circ C$ is the power temperature coefficient, $T_{PV}$ is the PV cell temperature, $N_{PV}$ is the number of PV panels, $T_{amb}$ is the ambient temperature, $NOCT = 41.5°C$ is the nominal operating cell temperature, $T_{air-test} = 20^\circ C$ is the fixed air temperature, and $G_{test} = 800 W / m^2$ is the fixed solar irradiance for testing.

A simplified SOC of the stationary storage [37], $soc_S$, is used as in (2.2-4) for its simplicity, where self-discharge and temperature are not taken into account, and the over-charging/discharging protections [35] are expressed by (2.2-5) and (2.2-6):

$$soc_S(t_i) = SOC_{S_0} + \frac{1}{3600 \cdot E_S} \int_{t_0}^{t} p_S(t_i)dt, \tag{2.2-4}$$

$$SOC_{S\_min} \le soc_S(t_i) \le SOC_{S\_max}, \tag{2.2-5}$$

$$-P_{S\_max} \le p_S(t_i) \le P_{S\_max}, \tag{2.2-6}$$

where $SOC_{S_0}$ is the initial $soc_S$, $E_S$ is the energy capacity (kWh) of the stationary storage, $SOC_{S\_max}$, $SOC_{S\_min}$ are $soc_S$ maximum and minimum limits, and $P_{S\_max}$ is the stationary storage power limit.

Regarding the EV battery, its dynamic SOC, $soc_{EV_v}$, is given by (2.2-7):

$$soc_{EV_v}(t_{i+1}) = SOC_{EV\_arr_v}(t_i) + \frac{p_{EV_v}(t_i) \cdot \Delta t_i}{E_v} \ \forall t_i \in [t_{arr_v}, t_{dep_v}], \ with\ v = \{1, 2, ..., N_v\}, \tag{2.2-7}$$

where $v$ is the index of the EV, $soc_{EV_v}$ is the SOC of $v$ vehicle, $SOC_{EV\_arr_v}$ is arrival SOC of $v$ vehicle, $N_v$ is the total number of EVs, $p_{EV_v}$ is the EV charging power of $v$ vehicle, $E_v$ is the energy capacity of $v$ vehicle, $t_{arr_v}$ and $t_{dep_v}$ are the arrival and departure time of $v$ vehicle respectively.

The EVs are charged using the PV energy, stationary storage energy, and grid energy. The distribution of these energies is calculated as follow by (2.2-8), (2.2-9), and (2.2-10) respectively:

$$E_{PV_v} = \int_{t_{arr_v}}^{t_{dep_v}} p_{PV}(t_i) \cdot \frac{p_{EV_v}(t_i)}{p_{EVs}(t_i)} dt_i \ \ \forall t_i \in [t_{arr_v}, t_{dep_v}], \tag{2.2-8}$$

$$E_{S_v} = \int_{t_{arr_v}}^{t_{dep_v}} p_S(t_i) \cdot \frac{p_{EV_v}(t_i)}{p_{EVs}(t_i)} dt_i \ \ \forall t_i \in [t_{arr_v}, t_{dep_v}], \tag{2.2-9}$$

$$E_{G_v} = \int_{t_{arr_v}}^{t_{dep_v}} p_G(t_i) \cdot \frac{p_{EV_v}(t_i)}{p_{EVs}(t_i)} dt_i \ \ \forall t_i \in [t_{arr_v}, t_{dep_v}], \tag{2.2-10}$$

where $E_{PV_v}$, $E_{S_v}$, and $E_{G_v}$ are the PV energy, stationary storage energy, and public grid energy respectively consumed by $v$ vehicle during the charging period.

### 2.2.6 PV-powered EV charging station simulation results and analyses

This section presents two case studies: PV parking shade for one private charger and PV parking shade for nine chargers at the workplace. The two cases were simulated under the same solar irradiance profile. Regarding the EVs, lithium-ion batteries were considered and it was assumed they have the same battery capacity of 50 kWh, while the driving characteristics and charging profiles covered a daily needed charge of 2–6 kWh, as described in Section 2.2.4, but they are not exclusive.

For all scenarios, the following assumptions are considered:

- Charging station location is in Compiegne, France, where the yearly average solar irradiance is not very high;
- PV panel is Sunpower SPR X21-345 with 21% efficiency under STC;
- Mounting position is fixed and optimized as follow: slope angle 38° and azimuth angle -2°;
- System loss are estimated at 14 % system loss;
- Lead-acid batteries are considered for the stationary storage and its limits are chosen 20% and 80% for $SOC_{S\_min}$ and $SOC_{S\_max}$ respectively.

With the objective of determining preliminary requirements and feasibility conditions of PV-powered EV charging stations that may bring some PV benefits, the following subsections present and analyse several scenarios as well as simulation results.

#### *2.2.6.1 Case 1 - Private charging station: PV parking shade for one private charger*

Case 1 considered a PV parking shade of nine PV panels, i.e., 3,1 kWp, like the example illustrated in Figure 2.2-5.

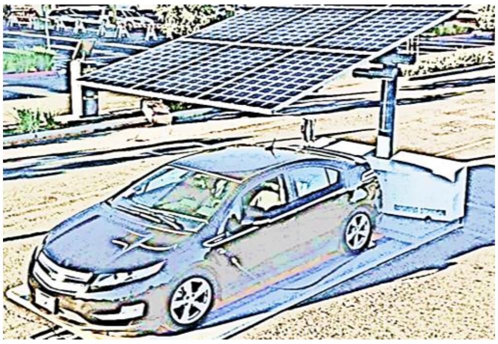


**Figure 2.2-5 PV parking shade**

In this case, the lowest monthly PV production is in December, as shown in Figure 2.2-6, with an average daily of 3.88 kWh. To reach 2–6 kWh, stationary storage and public grid connection are required for complementary energy. PV can either charge directly the EV or the stationary storage during the day and thereafter, the stationary storage can charge the EV during the evening/night. For this case, the public grid power limit was set to 9 kVA, for the stationary storage capacity and its power limit 4 kWh and 5 kW were chosen respectively.

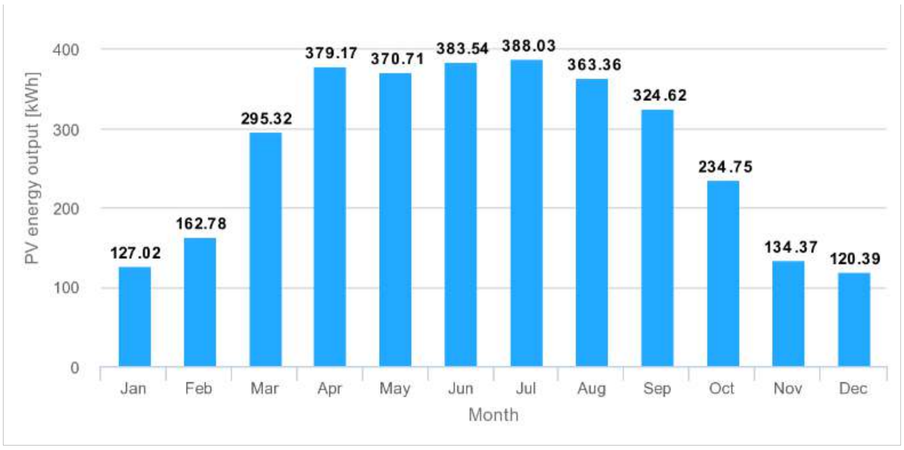



**Figure 2.2-6 Monthly PV production—case 1**

Figure 2.2-7 shows the solar irradiance $g(W/m^2)$ and $p_{PV\ MPPT}$ for 24 December 2019 in Compiegne.

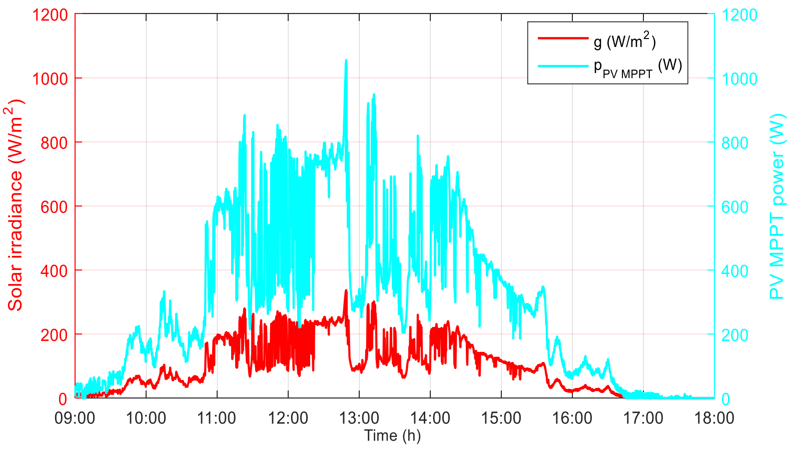



**Figure 2.2-7 Solar irradiance and PV MPPT power – case 1**

2.2.6.1.1 *Scenario* 1a

The hypotheses for the scenario 1a are shown in Table 2.2-1.

**Table 2.2-1 Hypotheses for the scenario 1a**

| EV number | Arrival time | SOC at arrival | Desired SOC at departure | Charging mode/power |
|---|---|---|---|---|
| EV1 | 10:30 | 60% | 68% | Slow/1,8 kW |

Figure 2.2-8 shows the system power flows and the stationary storage SOC evolution.

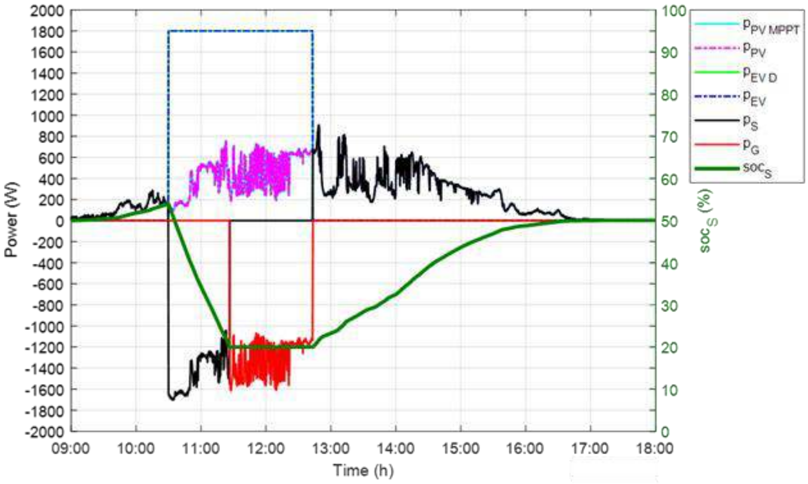



**Figure 2.2-8 Scenario 1a: system power flows and stationary storage SOC evolution**

As PV power is insufficient to fully charge the EV with constant power of 1,8 kW, the stationary storage charges the EV until the storage becomes empty, reaching its capacity limit around 11:30 and then the public grid supplies the EV, from 11:30 until EV departure. In this scenario, PV energy is not used optimally since it charges the EV for a period and the rest of time charges the stationary storage. Therefore, scenario 1b proposes a known parking time for the EV to see the impact of PV energy on the EV charging.

### *2.2.6.1.2 Scenario 1b*

The hypotheses for the scenario 1b are shown in Table 2.2-2. The park time is the time when the EV is in the charging station.

**Table 2.2-2 Hypotheses for scenario 1b**

| EV number | Arrival time | SOC at arrival | Desired SOC at departure | Park time | Charging mode/power |
|---|---|---|---|---|---|
| EV1 | 10:30 | 60% | 68% | 6h30 | Slow/0,615 kW |

Based on hypotheses presented in Table 2.2-2, including the park time as a known variable, the charging power $p_{PV_v}$ is calculated based on Equation (2.2-7). Figure 2.2-9 shows the system power flows and the stationary storage SOC evolution.

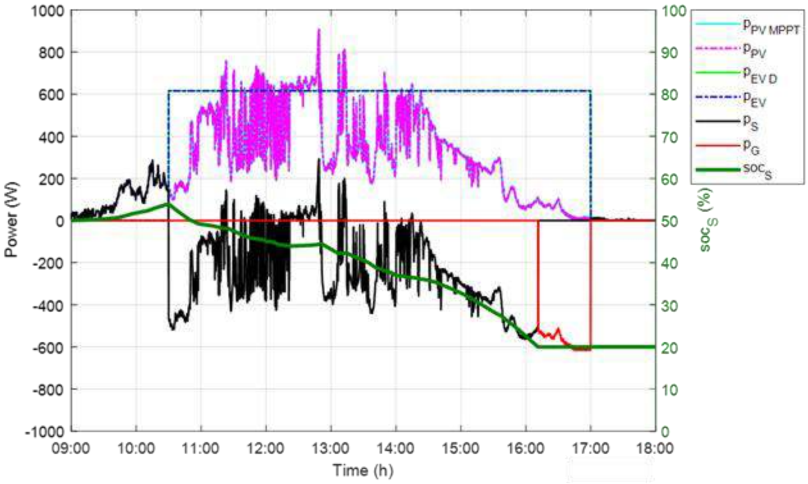
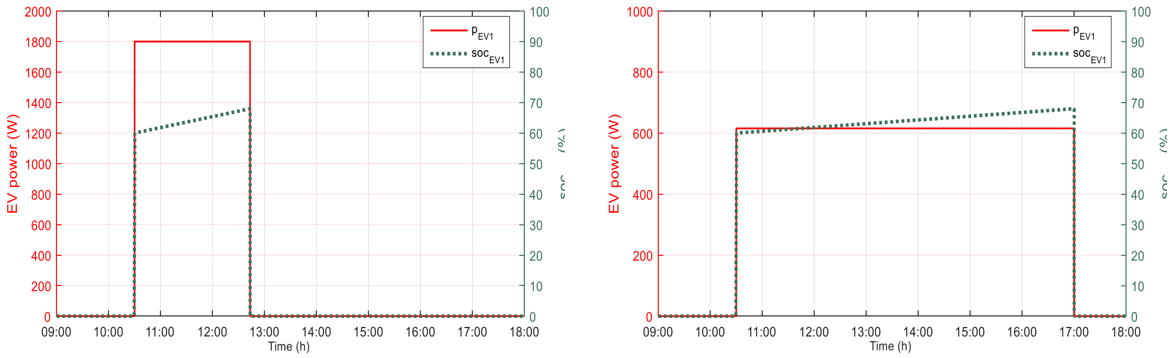


**Figure 2.2-9 Scenario 1b, system power flows and stationary storage SOC evolution**

As the parking time is known and longer than in scenario 1a, the recharging portion provided by PV has increased, and the stationary storage lasts longer, preventing its fast discharge, thus reducing the dependency on the public grid. The stationary storage becomes empty, reaching its capacity limit around 16:10 hours and then the public grid supplies the EV until departure.

*2.2.6.1.3 Scenario 1a versus scenario 1b*

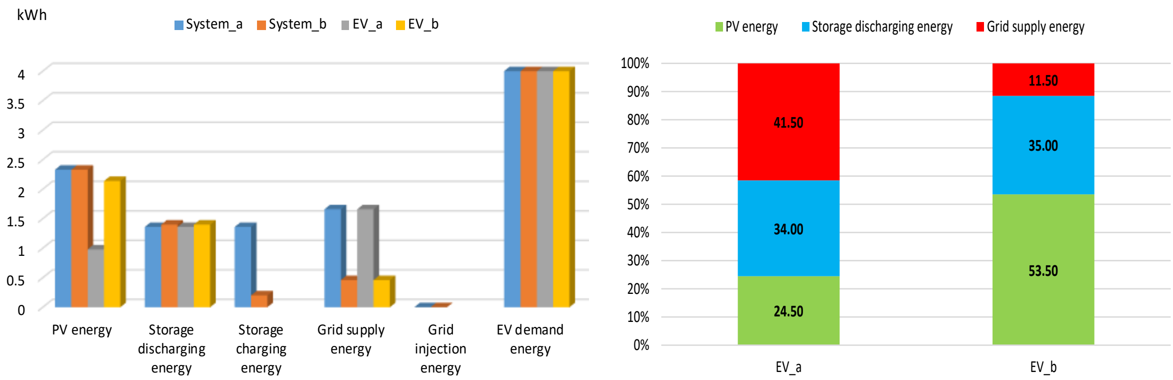
Figure 2.2-10 shows the EV charging power and EV SOC evolution for the two scenarios (a) and (b). It shows that the desired SOC at departure for the EV is respected in the two scenarios, while for scenario 1b the charging power is lower than scenario 1a and the charging period is longer as well.




(a) (b)

**Figure 2.2-10 (a) EV charging power and EV SOC evolution for scenario 1a and (b) EV charging power and EV SOC evolution for scenario 1b**

Figure 2.2-11 shows a comparison between the two scenarios and the attractiveness of scenario 1b, where the EV is charged with more than 50% of direct PV and only 11,50% of public grid power, whereas, in scenario 1a, the EV is charged with 24,50% of direct PV and more than 40% of public grid power.




(a) (b)

**Figure 2.2-11 (a) Energy system distribution, (b) EV energy distribution for scenarios 1a and 1b**

In conclusion, when the park time is known and long, PV benefits increase for the EV charging and the dependency on the public grid is reduced.

*2.2.6.2 Case2 - Publicly accessible charging station: PV parking shade with nine spots and nine chargers*

Figure 2.2-12 shows the installation of a PV parking shade, which consists of 84 PV panels in the Innovation Center of the Université de Technologie de Compiègne (UTC), i.e. 29,8 kWp. The stationary storage system has the characteristic of 185 Ah, 96 V giving an energy capacity of 17,76 kWh and the storage power limit is chosen at 7 kW to not exceed the maximum charging power in slow mode. However, no public grid power limit is set in this case. The lowest monthly PV production is in December, as shown in Figure 2.2-13, with an average daily of 36,22 kWh. If the nine EVs are connected, then each individual EV may receive 4,02 kWh, which represents the average needed amount of electricity to charge an EV for a daily trip of 20-40 km.

**Figure 2.2-12 PV parking shade installation for nine spots [38]**

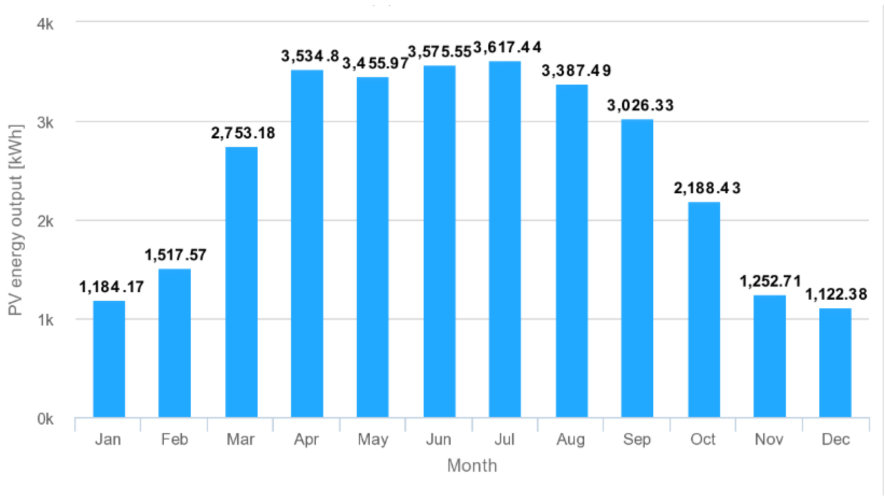



**Figure 2.2-13 Monthly PV production – case 2**

Figure 2.2-14 shows the solar irradiance $g(W/m^2)$ and $p_{PV\ MPPT}$ for 24 December 2019 in Compiegne.

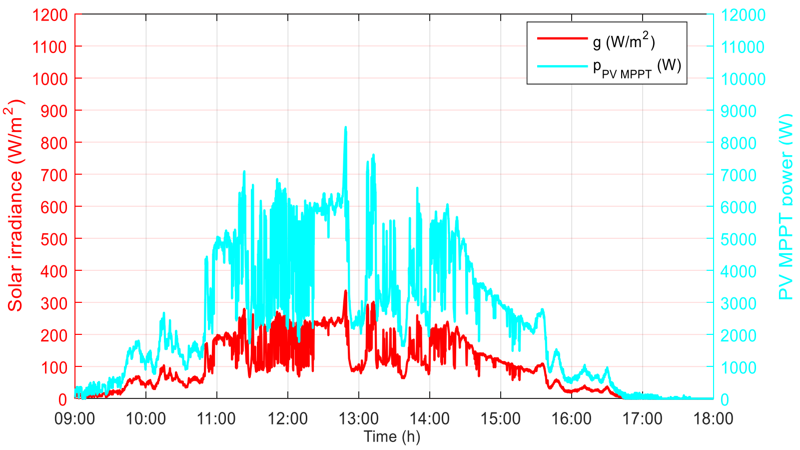


**Figure 2.2-14 Solar irradiance and PV MPPT power – case 2**

Different scenarios and simulation results are considered and analyzed to define the preliminary requirements and feasibility conditions for a PV-powered EV charging station with PV benefits increased in the following subsections.

*2.2.6.2.1 Scenario 2a*

The hypotheses for the scenario 2a are shown in Table 2.2-3.

**Table 2.2-3 Hypotheses for scenario 2a**

| EV# | Arrival time | SOC at arrival | Desired SOC at departure | Charging mode/power |
|---|---|---|---|---|
| EV1 | 09:30 | 65% | 75% | Slow/1,8 kW |
| EV2 | 10:30 | 62% | 70% | Slow/1, 8kW |
| EV3 | 12:00 | 61% | 66% | Slow/1,8 kW |
| EV4 | 13:00 | 58% | 66% | Slow/1,8 kW |
| EV5 | 14:30 | 57% | 68% | Slow/1,8 kW |

The total EVs demand energy is 21 kWh. Figure 2.2-15 shows the system power flows and the stationary storage SOC evolution. PV and stationary storage share power to charge the EVs, without the need of public grid supply. When the PV production is higher than the EV's demand power, PV charges the stationary storage so it can supply further power afterwards or other EV that can arrive.

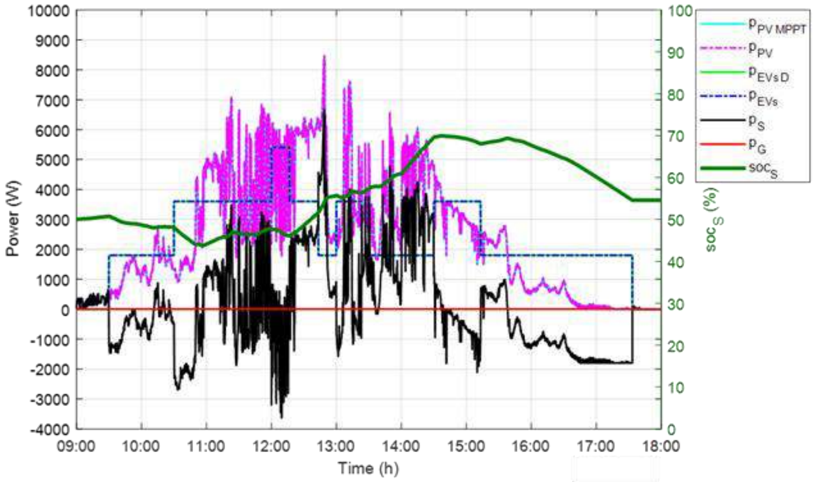



**Figure 2.2-15 Scenario 2a: system power flows and stationary storage SOC evolution**

*2.2.6.2.2 Scenario 2b*

The hypotheses for the scenario 2b are shown in Table 2.2-4.

The difference with the previous scenario 2a is that the departure time is now known, making it necessary for certain EVs to charge faster in order to reach their desired minimum SOC in time.

**Table 2.2-4 Hypotheses for scenario 2b**

| EV# | Arrival time | SOC at arrival | Desired SOC at departure | Departure time | Charging mode/power |
|---|---|---|---|---|---|
| EV1 | 09:30 | 65% | 75% | 15:00 | Slow/0,909 kW |
| EV2 | 10:30 | 62% | 70% | 16:00 | Slow/0,727 kW |
| EV3 | 12:00 | 61% | 66% | 14:00 | Slow/1,25 kW |
| EV4 | 13:00 | 58% | 66% | 14:30 | Slow/2,66 kW |
| EV5 | 14:30 | 57% | 68% | 17:00 | Slow/2,2 kW |

Then, the total EVs demand energy is 21 kWh. Figure 2.2-16 shows the system power flows and the stationary storage SOC evolution.

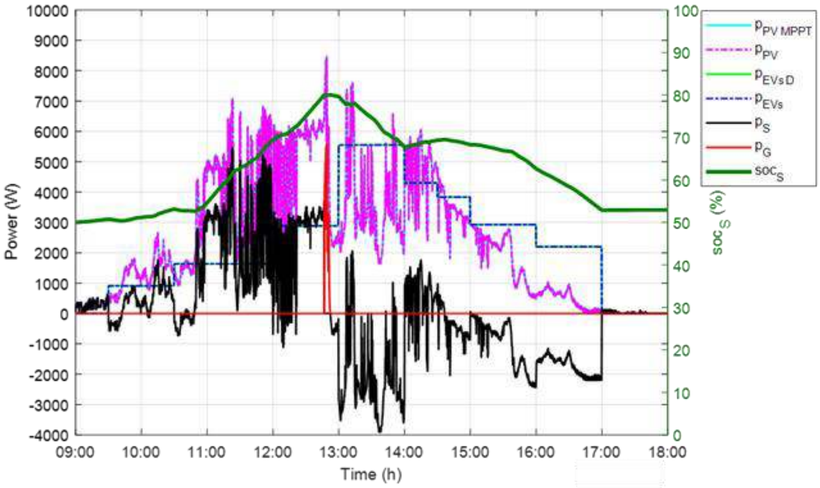
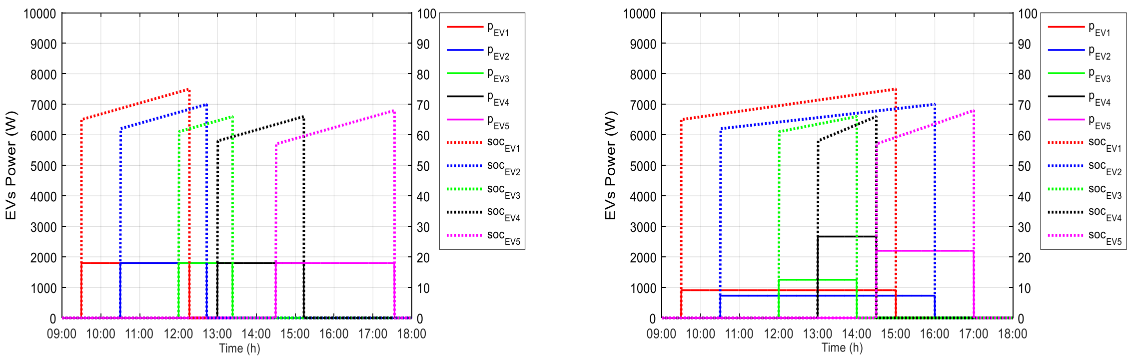



**Figure 2.2-16 Scenario 2b: system power flows and stationary storage SOC evolution**

PV and stationary storage share power to charge the EVs, without the need of public grid supply. When the PV production is higher than the EV's power demand, PV charges the stationary storage so it can supply further power afterwards. The stationary storage becomes full, reaching its maximum capacity around 12:50, therefore, PV injects power into the public grid. The EVs charging power and EVs SOC evolution for the two scenarios 2a and 2b are shown in Figure 2.2-17.




(a) (b)

**Figure 2.2-17 (a) EVs charging power and EVs SOC evolution for scenario 2a; (b) EVs charging power and EVs SOC evolution for scenario 2b**

A comparison between the two scenarios is shown in Figure 2.2-18. All EVs are charged mainly with PV energy, except for the last EV, i.e. EV5, where it comes in the late afternoon and PV production is low. As the charging mode is slow for all EVs, the public grid is not required to step in.

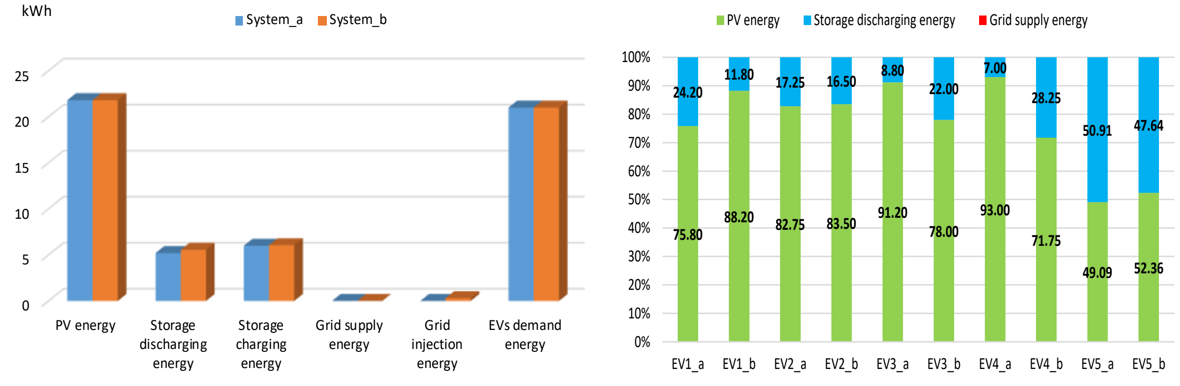



**Figure 2.2-18 (a) Energy system distribution; (b) EVs energy distribution for scenarios 2a and 2b**

In conclusion, scenario 2b may be more desirable compared to scenario 2a as it may improve the PV benefits for the EVs when the park time is known and longer than the actual needed time for charging in scenario 2a. It should be noted that when park time is large, therefore, some EVs charge simultaneously so the PV production is shared between them and reducing the portion of PV energy.

These two scenarios are focused on slow charging mode only. The next scenarios will consider slow and fast charging mode and more than 10% of energy charge to analyze the impact of fast charging on the EVs and their PV benefits.

#### *2.2.6.2.3 Scenario 2c*

The hypotheses for the scenario 2c are shown in Table 2.2-5.

**Table 2.2-5 Hypotheses for scenario 2c**

| EV# | Arrival time | SOC at arrival | Desired SOC at departure | Charging power | Mode |
|---|---|---|---|---|---|
| EV1 | 09:40 | 64% | 75% | 1,8 kW | slow |
| EV2 | 10:00 | 58% | 65% | 22 kW | fast |
| EV3 | 10:50 | 57% | 63% | 1,8 kW | slow |
| EV4 | 14:40 | 60% | 66% | 1,8 kW | slow |
| EV5 | 15:00 | 75% | 64% | 22 kW | fast |

The total EVs demand energy is 18.50kWh. Figure 2.2-19 shows the system power flows and the stationary storage SOC evolution.

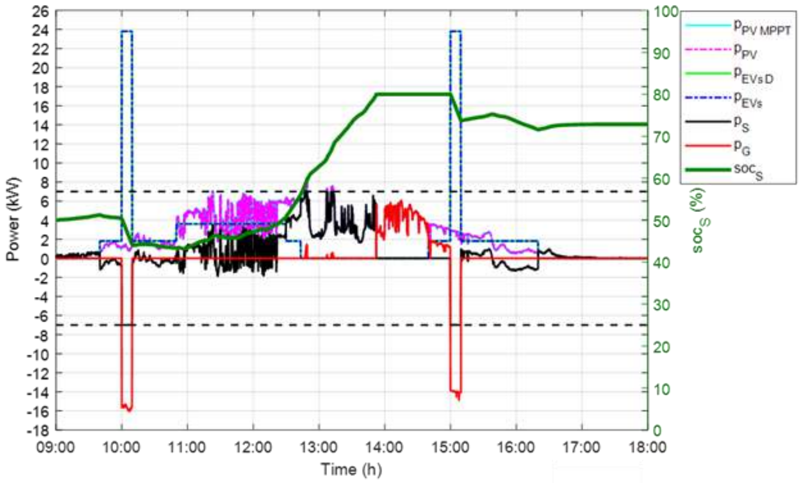



**Figure 2.2-19 Scenario 2c: system power flows and stationary storage SOC evolution**

PV and stationary storage share power to charge the EVs in slow mode. However, when an EV comes to charge in fast mode and the stationary storage has reached the power limit of 7 kW, the public grid steps in to supply the EVs, at 10:00 - 10:10 hours and 15:00 - 15:10 hours. When the PV production is higher than the EV's power demand, PV charges the stationary storage so it can supply further power afterward.

Moreover, PV injects power into the public grid, when the stationary storage reaches its capacity limit, SOC 80% around 13:50 - 15:00, and when it reaches the power limit, around 12:50 and 13:10.

#### *2.2.6.2.4 Scenario 2d*

The hypotheses for the scenario 2d are shown in Table 2.2-6.

**Table 2.2-6 Hypotheses for scenario 2d**

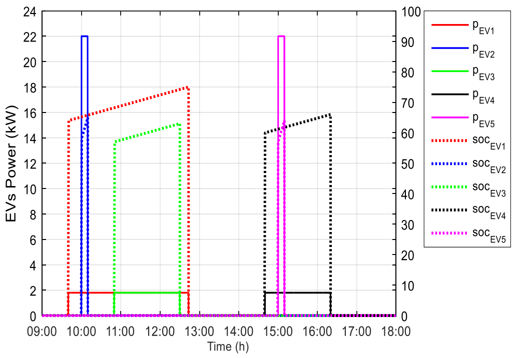
| EV# | Arrival time | SOC at arrival | Desired SOC at departure | Departure time | Charging mode/power |
|---|---|---|---|---|---|
| EV1 | 09:40 | 64% | 75% | 13:00 | Slow/1,65 kW |
| EV2 | 10:00 | 58% | 65% | 10:25 | Fast/8,39 kW |
| EV3 | 10:50 | 57% | 63% | 11:50 | Slow/2,99 kW |
| EV4 | 14:40 | 60% | 66% | 16:40 | Slow/1,49 kW |
| EV5 | 15:00 | 75% | 64% | 15:20 | Fast/10,49 kW |

The total EV's energy demand is 18.50 kWh. Figure 2.2-20 shows the system power flows and the stationary storage SOC evolution. The stationary storage is charged only by PV energy; therefore, its power must be limited not to exceed the slow charging power of 7 kW.

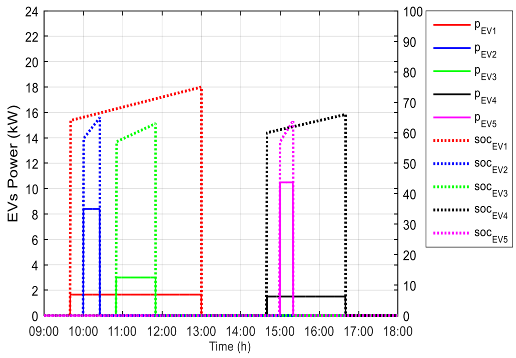

**Figure 2.2-20 Scenario 2d: System power flows and stationary storage SOC evolution**

PV and stationary storage share power to charge the EVs in slow mode. However, when an EV comes to charge in fast mode and the stationary storage has reached the power limit of 7 kW, the grid supplies the EVs, at 10:00 - 10:10 hours and 15:00 - 15:10 hours. When the PV production is higher than the EV's power demand, PV charges the stationary storage so it can supply further power afterward. Moreover, PV injects power into the grid when stationary storage reaches its capacity limit, SOC 80% around 14:10 - 15:00 hours, and when stationary storage reaches the power limit, around 13:10 hours.

The EVs charging power and EVs SOC evolution for the two scenarios 2c and 2d are shown in Figure 2.2-21.



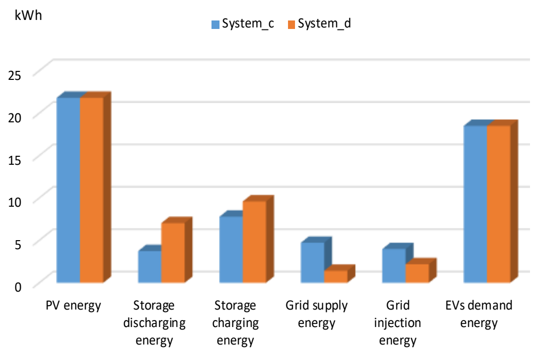

(a)



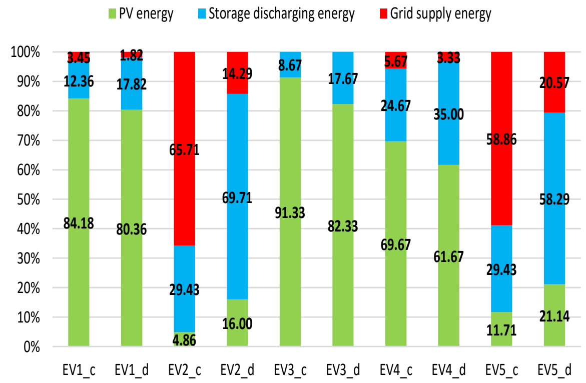

(b)

**Figure 2.2-21 (a) EVs charging power and EVs SOC evolution for scenario 2c; (b) EVs charging power and EVs SOC evolution for scenario 2d**

Figure 2.2-22 shows a comparison between the two scenarios. All EVs in slow mode are charged mainly with PV energy, except for EV4, where it comes in the late afternoon and the PV production is low. Whereas, for EV2 and EV5, in fast mode, are charged mainly with the public grid and for a small portion with PV. Moreover, EV2 and EV5, since they charge in fast mode, will affect negatively EV1 and EV4 respectively.




(a)




(b)

**Figure 2.2-22 (a) Energy system distribution; (b) EVs energy distribution for scenarios 2c and 2d**

In conclusion, scenario 2d shows that EV2 and EV5 consume more PV energy than in scenario 2c and the public grid dependency has been reduced. This shows that the variable charging power based on time duration availability can improve the PV benefits and the EVs can depend more on PV and less on the public grid.

The stationary storage could be emptied quickly, if its power was not limited, since for EVs charging in fast mode their charging power could reach up to 22 kW. Thus, in scenario 2c, EV2 and EV5 charge with a greater percentage of public grid energy. However, since the stationary storage is charged by PV sources only, as mentioned earlier, this could prove the attractiveness of scenario 2d over scenario 2c, as the PV energy and stationary storage energy combined are higher than scenario 2c, as shown in Figure 2.2-22.

#### *2.2.6.2.5 Scenario 2e*

The hypotheses for the scenario 2e are shown in Table 2.2-7.

**Table 2.2-7 Hypotheses for scenario 2e**

| EV# | Arrival time | SOC at arrival | Desired SOC at departure | Charging mode/power |
|---|---|---|---|---|
| EV1 | 09:40 | 64% | 75% | Slow/1,8 kW |
| EV2 | 10:00 | 58% | 100% | Fast/22 kW |
| EV3 | 10:50 | 57% | 63% | Slow/1,8 kW |
| EV4 | 14:40 | 60% | 66% | Slow/1,8 kW |
| EV5 | 15:00 | 75% | 64% | Fast/22 kW |

The total EVs demand energy is 36 kWh. Figure 2.2-23 shows the system power flows and the stationary storage SOC evolution. PV and stationary storage share power to charge the EVs in slow mode. However, when an EV comes to charge in fast mode and the stationary storage has reached the power limit of 7 kW, the grid supplies the EVs, at 10:00 - 10:50 hours and 15:00 - 15:10. hours at 10:50 hours, the stationary storage has reached its capacity lower limit, SOC of 20%, so public grid supplies more power to the EVs since the PV production is insufficient to meet the demand. When the PV production is higher than the EV's power demand, PV charges the stationary storage so it can supply further power afterwards. Moreover, PV injects power to the grid when stationary storage has reached the power limit, around 12:50 hours and 13:10 hours.

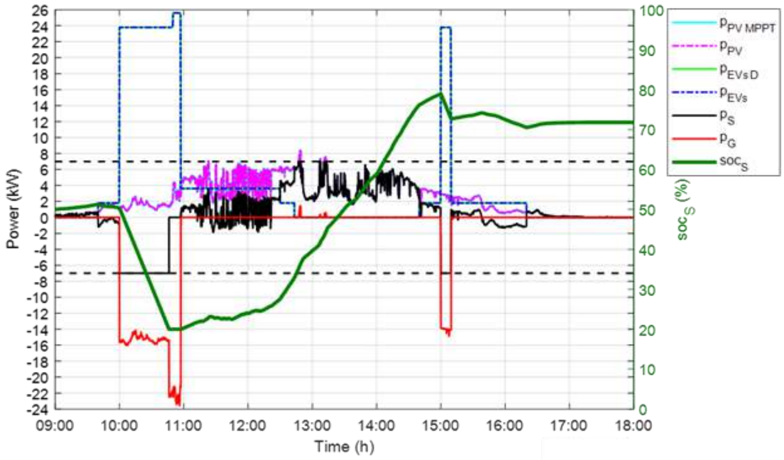



**Figure 2.2-23 Scenario 2e: System power flows and stationary storage SOC evolution**

The EVs charging power and EVs SOC evolution for scenarios 2e are shown in Figure 2.2-24.

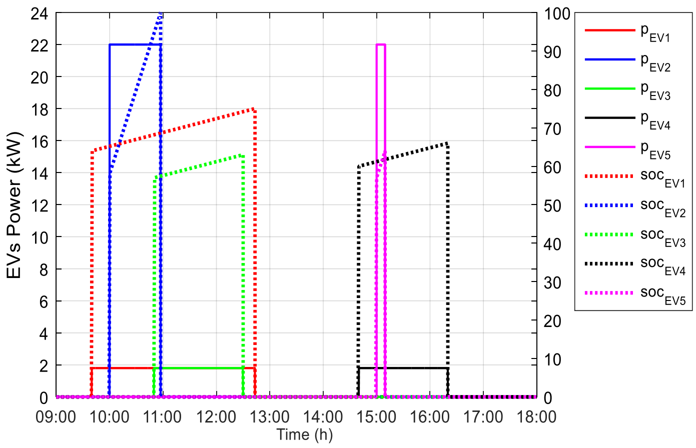



**Figure 2.2-24 EVs charging power and EVs SOC evolution for scenario 2e**

Figure 2.2-25 shows a comparison between the two scenarios. The difference in scenario 2e with scenario 2c is that EV2 want to charge 42% of its battery capacity in fast mode. Therefore, EV2 is charged mainly by the public grid and for a small portion with PV. Moreover, EV2 will affect negatively EV1 and EV3 and, therefore, the PV benefits for EV1 and EV3 have reduced since EV2 charges in fast mode for around 1 hour and the three EVs charge simultaneously for a while.

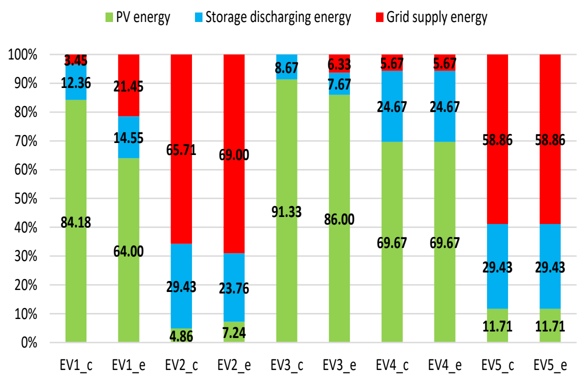


**Figure 2.2-25 EVs energy distribution for scenarios 2c and 2e**

In conclusion, scenario 2e shows how the fast charging mode affects negatively the other EVs currently in charge and their dependency on the public grid. The stationary storage could be emptied quickly, if its power was not limited, since for EVs charging in fast mode their charging power could reach up to 22 kW. In contrast to scenario 2d, in scenario 2e, EV2 charges with 22 kW and the requested SOC at departure is 100%. Therefore, the percentage of stationary storage energy remains low.

Therefore, the main issue for PV-powered EV charging stations, is how to increase the PV penetration for EVs charging. Under which conditions? What is the appropriate sizing of the system?

*2.2.6.3 Discussion*

In scenario 1, only one EV is charged in slow mode with a private charger. It is shown that the known park time could bring PV benefits and reduce public grid dependency, which will decrease the charging costs for the EV user. In Scenario 2, there are five EVs that are charged with public chargers. Regarding scenario 2a versus 2b, where all EVs are charged in slow mode, it is shown that scenario 2b may be more attractive compared to scenario 2a, where PV benefits are greater since the park time is known for each EV.

Regarding scenario 2c versus 2d, where three EVs are charged in slow mode and two EVs are charged in fast mode, it is shown that EVs charged in fast mode depend mainly on the public grid and on stationary storage energy while EVs charged in slow mode depend on PV energy. However, when the park time is known and longer than the time actually needed to charge, PV benefits could increase and public grid dependency could be reduced.

Regarding scenario 2e, the same conditions as for scenario 2c are applied but EV2 requests full charge (100%) in fast mode. It is shown that EV2 affects negatively EV1 and EV3 since they coincide some of the time, this will reduce PV benefits for EV1 and EV3. Moreover, EV2 is largely dependent on the public grid and stationary storage energy. The stationary storage output power is limited to 7 kW, so it will not be emptied quickly if some EVs want to charge in fast mode.

The simulation results show that for fast charging modes EVs depend mainly on public grid energy. Moreover, the public grid energy tariff may be dynamic and if so, therefore high in peak times. Therefore, EV users who want to charge in fast mode are supposedly willing to pay higher bills. However, EV users may tend to change their behavior and choose to charge in slow mode since it is cheaper. Hence, an economic model is necessary for the PV-powered charging station to optimize the EV charging power, have the best power distribution for energy sources, and have the lowest cost for charging EVs, which is a key factor to influence EV users.

Nevertheless, uncertainties always exist in real world. However, in the present study, the uncertainty of the demand profile by EVs is always covered, first by PV, then by stationary storage and finally by the public grid when there is uncertainty in PV generation to ensure power at all time. Regarding EV's capacity, it is assumed that all EVs are the same. For EV's SOC and operating schedules, these are taken as assumptions, where they represent the data and choices of EV users that they choose through the human-system interface. Demand profile of EVs is hard to predict as it depends on various factors (type of user, charging preference and energy demand). Therefore, the arrival time of an EV, SOC of an EV at arrival and its requested SOC at departure have been chosen arbitrarily but are expected to cover many cases.

Finally, to increase PV benefits, the preliminary requirements and feasibility conditions for PV-powered charging stations may be summarized as follows:

1. Slow charging is characterized by:
    - Charging power of up to 7 kW;
    - Based on PV energy and stationary storage, which is charged by PV sources only;
    - Stationary storage should be well designed and its power should be limited;
    - EV battery filling up to 6 kWh;
    - User acceptance for long and slow charging.

2. For fast charging mode:
    - Charging power from 7 kW up to 22 kW;
    - Based on public grid energy;
    - Stationary storage should be well designed and its power should be limited at 7 kW;
    - User acceptance of higher charging costs.

Moreover, PV power generation depends on the geographical location and weather conditions, as well as on solar irradiance and the temperature of the PV modules. Proper sizing of the stationary storage is required. A user interface is required to facilitate the interaction between the EV users and the charging station and to take into consideration the choices made by EV users. It is advantageous when parking time (the length of time during which the EV is parked and available for charging in the charging station) is known, and longer parking times help to increase PV benefits. Inherent limitations are the limits on PV energy production over the year due to geographical location for the scenarios taken for this study. The physical limits of stationary storage and sizing considerations need to be examined and adjusted according to charging station dimensions. However, the public grid can always provide energy where required, or purchase PV energy when there is an excess of PV production, as in case 2 where no grid limits were imposed.

### 2.2.7 Conclusions

This chapter focuses on the preliminary requirements, feasibility conditions, and business model for PV-powered EV charging stations in an urban area. The simulation results show that the EV charging demand is not constrained: the EV user can charge in either slow or fast mode, and there are no restrictions on EV battery capacity ($10\% < soc_{EV_v} < 100\%$). However, the PV benefits increase when an average daily urban/peri-urban trip of 20–40 km is considered, with an EV consumption of 10–15 kWh/km, which corresponds to a required daily charge of 2–6 kWh. Our results show that the greatest PV benefits are obtained with daily rather than weekly EV charging, and where parking time is known.

Regarding the requirements and feasibility conditions, two charging modes are possible: a slow mode using mainly PV energy and storage and with an EV filling capacity not exceeding 6 kW, and a fast mode between 7 kW and 22 kW using mainly public grid energy. The stationary storage system needs to be appropriately sized, and users must be willing to accept either longer charging times in the case of slow mode, and or a higher charging price in the case of fast mode.

The two main concerns highlighted in the case studies are, first, the control of an EV charging system combining PV power, stationary storage and the public grid, and, second, a business model that can influence consumer behavior through variable prices for charging. Possibilities for moving EVs between charging stations and parking spaces need to be examined, with a view to optimizing the use of a limited number of charging terminals. This requires users to be available to move their EVs, but it can increase the PV benefits of EV charging.

The charging mode can influence the PV benefits according to the degree of dependency on the public grid. In slow charging modes EVs can be charged mainly from PV energy and the stationary storage system, while in faster modes there is greater reliance on the public grid. Ultra-fast charging can not only reduce PV benefits, but also negatively impact the electricity distribution network, especially when large numbers of EVs are charging simultaneously.

Future studies will concentrate on defining the proper size of the stationary storage, adjusting its physical limits according to charging station dimensions, and proposing a business model with appropriate charging prices for EV users. Simulations will then need to be validated by real-time experimental tests. A human-system interface will need to be created according to the PV-powered charging station definition and requirements. Studies regarding the new vehicle-to-everything (V2X) services associated with PV-powered EV charging stations will also be necessary.

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## 2.3 Assessment of PV benefits for PV-powered EV charging stations

This chapter[3] focuses on a quantitative estimation of the PV benefits to be obtained from PVCSs (PV-powered charging stations) incorporating PV sources, stationary storage, and public grid connections. The proposed methodology is based on a technical and economic tool for use by local stakeholders to help them determine the preliminary requirements and feasibility conditions for PV-powered EV charging stations with a view to optimizing PV benefits. Aspects for inclusion are the space needed, the cost of the investment, and a qualitative assessment simulating the characteristics of the infrastructure thus dimensioned.

### *2.3.1 Introduction*

The environmental benefits of EVs can be optimized only if charging energy can be produced with zero or very low $CO_2$ emissions. The energy transition encourages the growth of PV power generation, since this may coincide with the periods where EVs are parked at the workplace (when solar irradiance is the highest) and consequently reduce the burden on the public grid [1]. PV-power infrastructure for charging EVs can promote the local consumption of PV energy, reduce the dependency of charging stations on the power grid, and directly reduce $CO_2$ emissions [2].

PVCSs can therefore contribute to the sustainable development of EVs and society. A question that arises is how local authorities can be helped to make decisions about the deployment of MGs incorporating PV sources. Economic, social, and environmental factors are the key considerations in planning the location of PVCSs. The environmental and economic analysis of a PVCS as described in [3] compared an uncontrolled load scenario with an optimal load scenario. The paper [4] analyzed an economic evaluation method for a PVCS using a cost estimation of second-use EV batteries. A study is presented in [5] for the design a PVCS where the aim is to increase revenue.

In [6] preliminary requirements and feasibility conditions are identified for a PVCS where the aim is to increase the use of PV energy for recharging EVs while reducing the energy taken from the power grid. An energy distribution method is proposed for determining the share of each of the different power sources in EV charging according to arrival time, departure time, state of charge (SOC) at arrival, desired SOC at departure, and charging mode.

The study in [7] evaluates the feasibility of PVCS with stationary battery storage in China and United States using a simulation model that estimates the cumulative $CO_2$ emissions, yearly energy costs and system's energy balance based on the PV energy share. The authors show that PV shares of 50% and 75% of the annual charging electricity

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[3] This chapter is based on the following publication: Y. Krim, M. Sechilariu, F. Locment, "PV Benefits Assessment for PV-powered Charging Stations for Electric Vehicles", Applied Sciences, vol. 11, no.9, pp 4127, 2021, https://doi.org/10.3390/app11094127.

are feasible, whereas a 100% PV share is possible but could lead to high system costs. In [8], an extended method of coordination distribution is proposed, based on power prediction for the microgrid PV power generation with plug-in EVs to improve the local consumption of renewable energy in the MG by guiding the orderly charging of EVs.

A neural network and clustering algorithm are used to construct a power predicting model to characterize the PV generation uncertainty and EV charging profile. In [9], a linear programming approach is developed to share the PV energy with EVs in order to satisfy users and also maximizes PV utilization. They evaluate the performance of the approach on a real case and synthetically datasets to demonstrate that it distributes the available electric charge between EVs through the seasons with varying profiles of demand.

In [10], the focus lies on the economic aspects and feasibility of EV charging system made up of PV sources connected to the grid and equipped with stationary storage. In this case, a support tool was modeled and developed, making it possible to size and manage EV charging stations with only a few input parameters. A technical and economic analysis using the tool HOMER (Hybrid Optimization Model for Multiple Energy Resources) software of PVCS under different irradiance conditions is presented in [11]. They show that a region with strong sunshine, is more likely to invest in PVCS than other regions with lower solar irradiance, but the charge type is not investigated while this would have helped to assess the performance of PV energy in recharging EV. As in slow charging, the PV benefits can be improved, where the EVs can depend more on PV and less on power grid whereas in fast charging, the energy demand is high, which increases the dependency on the power grid.

The optimal technical design of PV and of stationary storage systems for charging EVs is decisive to ensure their economic feasibility, which corresponds to the system components sizing with minimum cost [12]. In [12] the study is realized using HOMER software to analyze the economic and technical performances for standalone PVCS associated with battery as a stationary storage system. The off-grid PVCS can be considered as a good solution to reduce the $CO_2$ emissions, but it generally works with slow charging terminals and for EVs with a short daily trip. In [13], an analysis is made of PV car parks that meet the aforementioned benefits. Following this techno-economic feasibility study, the PV installation is not always economically feasible, especially for areas where electricity prices are relatively low.

Finding sustainable and economic methods for the deployment of PV energy is crucial for the improvement of PV benefits. Therefore, in [14] a techno-economic environmental assessment of two case studies, in Japan and China, of residential PV installations with batteries or EVs allowing charging and discharging (V2H) is conducted, with the projection of the costs of these technologies up to 2030. The high electricity prices in Kyoto, Japan, presents a good opportunity for “PV + EV”, i.e., V2H, technologies to develop. The areas where electricity prices are lower, such as Shenzhen, China, have a potential reduction of $CO_2$ emission, but they are not economically beneficial.

Through the aforementioned literature review, it can be noticed that some problems have not been addressed by the existing investigations:

(1) Currently, there is not enough research on preliminary requirements and feasibility conditions for PVCS.
(2) The decision-making model should be improved including the PV benefits assessment information.
(3) Lack of analysis of PV benefits under several solar irradiance conditions and different EVs charging profiles.

In order to resolve the above issues, this paper focuses on PV benefits assessment for PVCS, and it presents a methodology based on a model giving an economic and technical comparison under different conditions of load and weather conditions, helping the sizing, planning and management of such systems. This work brings the following improvements:

(4) An effective methodology and easy to use Excel-based tool.
(5) A flexible sizing of the PVCS according to the users’ needs and budgets.
(6) A qualitative analysis of PVCS under three types of solar irradiances, two charging profiles and three predefined scenarios and personalized scenario of occupancy rates (OR) of electric charging terminals.

This infrastructure is based on PV panels installed on roofs of houses/buildings or car parking shades, EV charging terminals, electrochemical stationary storage, power electronics, and public grid connection. Based on various input parameters, the tool becomes a decision-making one.

Thus, the study aims to assess the benefits of PV for PVCS and presents a methodology based on a pre-sizing tool. This tool, divided into three phases, gradually leads the user to a choice of infrastructure compatible with the local constraints, particularly spatial and economic:

- The first one is to determine the maximum number of charging terminals and PV panels that can be installed taking into account the location constraints, as well as the recommended stationary storage capacity for optimal operation of the PVCS;
- The second one is a phase for adjusting the PVCS total cost using four parameters: the type of PV panels, number of PV panels, number of terminals, and the stationary batteries capacity;
- The third one offers a detailed qualitative analysis of the user-defined configuration in phase 2. Its objective is to assess the performance and then to improve the PVCS sizing and operating modes aiming at increasing the use of PV energy for EV charging, while minimizing energy supplied by the power grid. In phase 3, the PVCS performance is evaluated by an energy balance obtained by operating mode simulation.

This tool gives the possibility to personalize the charging profile of EVs highlighting the contribution of the energy provided by the PV panels for recharging. This paper is organized as follows: Section 2.3.2 gives an overview of the methodology used in the tool's three phases development, and finally, Section 2.3.3 draws the main conclusions and perspectives.

### 2.3.2 PV benefits assessment methodology

The objective of this part is to detail the methodology that was followed to program the technical and economic decision support tool. The tool is devoted to local stakeholders, allowing to identify the preliminary requirements and feasibility conditions for PVCS, leading to PV benefits growth: the needed space, the generated cost of investment and a qualitative assessment simulating the ecological character of its infrastructure thus dimensioned. There are three different phases, each providing the user with additional information. For each phase, the study assumptions, the input data and how the algorithm processes data in order to calculate the output data are detailed. This tool must be easy to use and understandable for a novice user, while responding to certain precision requirements that it is representative of reality. The tool is developed in Excel, with the Visual Basic for Applications language.

The assumptions of this methodology are listed below:

- The consumption of an EV is assumed to be 15 kWh/100 km for "normal" driving and 10 kWh/100 km for economical driving [15];
- MPPT for PV power is considered to be always optimal;
- Losses due to MG system are estimated at 14% (average value given by PVGIS software);
- All considered charging terminals can offer a charging power less than or equal to 22 kW. This limitation is chosen in order to reduce the dependency on the power grid in favor of PV energy in the EV charging [6].

#### *2.3.2.1 Phase 1: Maximum pre-sizing*

The goal of this first phase is to determine the maximum number of charging terminals and PV panels that can be installed with respect to the location constraints, as well as the maximum storage capacity. At the end of this phase, the overall cost estimate is given.

Figure 2.3-1 describes the five steps of the phase 1 by using a detailed flow chart. The five steps are:

- The sizing of charging terminals;
- The area of the infrastructure;

- The sizing of the PV panels;
- The sizing of the storage;
- The calculation of the total and maximum price of the infrastructure.

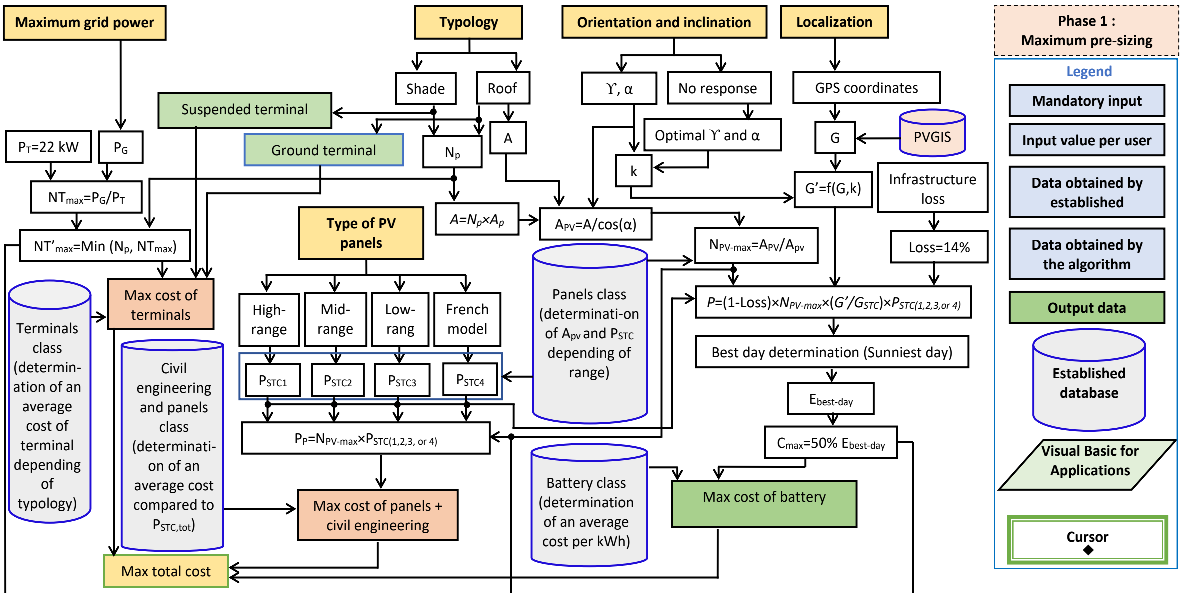


**Figure 2.3-1 Flow chart of phase 1**

#### 2.3.2.2.1. *Requisite data*

The necessary input data, requested from the user during phase 1, are the following:

- Available maximum public grid power $P_G$, which corresponds to the maximum value of the power, in kW, that the power grid can supply the future PVCS;
- Typology corresponding to the choice of PV panels installation on the roof or on the car parking shade;
- Type of the charging terminals according to the typology PV panels installations: for a rooftop installation, ground type charging terminals are assigned, and for a shade-type installation, suspended charging terminals are assigned;
- Number of parking spots to be covered $N_p$;
- Available area $A$ corresponding to the roof area available for the PV panels installation and to the PVCS available area for car parking shade;
- Type of PV panels according to the desired range, i.e. high-range, mid-range, low-range, and the French model, corresponding to monocrystalline panels defined according to PV power at standard test conditions (STC) $P_{STC}$ and PV conversion efficiency $\eta$:
    - High-range: $\eta = 22\%$, $P_{STC\ 1} = 400\ W$;
    - Mid-range: $\eta = 19,6\%$, $P_{STC\ 2} = 330\ W$;
    - Low-range: $\eta = 18,4\%$, $P_{STC\ 3} = 300\ W$;
    - French model: $\eta = 18,1\%$, $P_{STC\ 4} = 300\ W$;
- PV orientation $O_z$ and PV inclination $\alpha$, which will make it possible to determine the irradiance received by the PV panels;
- Depending on the location, latitude and longitude, the weather data profile is generated through a download link allowing to obtain the solar irradiance data from Photovoltaic Geographical Information System (PVGIS) software [16].

These aforementioned inputs data are entered according to the interface depicted in Figure 2.3-2.

The five steps of the phase 1 shown on the flow chart schematized in Figure 2.3-1 are presented below.

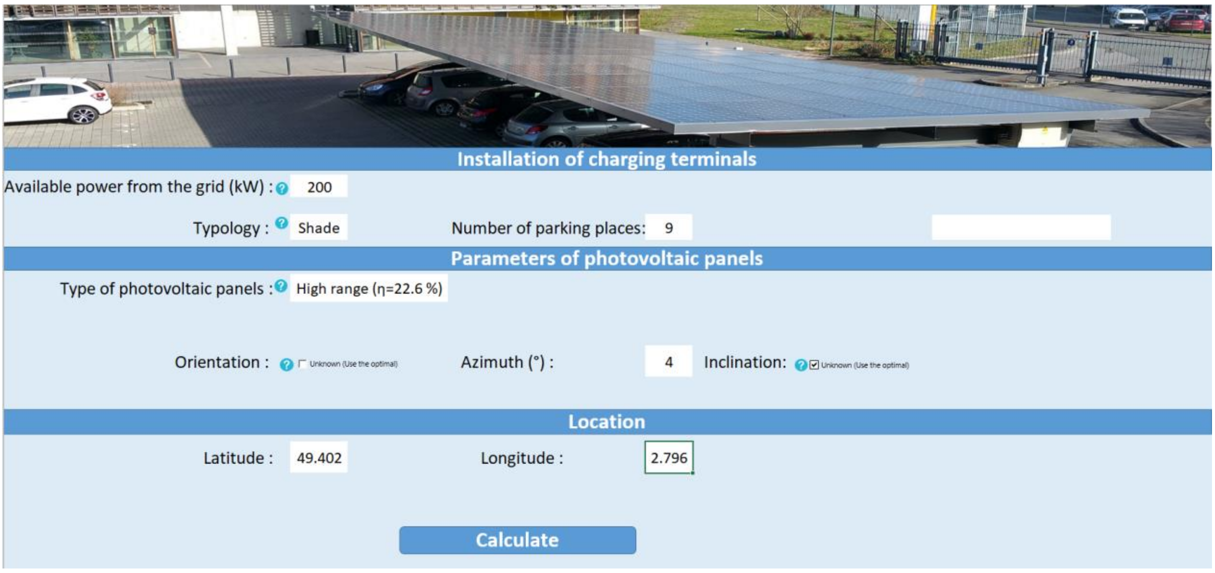


**Figure 2.3-2 Interface for input data entry** (numerical values for the maximum sizing)

*a-First step: sizing of charging terminals*

The purpose of this step is to determine the real maximum number of charging terminals $NT'_{\max}$ that can be installed. The PVCS is a MG grid-connected system, therefore, the theoretical maximum number of charging terminals $NT_{\max}$ calculation depends on the available maximum public grid power $P_G$ and the power delivered by each terminal $P_T$ , as expressed by equation (2.3-1).

$$NT_{\max} = \frac{P_G}{P_T} \tag{2.3-1}$$

Finally, the real maximum number of terminals $NT'_{\max}$ is the minimum between $NT_{\max}$ and the number of parking spaces $N_p$ entered by the user.

*b-Second step: area of the infrastructure*

The PVCS area depends on the type of installation (a rooftop or a car parking shade PV installation) and the available area $A$ . This latter is entered directly by the user of the tool in the case of a roof installation, while for car parking shade installation, the area is calculated according to the number of parking spaces $N_p$ and the conventional surface of a parking spot $A_p$ as in equation (2.3-2).

$$A = N_p \cdot A_p \tag{2.3-2}$$

*c-Third step: sizing of the PV panels*

From the area $A$ and the inclination of the PV panels $\alpha$ , the area of the all PV panels $A_{PV}$ is determined by equation (2.3-3).

$$A_{PV} = \frac{A}{\cos(\alpha)} \tag{2.3-3}$$

Next, the maximum number of PV panels $N_{PV-\max}$ is determined by dividing the area of all PV panels $A_{PV}$ by the area of one PV panel $A_{pv}$ as expressed in (2.3-4).

$$N_{PV-\max} = \frac{A_{PV}}{A_{pv}} \tag{2.3-4}$$

*d-Fourth step: sizing of the storage*

The solar irradiance $G$ data for the optimum location, orientation $\Upsilon$ and inclination are obtained from the PVGIS tool, whose data are available at present for every 10 min on any day, for the years from 2005 to 2016. The corrected irradiance value $G'$ is calculated according to a correction factor $k$ and $G$ ((2.3-5):

$$G' = k \cdot G \tag{2.3-5}$$

where the factor k depends on $\Upsilon$ and $\alpha$ , as summarized in Table 2.3-1.

**Table 2.3-1 Correction factor of the solar irradiance [16]**

| Inclination α / Orientation Ƴ | 0° | 30° | 60° | 90° |
|---|---|---|---|---|
| East | 0,93 | 0,90 | 0,78 | 0,55 |
| South-East | 0,93 | 0,96 | 0,88 | 0,66 |
| South | 0,93 | 1,00 | 0,91 | 0,68 |
| South-West | 0,93 | 0,96 | 0,88 | 0,66 |
| West | 0,93 | 0,90 | 0,78 | 0,55 |

The total PV power $P$ produced by the PVCS is calculated according to Equation (2.3-6):

$$P = N_{PV-\max} \frac{G'}{G_{STC}} P_{STC} \tag{2.3-6}$$

where $P_{STC}$ is the PV panel power at standard test conditions estimated from a database of different available ranges of PV panels. This power calculation is made for the best sunny day in terms of irradiance, according to data from PVGIS.

The obtained power is corrected by considering the losses due to the infrastructure estimated at 14%. Then, by integration, the total energy produced in this best day $E_{best-day}$ is obtained. Aiming at a good trade-off between cost and operation, the considered hypothesis is that the maximum capacity $C_{\max}$ of stationary batteries must allow to store at least half of the energy produced on this best day, hence the following equation (2.3-7):

$$C_{\max} = 50\% \cdot E_{best-day} \tag{2.3-7}$$

*e-Fifth step: calculation of the total and maximum price of the infrastructure*

The total PVCS cost is obtained by adding three costs:

- The cost of the infrastructure of the PV panels and of its implementation is estimated according to the total peak power of the PV panels depending on the four ranges (high, mid, low, and French model). For the PV infrastructure installed on the roof the estimated cost is given according to the data summarized in Table 2.3-2 while the estimated costs of the PV infrastructure installed on the car parking shade is presented according to the data summarized in Table 2.3-3. These tables allow, after mathematical linearization, to associate a cost as function of the total peak power of the of the PV panels $P_p$ obtained by (2.3-8):

$$P_p = N_{PV-\max} \times P_{STC(1,2,3,or\,4)} \tag{2.3-8}$$

- The cost of the stationary storage (batteries) for the PVCS is estimated from the data presented in Table 2.3-4;
- The cost of charging terminals depends on the type of terminals (on the ground for the roof type and suspended for the shade type) and on the real maximum number of terminals $NT'_{\max}$ . This cost is determined using a database establishing an average price for the two types of terminals.

**Table 2.3-2 Infrastructure costs excluding tax for PV panels installed on the roof**

| Peak power range | Cost range |
|---|---|
| < 3 kWp | 2,5 to 2,2 € /Wp |
| 3 to 9 kWp | 2,2 to 1,8 € /Wp |
| 9 to 36 kWp | 1,8 to 1,2 € /Wp |
| 36 to 100 kWp | 1,2 to 1 € /Wp |
| 100 to 500 kWp | 1 to 0,9 € /Wp |
| > 500 kWp | < 0,85 € /Wp |

**Table 2.3-3 Infrastructure costs excluding tax for PV panels installed on the car parking shade**

| Peak power range | Cost range |
|---|---|
| < 100 kWp | 1,2 to 1,4 €/Wp |
| 100 to 500 kWp | 1,2 to 1,05 €/Wp |
| > 500 kWp | 1,05 to 0,95 €/Wp |

**Table 2.3-4 Batteries cost in € / kWh depending on the type of battery.**

| Battery type | Cost range |
|---|---|
| High-range lithium batteries (e.g. LG Chem, Tesla Powerwall, Mercedes Benz) | 500 to 1 200 €/kWh |
| Absorbed glass mat (AGM) solar batteries | 200 to 250 €/kWh |
| Gel solar batteries | 200 to 300 €/kWh |
| Lead-acid solar batteries | 100 to 300 €/kWh |

Although the data included in Table 2.3-2, Table 2.3-3, and Table 2.3-4, as well as the cost of charging terminals come from French databases, this does not influence the proposed methodology, and other costs can be entered to agree with other references.

Concerning the phase 1, the weakness of the approach lies in its dependency on the construction of the PVGIS download link. Indeed, PVGIS changes the construction logic; the tool will then generate a bad link, and the download cannot therefore be carried out.

Finally, as presented in Figure 2.3-3, the first phase of the tool offers a maximum sizing of the PVCS (the cursors of adjustment of PV panels quantity, of terminals number and of the stationary battery capacity are at the maximum positions). The unit kWp in Figure 2.3-3, which does not belong to International System of Units while often in common use, denotes kW at STC.

The inputs used in this part are for an existing PVCS, i.e., the smart transport and energy living lab platform [28]. The output results of phase 1 are the maximum size of the PVCS before adjustment.

The obtained results potentially overestimate the PVCS costs considered in the first calculation; these can therefore be adjusted in the phase 2. Thus, the moving of cursors means the automatic passage to phase 2 to adjust the maximum pre-dimensioned parameters of the PVCS, e.g., to adjust the quantity of PV panels, quantity of charging terminals and batteries capacity.

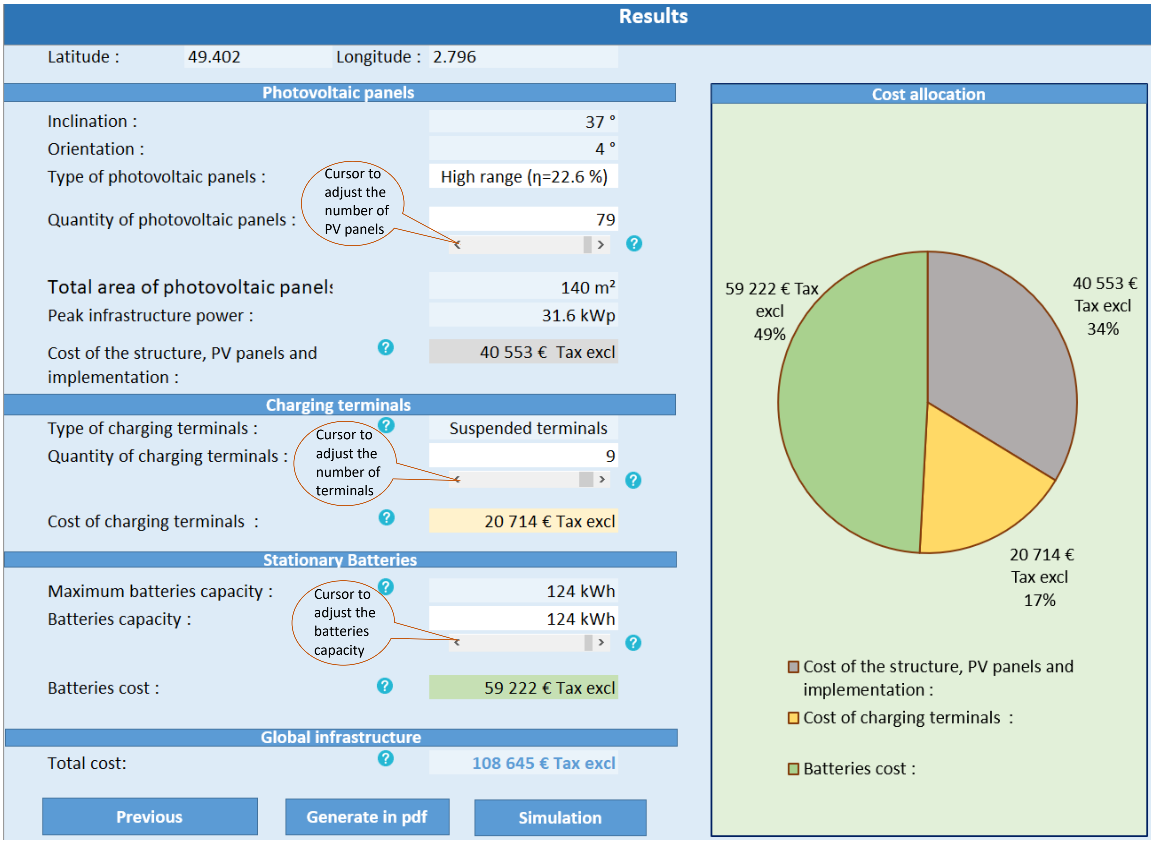


**Figure 2.3-3 Interface for the maximum sizing in the phase 1**

*2.3.2.2 Phase 2: Cost adjustment*

The total cost of the PVCS can be amended in the second phase. Figure 2.3-4 shows the flow chart of phase 2.

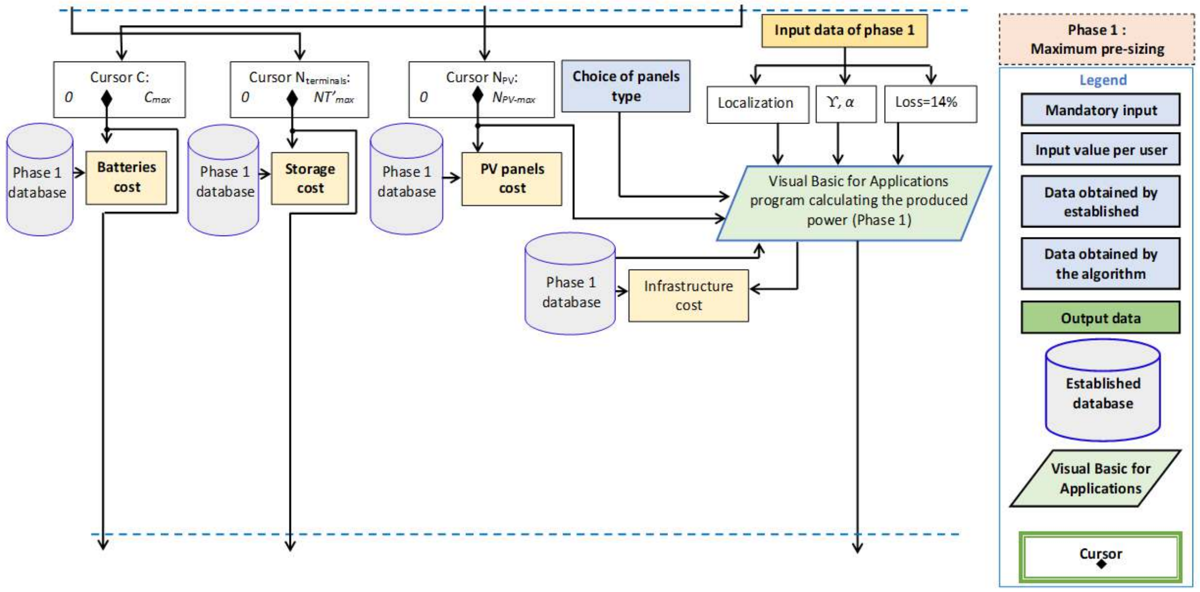


**Figure 2.3-4 Flow chart of phase 2**

The total cost is adjusted using four parameters:

- The type of PV panels via the same scrolling menu as in phase 1;
- The number of PV panels $N_{PV}$ via a cursor varying from 1 to the maximum number of PV panels $N_{PV-\max}$ estimated in phase 1;
- The number of terminals $N_{terminals}$ via a cursor varying from 1 to the real maximum number of terminals $NT'_{max}$ estimated in phase 1;
- The stationary batteries capacity $C$ in kWh via a cursor varying from 0 to the maximum capacity $C_{\max}$ estimated in phase 1.

This second phase allows the user to change the parameters influencing the cost. The idea is to give to the user an overview of the possible combinations within a predetermined budget. Figure 2.3-5 presents the interface, highlighting the importance of each pole of expenditure (pie chart), where kWp denotes kW at STC.

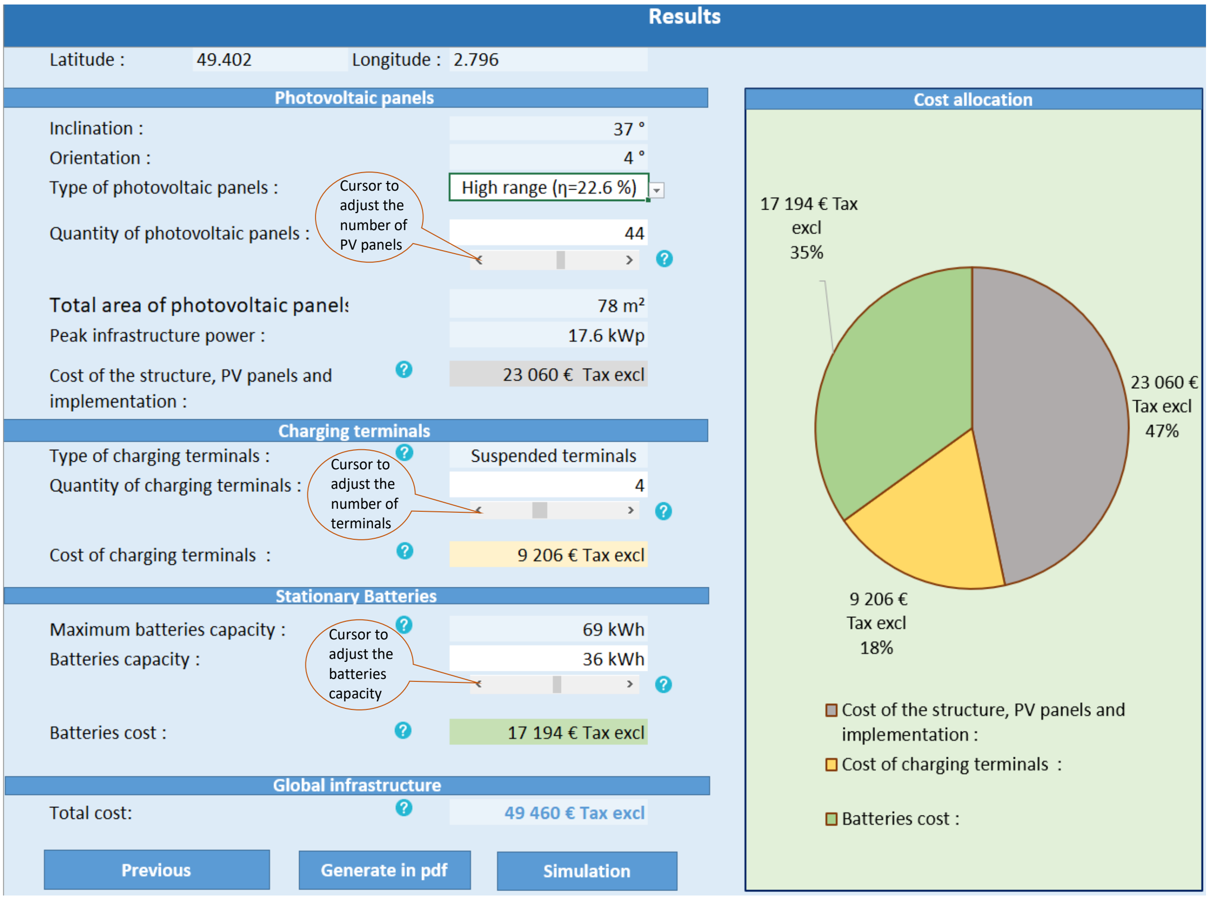


**Figure 2.3-5 Interface for adjustment of the total PVCS costs**

The interface allows to returning to the home page to enter new input data by clicking on “Previous”, or to print the current results in PDF format by clicking on “Generate in PDF” or perform a simulation of the energy balance of the infrastructure by clicking on “Simulation” (Figure 2.3-5).

### *2.3.2.3 Phase 3: PVCS Performance Assessment*

The phase 3 offers a detailed qualitative analysis of the new user-defined configuration in phase 2. The objective is to assess the performance of the PVCS and then to improve its sizing and operating modes, aiming at increasing the use of PV energy, while minimizing the energy supplied by the power grid. Once the dimensioning of the infrastructure has been chosen, the operating mode simulation makes it possible to evaluate its performance by proposing an energy balance according to different charging scenarios and weather conditions. The simulation algorithm proposes an arbitrary distribution of the number of EVs connected either in fast charging mode or in slow charging mode. This distribution is carried out every 2 h, between 6:00 a.m. and 22:00 p.m. To change the scenario, it is possible to choose one of the scenarios from the “Scenario” scrolling menu. The charging table is automatically modified according to the choice. The tool gives the possibility to personalize the charging profile of EVs and consequently improves the contribution of the energy provided by the PV panels for recharging. Figure 2.3-6 shows the flow chart of the phase 3.

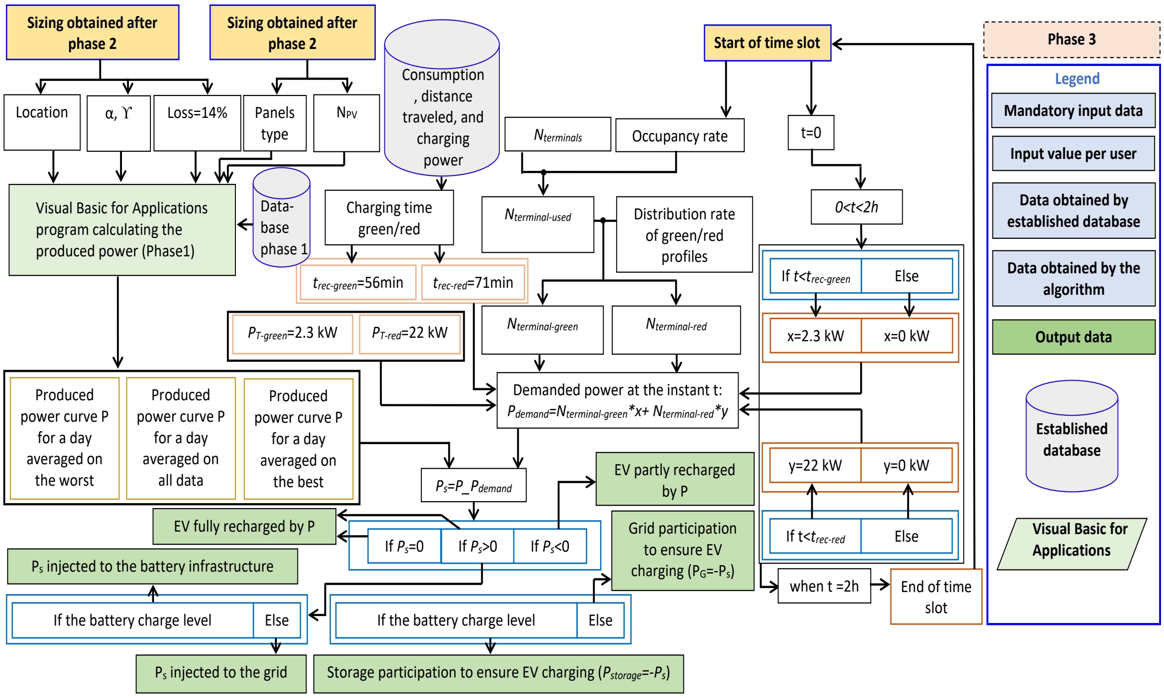


**Figure 2.3-6 Flow chart of phase 3**

### *2.3.2.3.1 General assumptions*

Additional working assumptions are formulated for phase 3. Firstly, the PVCS sizing obtained at the end of phase 2 is an input to phase 3, and the solar irradiance data used in phase 1 is also used in this phase.

The storage of the excess energy produced by PV is ensured by stationary batteries within their storage capacity limits, which maximum capacity is obtained or chosen at the end of phase 2. The SOC of the stationary batteries, at the start of the day at 8:00 am, is considered to be 50%. It is assumed that the charge and discharge of the stationary storage are equally distributed among all the batteries that compose it.

In addition, in this study, it is considered that users cover a distance of 43 km daily, an average value among EV users according to the U.S. National Household Travel Survey NHTS dataset, as in [14]. The battery capacity of EVs is assumed to be 50 kWh, which corresponds to the average battery capacity of EVs on sale in 2020 [17].

Two user profiles of the PVCS are then defined. The first profile, named green profile, represents a user of the PVCS adopting eco-driving by lowering the vehicle's consumption and promoting PV benefits, thanks to the daily EV recharging, thus allowing him to do each time small charges. Conversely, a PVCS user with a red profile charges its EV infrequently, which requires more energy for each charge. In addition, the red user does not adopt eco-driving. In addition, for the green profile, the consumption is estimated at 10 kWh per 100 km while for the red profile, it is 15 kWh per 100 km. Two different charging powers are also assumed: the green profile uses the slow charging mode based on 2.3 kW, $P_{T\_green}$ , while the red profile uses the fast-charging mode based on 22 kW $P_{T\_red}$ . Table 2.3-5 summarizes these two different user profiles.

**Table 2.3-5 User profiles of the PVCS**

| Profile | Drive mode | Charge type | Maximum charging power | Estimated consumption |
|---|---|---|---|---|
| Green | Eco-drive | Slow charge | 2,3 kW | 10 kWh/100 km |
| Red | Normal drive | Fast charge | 22 kW | 15 kWh/100 km |

##### *2.3.2.3.2 Preliminary calculations*

For a green profile the energy required for recharging an EV $E_{rec-green}$, which covers only half of the 43 km daily above mentioned, is calculated by equation (2.3-9) while the EV charging time $t_{rec-green}$ is expressed by (2.3-10):

$$E_{rec-green} = \frac{10}{100} \cdot 21.5 = 2.15kWh \tag{2.3-9}$$

$$t_{rec-green} = \frac{E_{rec-green}}{P_{T-green}} = \frac{2.15}{2.3} = 53\,\text{min} \tag{2.3-10}$$

As for the red profile, it is considered that the EV is charged every 4 days and covers 43 km per day. Thus, the energy required for recharging an EV for a red profile $E_{rec-red}$ is calculated following (2.3-11) and the EV charging time $t_{rec-red}$ is given by (2.3-12):

$$E_{rec-red} = 4 \cdot \frac{15}{100} \cdot 43 = 25.8kWh \tag{2.3-11}$$

$$t_{rec-red} = \frac{E_{rec-red}}{P_{T-red}} = \frac{25.8}{22} = 71\,min \tag{2.3-12}$$

##### *2.3.2.3.3 Charge scenarios*

Four scenarios are studied to assess the share of PV energy in the charge of EVs and to better adapt the operation to increase the share of PV and reduce the energy supplied by the power grid. According to the chosen scenario, the profile distribution rates vary:

- Virtuous scenario: 100% green user profiles;
- Critical scenario: 100% red user profiles;
- Realistic scenario: 30% red user profiles and 70% green user profiles. This scenario is intended to be realistic because the red users are, by definition, less regular users of PVCS;
- Personalized scenario: this is proposed to give the tool user the possibility to choose the number of terminals used as well as the distribution between the users of the PVCS with green and red profiles. It is only limited by the number of terminals chosen at the end of phase 2.

In addition, for all these scenarios, an occupancy ratio (OR) of electric charging terminals are arbitrarily fixed, reflecting the arrivals and departures of users throughout the day. The OR is a percentage of the number of terminals used during a 2-hour time slot. If the percentage applied to the number of terminals does not result in an integer value, the value is rounded by default to the next whole number:

- 8:00 a.m. to 10:00 a.m.: OR = 50%;
- 10:00 a.m. to 12:00 p.m.: OR = 100%;
- 12:00 p.m. to 2:00 p.m.: OR = 50%;
- 2:00 p.m. to 4:00 p.m.: OR = 100%;
- 4:00 p.m. to 6:00 p.m.: OR = 75%.

These default values can nevertheless be changed manually by the tool user.

##### *2.3.2.3.4 Algorithmic logic*

From the OR and the number of terminals $N_{terminals}$ chosen in phase 2, the algorithm is able to calculate the number of terminals used $N_{terminal-used}$ per 2-hours' time slot. Then, one of the four possible scenarios is chosen and the algorithm determines the number of fast charging $N_{terminal-red}$ and slow charging $N_{terminal-green}$ terminals, and afterwards, calculates the total demanded power $P_{demand}$ as expressed in Equation (2.3-13):

$$P_{demand} = N_{terminal-red} \times P_{T-red} + N_{terminal-green} \times P_{T-green} \tag{2.3-13}$$

The algorithm then calculates the difference between the power requested by all the used terminals and the power supplied by the PV panels. If this difference $P_{diff}$ is greater than or equal to zero, then the EV is recharged only by a power $P$ coming from the PV panels. By contrast, if the power $P$ is less than the difference $P_{diff}$ , the excess noted $P_s$ is sent to stationary storage provided that it has not reached a SOC greater than 80%. In case of stationary batteries are fully recharged, the surplus is injected into the power grid. If the difference $P_{diff}$ is less than zero, then the EV cannot be fully recharged by the power supplied by the PV panels. To achieve the required charging power, the complement $P_s$ is provided by stationary storage, provided that it has not reached a charge level below 10%. In this specific case, it is the power grid that completes the charge of the EV.

To illustrate the simulation, based on arbitrary inputs data and the PVCS sizing adjusted in phase 2, some results are given in Figure 2.3-7.

The energy rating is based on the share of energy supplied by the PV panels compared to that supplied by the power grid. With the reduction in the number of EVs in fast charge mode, PV benefits increase for the EV charging, and the dependency on the public grid is reduced.

The simulation presents three predefined scenarios with three predefined hourly occupancy percentage.

The realistic scenario is proposed by default (Figure 2.3-7a). If one of the scenarios is chosen from the scrolling menu, the table indicating the number and type of terminals occupied per time slot is pre-filled (Figure 2.3-7b). Following the choice of scenario, the energy balance comes in three types of days:

- An average sunny day, resulting from an average obtained over a period extending between 2005 and 2016 (Figure 2.3-7c);
- A poorly sunny day, corresponding to an average carried out over the least sunny month (Figure 2.3-7d);
- A very sunny day, corresponding to an average carried out over the sunniest month (Figure 2.3-7e).

The results are available in two forms:

- A circular diagram, representing the percentage of each energy source to ensure the recharging of EVs. It makes it possible to account for the distribution of energy from PVCS (energy from PV) and external energy (from power grid);
- A histogram, allowing a more detailed analysis of the energy distribution per two-hour time slot.

If the scenario is changed, the results are updated automatically.

Figure 2.3-7 shows that, obviously, the participation of PV production in EV charging increases for the very sunny days compared to less sunny days. In this support tool, it is the user who chooses the charging mode (slow or fast) that suits him best (parking time, electricity bill, etc.). For slow charging mode, the level of the delivered power is low, which enables PV and stationary storage system to share the requested charging power of the EVs, without the need to the public grid (histogram of Figure 2.3-7c during time slot 16 h to 18 h). Whereas, in fast charging mode, the level of the delivered power is high. Therefore, EVs are charged mainly with the public grid and for a small portion with PV, because the stationary storage system will reach rapidly its minimum limit, and PV production is not sufficient for charging (histogram of Figure 2.3-7c during time slot 14 h to 16 h).

In conclusion, the slow charging mode improves the PV benefits, where EVs are charged mainly with PV energy. In addition, this charging mode can not only improve PV benefits but reduce the impact on the electricity distribution network, and the user can charge EVs with the lowest cost.

This study does not include optimization elements such as analysis of the maximization of the number of EVs charging stations at the expense of the power available for individual EV or minimizing the charging time so that as many EVs as possible can be charged in one day. The work presented in this chapter was carried out following [17] results where some optimization elements are introduced. Nevertheless, further investigations will be necessary.

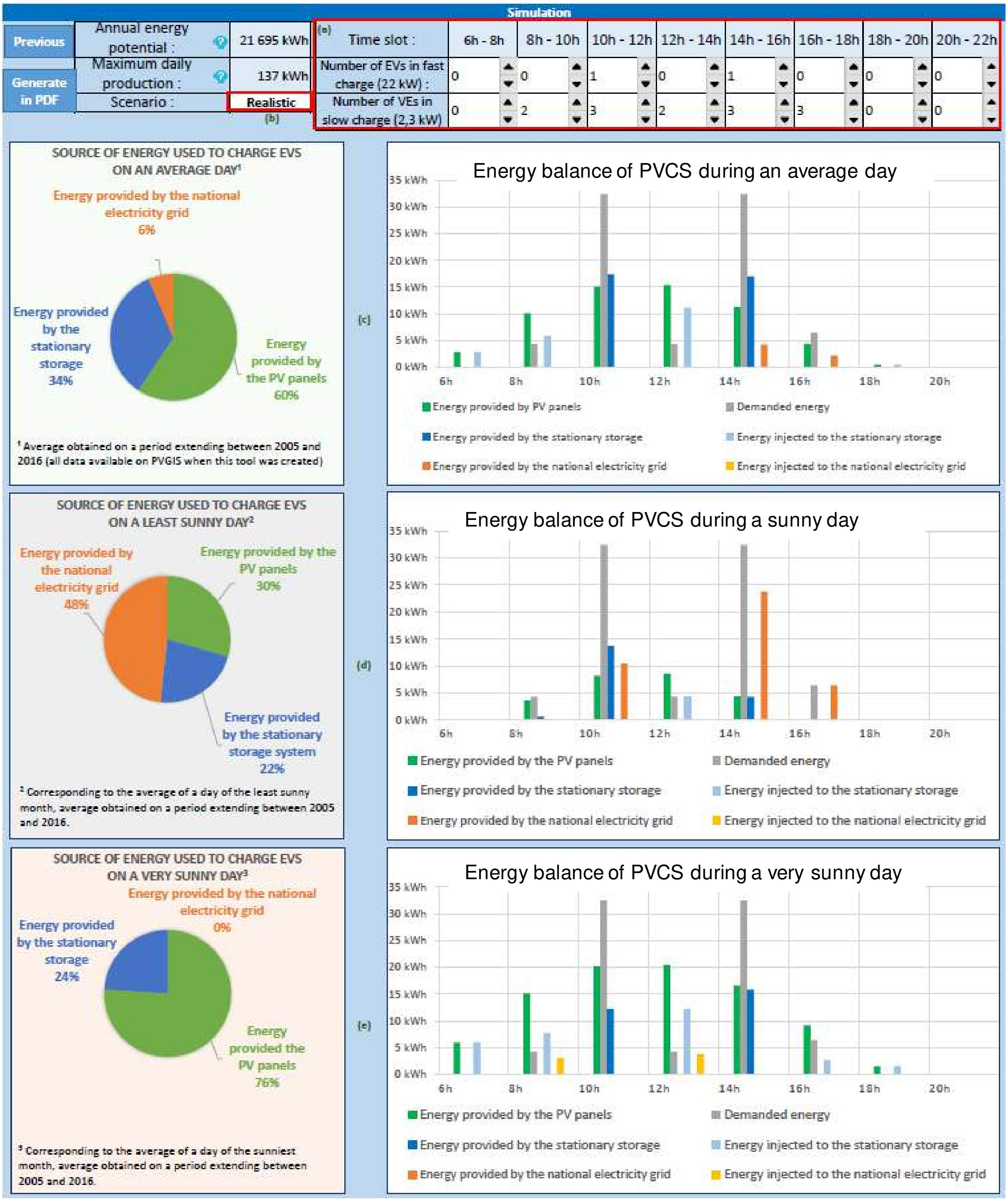


**Figure 2.3-7 Interface for PVCS energy: realistic scenario (a), number and type of terminals occupied per time slot (b), results for average sunny day (c), results for poorly sunny day (d), and results for very sunny day (e)**

### *2.3.3 Conclusions*

This study looks at energy management aimed at increasing PV benefits. An important part of the work described was the development of a technical-economic tool intended to help local stakeholders determine criteria for the installation of a PVCS. The design methodology included the use of an algorithm, resulting, phase by phase, in the constitution of the techno-economic tool, which was coded on an easy-to-use interface.

The user of the tool, after entering some easily obtainable items of data, is given the pre-sizing of the infrastructure, a budget associated with this sizing that can be adjusted, and a qualitative evaluation simulating the ecological characteristics of the infrastructure thus dimensioned.

The tool's manageability and simplicity in comparison to alternative computation software make it suitable for a wide spectrum of target populations, some with specialist knowledge and others without. The charging mode can affect the PV benefits obtained, and EVs can be more or less reliant on PV as opposed to the public grid. In slow charging mode EVs can be charged mainly from PV energy and the stationary storage system, while in fast charging they will be charged mainly from the public grid. The fast-charging mode can not only reduce PV benefits but also have an impact on the power grid and increase electricity bills.

In its current state the tool addresses EV charging only, but subsequently it could be used in relation to the charging of other kind of EVs, such as PHEVs and types of vehicles other than passenger cars. Future studies will concentrate on improving the tool by integrating other parameters such as $CO_2$ emissions and the total levelized cost of energy, which covers the lifespan cost of the PV installation, the replacement cost of the stationary storage system during the project lifetime, the maintenance cost of the PV system and the storage system, as well as the annual degradation of the PV production. Other optimization elements that might be considered in further research work are maximizing the number of EV charging stations, minimizing charging time, and possibly even the rotation of EVs in order to take full advantage of the PVCS. PV production forecasting is also required for the optimization of sizing and management of PVCSs, since it allows a better alignment of PVCS use with production programs and consequently a reduction in the total levelized cost of energy.

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# 3 POSSIBLE NEW SERVICES ASSOCIATED WITH THE PV-POWERED INFRASTRUCTURE FOR EV CHARGING (V2G, V2H)

The capacity of EV batteries means that they can be used as an energy storage system, given that vehicles are often sitting idle when their users are at work or at home. The stored energy can be used to supply some system (such as the public grid or the home) when needed. The EV can act both as a storage system and as a generator to provide new services. This chapter presents possible new services linked to PV-powered infrastructures for EV charging, including V2G and V2H.

The chapter has two parts. The first gives an overview of current status and progress in relation to the possible impacts of V2G and V2H and includes a state of the art on the different services that can be provided by EVs to other systems. It presents some realized projects, the technological risks of the V2G service, and technical specifications of existing V2G charging stations. A successful implementation of these services will depend on the growth of the EV fleet. For the moment, V2G systems are not yet ready for industrial-scale use, with a number of difficulties remaining to be overcome and requiring solutions.

The second part looks at a peak and valley searching algorithm (SPVA) able to deal with the intermittency of PV generation and EV charging demand and which features V2G as a way of mitigating the impact on the public grid. PV-powered EV charging stations represent a promising application for this algorithm, which is able to ensure the balance of the public grid, satisfy the charging demand, and reduce the public grid energy cost. SPVA defines the optimal charging/discharging start times of EVs, their arrival time, departure time, initial state of charge, and the minimum or maximum state of charge at the time of departure, to achieve peak shaving and valley filling while reducing the costs of energy from the public grid, which is beneficial to the public grid and EV users.

## 3.1 Overview, current status, and progress on possible impacts of V2G and V2H

### 3.1.1 Introduction

This part of the study looks at the different services that can be provided by EV batteries to other systems, i.e. the public grid, homes, and buildings. The state of the art below covers basic concepts, conditions of implementation, experiments carried out, and feedback obtained in relation to these different services.

### 3.1.2 State of the art

In France the average vehicle is in use for only 6 hours per week, for an average daily journey of 21 km (i.e. a consumption of about 4,2 kWh, recoverable in 1h30 hours with a slow charge of 3 kW). The proportion of vehicles in any vehicle pool that are parked simultaneously rarely drops below 80%. One way of reducing the cost of ownership of an EV is to use its battery as storage for the public grid when it is connected to the grid. This is possible as long as EVs have good energy flexibility as well as time flexibility.

Aspects of the above considerations that have been widely examined are: integration of intermittent renewable energies, minimization of charging costs by benefitting of low electricity prices, voltage regulation, and frequency regulation. It has been shown that the most economically profitable electricity markets for EVs are those that pay for availability (in € / MW) and not for use (in € / MWh), and those that require little energy but require strong responsiveness. Frequency tuning thus represents one of the best opportunities among network services for a fleet of EVs. The purpose of this work is to identify these services, present a state of the art, and give some functional specifications for a technical and economic regulation tool for charging stations based on PV power. The new services studied are classified into three categories [1]:

- V2G - Technologies that allow an EV to be connected and recharged from a terminal are known grid-to-vehicle (G2V) technologies (Figure 3.1-1). Electricity flows from the power grid to the EV (unidirectional model) and the EV is considered to be an electricity consumer. Conversely, when the EV supplies the power grid according to the needs of the electricity network (bidirectional model) and offers it a service of flexibility, technologies are labelled V2G. The term V2G, literally “from the vehicle to the grid”, means reinjecting the electricity contained in the batteries of an EV into the public grid when it is parked and standing idle [2]. The EV thus communicates with the power grid, more precisely with the *smart* power grid, to carry out this action: the batteries of an EV fleet become energy storage units. V2G services require bidirectional charging stations. Regulating the frequency of the public grid, smoothing the peak of electrical consumption as well as voltage support are the three main services that have been studied, implemented and tested.

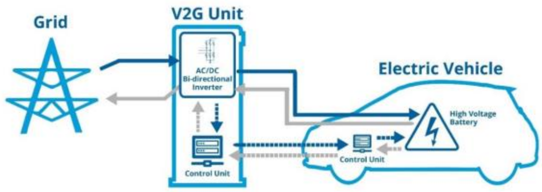


**Figure 3.1-1 V2G components** *(Source: automobile-propre.com)*

- Vehicle-to-home (V2H) and vehicle-to-building (V2B) - These are variants of V2G (Figure 3.1-2). In the case of V2H, the EV supplies a dwelling for self-consumption and in the case of V2B, a cluster of EVs powers a residential or business building. Unlike in V2G where a dwelling or building is permanently connected to the power grid, in a V2H or V2B system electrical energy is not fed back into the power grid. There is therefore no "outgoing" electricity meter. However, in the event of a power failure by the power grid, V2H and V2B make it possible for the dwelling or the building to continue to access an electricity supply.


**Figure 3.1-2 V2H/V2B components** *(Source: automobile-propre.com)*

### *3.1.2.1 Frequency regulation*

An electricity network has a fixed nominal frequency. In Europe the frequency is fixed at 50 Hertz, but this value is not universal: in the United States, for example, the nominal frequency of the network is fixed at 60 Hertz. The frequency is fixed according to various considerations. The higher the nominal frequency, the greater the energy required. However, if the frequency is low, this can cause problems for some electrical installations and appliances: light bulbs, for example, may start to flicker. The quality of electrical energy may vary, and voltage peaks, harmonics, etc., may be experienced. The phenomenon of frequency variation may occur in particular when there are large differences between consumption and production. As shown in Figure 3.1-3, during a period of overconsumption, the load increases and therefore the frequency decreases. Conversely, during a period of underconsumption, the load decreases and the frequency increases. Departures from nominal frequency level are most likely to occur during peaks and troughs in consumption.

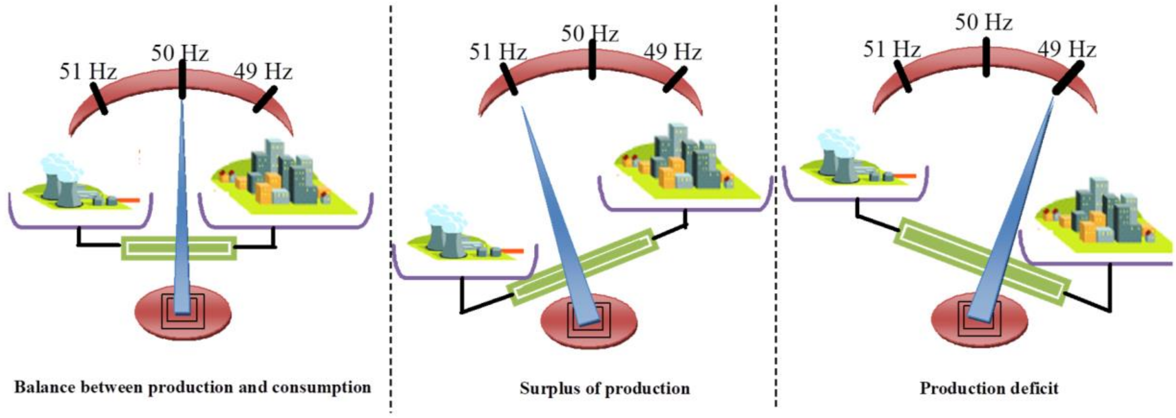


**Figure 3.1-3 Frequency variation according to production and consumption balance**

The objective of frequency regulation is to limit the variation to an order of magnitude of 0.1 Hertz. Too large variations in frequency make electricity unusable. For example, if the frequency of the network varies and goes outside the operating range of an electronic device, this may cause malfunctions. Automatic regulation mechanisms are implemented in order to maintain the frequency in an acceptable zone (± 0.5 Hz around 50 Hz) and avoid load shedding or blackouts. The transmission system operator (TSO) contracts with producers an active power reserve that can be mobilized at any time to bring the system back into balance. This will feature a primary reserve allowing frequency deviations to be contained within a few seconds, and a secondary reserve that can bring the frequency back to its nominal level within a few minutes [3]. In addition, a tertiary reserve makes it possible to settle longer-term differences (from tens of minutes to several hours), to replace the secondary reserve if the latter is exhausted or is not sufficient to cope with a new imbalance, and also to replace the primary and secondary reserves and anticipate imbalances. As an example, for France: the production system contributes approximately 540 MW for the primary reserve, and the secondary reserve is between 500 MW and 1180 MW, where all producers operating generation groups of more than 120 MW in France are required to participate.

Since frequency variations have short time constants, a fast response mechanism such as a collection of batteries will be better able to follow the frequency precisely and, therefore, limit excessively large deviations from the equilibrium value of 50 Hz or 60 Hz. The superior performance of these fast response units in comparison to conventional means such as thermal power stations makes it possible to stabilize the power grid with fewer megawatts reserved for frequency regulation.

*3.1.2.2 SEPTA project*

In the United States, SEPTA (Southeast Pennsylvania Transportation Authority), Constellation (an energy production and distribution company) and Viridity Energy (a consulting firm specializing in energy) have joined forces to put in place an 8.75 MW storage system with batteries (Figure 3.1-4) [4]. The services provided through the use of batteries are of three types:

- recovering braking energy from trains and then reinjecting it during phases acceleration of these trains;
- in the event of a power failure, being able to reuse this same stored energy;
- participating in the frequency regulation mechanisms of the grid.


**Figure 3.1-4 SEPTA project** (Source: septa.org)

As regards the technical implementation, resources mobilized on the frequency regulation market are traditionally controlled in the United States by means of a control signal sent every 4 seconds. To encourage the use of fast resources in the regulation market, PJM (which manages the electricity transmission network that coordinates the electricity market in 13 states and Washington D.C.) has created a new control signal, which is sent every 1,5 seconds. By convention, PJM calls the traditional signal at 4 seconds *RegA* and the fast signal at 1,5 seconds *RegD*. Thus, from now on, when a resource submits an offer on the regulation market, it must specify which signal it wishes to be controlled by: either RegA or RegD. To qualify for RegD, resources undergo a battery of tests to determine whether or not they are able to follow this fast signal (Figure 3.1-5). Although the fast resources mobilized following RegA are considered to be more efficient, it should be remembered that the two types of resources are complementary. Traditional resources are slower at start-up and have more difficulty following the set point signal, but they offer a larger energy reserve than that offered by fast resources.

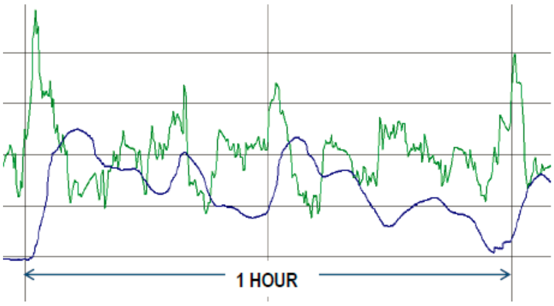


**Figure 3.1-5 RegA (blue) and RegD (green) signals** (Source: pjm.com)

### *3.1.2.3 Los Angeles Air Force Base V2G project*

California has a regional electricity network that features a high proportion of renewable energies (42% of production in 2017). Faced with air pollution and environmental problems, California plans to deploy more than 1,5 million EVs by 2025. In addition, the unpredictability in the production of renewable energies such as solar and wind gives rise to frequency instability in the electricity network. For these two reasons, the United States is carrying out an experiment with V2G technology. The first goal of this experiment is to assess the ability of V2G technology to lower the cost of an electric car. It also aims to identify legislative and technical obstacles and to improve the technology used. The project has deployed 42 EVs (Nissan Leaf V2Gs and modified Ford hybrid pickups) equipped with a bidirectional charging mechanism (Figure 3.2-6). Coritech supplied the bidirectional electrical terminals in association with Princetown. Vehicles have the capacity to simultaneously discharge 700 kW when all of them are connected to a charging station.

The primary purpose of the project is to determine whether a flexibility service linked to the California electricity system, made possible by the V2G system, changes the economic equation for EVs. According to the Berkeley Lab, the preliminary results of the project estimate a gain of around $ 100 per vehicle per month for the fleet operator resulting from this flexibility service. This figure must be assessed in the light of the additional costs specifically linked to V2G, including the purchase and installation of bidirectional systems and communication between meters and the network operator. As one example, currently, direct CAISO (California Independent System Operator) access to its on-base meter via its private energy communications network alone costs up to $ 500/month, suggesting under some scenarios 4 PEVs would be participating in the market simply to cover communication costs to their meter. Luckily, this project has secured a CAISO waiver allowing much cheaper dial-up meter reading. At the end of the project, the Defense Department will analyze feedback to decide how to develop its entire fleet.

But the project also has some secondary objectives, namely:

- examining obstacles to the development of these services (in particular regulatory and related to the regulation of the electricity market);
- putting forward alternative models that would enable these obstacles to be overcome;
- identifying the key interlocutors and partners to include in the discussions;
- testing and selecting the best technical solutions for bidirectional charging stations and batteries developed by manufacturers, equipment manufacturers, etc.

Currently, EVs at Los Angeles Air Force Base are helping to balance the electricity system in California by injecting electricity during peak periods and consuming temporary overproduction. Intermittent PV energy represents 6,4% of the Californian energy mix, compared to 0,3% for the whole of the United States, and this causes variations in production.


**Figure 3.1-6 Los Angeles Air Force Base V2G project** (Source: chargedevs.com)

The pilot was successful in providing frequency regulation to the CAISO market for a total of 243 MWh of regulation up and 102 MW h of regulation down from May 2016 to September 2017.

### *3.1.2.4 Smart Solar Charging: Bi-Directional AC Charging (V2G) in the Netherlands*

In the Netherlands, in the province of Utrecht, a V2G pilot project was set up in June 2015 to provide information about consumer behavior. The initial phase saw the installation of 20 chargers capable of charging and discharging 40 Nissan Leaf EVs. Utrecht's ambition is to become the first region in Europe with a regional energy system based on AC V2G and requiring a total of 1 000 AC V2G chargers, 1 000 shared EVs, and 10 000 new installed solar panels. This project has the long-term goal of avoiding the cost of renovating the energy infrastructure, which is too small to hope to continue to regulate the electric frequency properly (Figure 3.1-7). Utrecht, like California, has high solar energy production. Most homes have PV panels and the V2G project was carried out taking this specificity into account. V2G vehicles allow people whose homes produce PV energy to inject some of this renewable energy into their V2G vehicles during periods of high production (bright sunshine, etc.), and to feed electricity back into the grid when PV production is lower. According to [5], V2G technology can make electricity on average 80% cheaper for owners of PV panels. This is a case of direct collaboration between the individual and the electricity network, helping the former to reduce electric bills and the latter to stabilize the frequency of the grid.

In order to make a true regional energy system within the open market economy of the Netherlands, each EV has an aggregator that manages its charging, based on the balance between the production and consumption of the renewable energy integrated in the system. By selecting the optimal charging times, when the prices are at their lowest, aggregators increase the share of renewables in the energy mix. After the introduction of aggregators, in March 2016 Renault announced they would supply 150 Renault ZOE models through 2017 to the city of Utrecht. In a second stage the 150 Renault ZOE models are to be replaced by AC V2G models, to be able of feeding energy stored in the batteries of parked EVs to the grid to meet peaks of demand.

Results show substantial effects of regulating and reserve power (RRP) provision in terms of monetary benefits, battery throughput and SOC distribution. RRP has resulted in monetary benefits in the range between € 120 and € 750 annually per EV owner, depending on the EV and user category. This is accompanied by increased battery throughput and lower SOC distributions.


**Figure 3.1-7 DC V2G charge with a Nissan LEAF, (b) AC V2G charger [5]**

### *3.1.2.5 GridMotion*

In association with several energy companies, the French automobile manufacturer PSA has launched GridMotion whose objective is to assess the savings that users of EVs could make thanks to V2G solutions. Concretely, the project consists in both shifting the load of vehicles to periods when the cost of electricity is lowest but also offering the possibility of re-injecting energy from the battery into the network if necessary. Led by PSA, the partners in this two-year experiment are Direct Energie, Enel, Nuvve, Proxiserve, and the Technological University of Denmark. Two fleets are used for the tests:

- A first fleet with fifteen users of Peugeot iOn, Partner Electric, Citroën C-Zero, or Berlingo. This fleet exists to test solutions that use unidirectional charging stations. Charging then takes place when the price of electricity is lowest.
- A second fleet of fifteen vehicles comprising Peugeot iOn and Citroën C-Zero. This fleet is used for experiments involving two-way charging stations that were supplied by the Italian energy company ENEL. These stations help to balance the electricity network by alternating short periods of charge and discharge

while taking into account the energy needs of users for their trips. In practice, charging takes place where there is excess electricity production in the network, and discharging where there is excess consumption.

#### *3.1.2.6 Volkswagen V2G technology for MEB-Based EVs*

In March 2021 Volkswagen declared that it was starting work on V2G technology for bi-directional EV battery charging. From January 2022, any EV from the Volkswagen Group that uses the MEB (Modular electric drive matrix) electrical platform, will be able to provide services to the power grid by returning electricity on demand. This concerns vehicles that are branded Seat-Cupra, Skoda, VW, and Audi.

This novel V2G technology from Volkswagen may represent an interesting solution for storing unused renewable energy that cannot be stored due a to lack of energy storage devices [6] and that is estimated at 6 500 GWh in Europe. The idea is that power grid operators store this electricity in EV batteries and use it later to support the electricity network during peak hours.

A business opportunity that may be realized by V2H technology is to use the EV battery to store PV production from roof-mounted panels and to return it to a dwelling. The idea of storage is similar to stationary storage, except that with V2H technology it is almost for free. Unfortunately, this usage can reduce the lifespan of the EV battery. To overcome this drawback, Volkswagen is considering a business model based on remuneration for the use of electricity stored in the EV battery. To monetize the stored electricity, Volkswagen is seeking to make it available to utility companies and grid operators. The income will be shared between the owners of the EVs and the company.

Volkswagen’s marketing of V2G technology as a source of income may encourage people to consider driving an EV.

#### *3.1.2.7 First V2G charging pilot in the US Midwest*

In cooperation with the Indiana-based Energy Systems Network (ESN) and Battery Innovation Center (BIC), the Californian software company EV Connect has announced the deployment of Indiana's first large-scale charging system compatible with V2G technology. EV Connect provides intelligent charge management for EVs using Rhombus 500 kW bidirectional bus-scale superchargers. Objectives are testing battery conditions and communication protocols, to help industry actors involved in V2G technology to determine the impact of V2G on their products. The bidirectional chargers have potential uses in V2H, in vehicle-to-load (V2L), and vehicle-to-vehicle (V2V). However, the technology has not been widely deployed due to a lack of real data on battery performance over time, a lack of integration in wholesale energy markets, and a lack of support from EV manufacturers.

The data collected through the program will guide the BIC and Midwest utilities in developing policies for grid-interactive EV battery programs.

#### *3.1.2.8 BMW Smart Charging*

A smart charging program is being operated by the BMW group in California to improve EV charging from renewable production. BMW smart charging is linked to BMW’s ChargeForward program (running from March 2021 through March 2023), which offers incentives to the drivers of BMW EVs to increase the proportion of renewable energies in charging their vehicles. It is accessible to drivers of BMW plug-in vehicles who live in Central or Northern California. The incentives offered by this program can compensate the additional costs for some drivers, depending on their electricity tariff [7]. The smart aspects this recharging program reside in:

- charging EVs during periods of low demand for electricity;
- charging EVs when there is a higher-than-usual quantity of renewable energy being pumped into the power grid;
- using BMW ConnectedDrive, which allows connectivity between EVs, drivers and their environment, and a personalized BMW ChargeForward smartphone app enabling participants to refuse or accept smart EV charging; where they accept, EV charging is scheduled to meet the needs of the power grid.

Using smart charging can enable EVs to accept an additional 1 200 kWh of renewable energy per vehicle per year, which is equivalent to four months of recharging with clean energy for an EV. Other results of this program are [8]:

- more than 1 million miles powered by 100% renewable energy in one year;
- according a study in Northern California realized by the University of California Berkeley, intelligent EV charging can reduce $CO_2$ emissions by an additional 32%;
- for EVs with access to charging infrastructure at workplaces, smart charging allows EVs to double their consumption of renewable energy;

The BMW Group and Pacific Gas & Electricity Company are working together to explore V2G strategy possibilities.

### *3.1.3 Integration and development of renewable energies*

The diversity of renewable energies is already having a significant effect on electricity prices in Europe. Nuclear and fossil fuel power plants cannot necessarily adapt their production quickly to weather conditions favorable to the production of renewable energy (either for technical reasons or for economic reasons). The European electricity market has therefore been experiencing episodes in recent years where the price of electricity suddenly drops when the production of renewables soars. There are even periods when the price of electricity becomes negative. These episodes where the user is paid to consume electricity are quite frequent in Germany, the country generating a third of its electricity production through renewable energies.

The variability in electricity prices is expected to increase in the coming years across Europe. Electricity production should see an increased share of renewable energies in the energy mix, driven both by a drop in the cost of production of PV and wind energy and by a political commitment to decarbonize electricity production. This production will depend on variable weather factors. As shown in Figure 3.1-8, V2G allows the two elements to be combined and the batteries of parked cars to be used as a source of storage when the production of electricity via renewable energies exceeds demand. These cars can return this energy to the grid when the demand / supply ratio is reversed. Their owners thus have the benefit of low-cost electricity rates on very sunny or windy days, and can sell this surplus at a better price later. For the operator of the electricity network, the interest is to better manage the ups and downs of renewable electricity production.

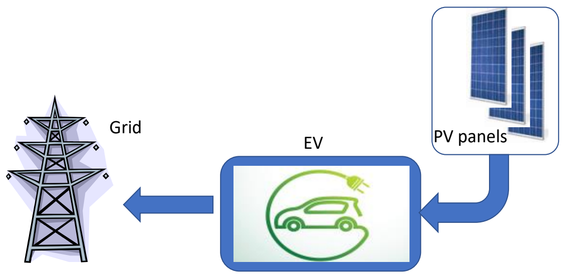


**Figure 3.1-8 Integration and development of renewable energies for V2G technology**

### *3.1.4 Technological risks of V2G*

#### *3.1.4.1 Battery life*

Average battery life is 1 000 to 1 500 charge cycles. This is equivalent to approximately 200 000 to 500 000 km, depending on how the EV is used. The length of battery life will depend on the charge / discharge currents applied but also on the discharge depth as well as on environmental conditions, in particular temperature.

#### *3.1.4.2 Additional investment and maintenance costs*

The power electronics required to set up V2G will be more expensive than a simple unidirectional charging system for EVs. It is also necessary to add the extra cost of battery charge / discharge cycles due to V2G. The electrical transformers will in theory be resized to accept load cycles and limit overloads that are followed by rest time. Where there is incorrect sizing or "permanent overload", their lifespan may even be reduced.

#### *3.1.4.3 Changing the batteries*

They are easily interchangeable provided that the system was designed with this consideration in mind. Otherwise, such a change can prove to be complex and therefore costly.

#### *3.1.4.4 Complexity of implementation*

A system that reduces the cost of recharging and owning vehicles without any user intervention will necessarily be more complex to implement.

#### *3.1.4.5 Fragmented market*

Users of V2G-base services must be willing to purchase electricity from sources that can be connected and disconnected from their network at the whim of EV users, that is to say with an element of unpredictability. The larger the managed EV fleet, the lower the aggregated unpredictability. Services that use V2G will have an interest in being able to have power reserves the order of megawatts to be able to call on, and this implies the existence and connection of hundreds of thousands of vehicles.

#### *3.1.4.6 Battery recycling*

Battery Directive 2066/66 / EC specifies that “In terms of liability, producers of batteries and accumulators and producers of other products in which a battery or accumulator is incorporated are responsible for the management of waste batteries and accumulators that they put on the market". This means that manufacturers wishing to place a manufactured product on the market must have access to a system for collecting and recycling the product at the end of its life, when it represents dangerous toxic waste. The recycling sector has been developing as the number of spent units has increased. The new metal refining company (SNAM), located in the Rhône area in France, handles 90% of the European market for recycling traction batteries. This indicates that there are still few battery recycling companies and still a low number of EVs at the end of their useful life in Europe today.

### *3.1.5 Technical specifications of existing V2G charging stations*

The few technical specifications that we have been able to obtain are those for a bidirectional charging station allowing the discharge and recharging of VEs at a power of 10 kW (Figure 3.1-9 and

**Table 3.1-1**). This system marketed by Enel [9], the main producer of electricity in Italy, is presented as capable of providing the following services:

- Smoothing of consumption;
- Network balancing;
- Emergency power supply in the event of a power outage.


**Figure 3.1-9 Fasto V2G charging station** (Source: les-smartgrids.fr/v2g-experimentations-grande-echelle/)

**Table 3.1-1 Fasto V2G charging station**

| | |
|---|---|
| Input | |
| Voltage | 400 V AC – 3 phases + Earth + Neutral |
| Frequency | 50/60 Hz |
| Power at nominal point | 10,7 kVA |
| AC Current per phase | 16 A |
| Power factor | > 0,95 |
| Total Harmonic Distortion | < 3% |
| Output (charge) | |
| Power at maximum | 10 kW |
| Current at maximum | 31 A |
| Voltage | 50 – 500 V DC |
| Efficiency | > 93% |
| Output (discharge) | |
| Power at maximum | 9,3 kVA |
| Current at maximum | 13,5 A |
| Voltage | 400 V AC – 3 phases + Earth + Neutral |
| Power factor | Pure sine wave |
| Electrical specifications and protections | |
| Technology | Rectifier |
| Protection short-circuit | Yes |
| Protection overload | Yes |
| Protection leakage current (AC) | Yes |
| Protection leakage current (DC) | Yes |
| Protection anti-islanding | Yes |
| Emergency stop button | Yes |
| Insulation system | Low frequency |
| Charge / discharge mode | Mode 4 |
| Charging protocol | CHAdeMO (TEPCO) |
| Discharging protocol | CHAdeMO MMC & Nissan |
| Connector type | JEVS G105 |

### *3.1.6 Conclusions*

The scenario in which EVs are used as an “electricity storage facility” shows how the traditional demarcation between producers and consumers of electricity is changing. Today, households are increasingly producing their own electricity using, for example, PV panels. The use of smart meters, which record and store data relating to both production and consumption, facilitates and encourages the resale of electricity produced by an individual to neighboring communities or households. Network operators are reacting to this new environment and modernizing their networks so that they are better adapted to this new production/consumption paradigm. However, the modest scale of projects shows that V2G is still a long way from its stated ambition for the long term. The intraday price differences on the electric market are already a powerful economic argument for V2G.

Its success will depend on the growth of the EV fleet. V2G systems are not ready for industrial-scale operation today. There are still many difficulties to be overcome and solutions to be found. In order for V2G, V2H, V2B and other V2X systems to be profitably marketed, the size of the EV sector will need to reach a certain threshold.

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## 3.2 PV-Powered charging station for EVs: power management with integrated V2G

The growing number of EVs is leading to an increase in the demand for power from the public grid, and PV-based charging stations for EVs can help solve some peak power problems. At the same time, V2G technology is being developed and applied to provide ancillary services to the grid during peak periods, with EV batteries having a dual "load-source" role. In this chapter[4], a dynamic peak and valley searching algorithm (SPVA), based on energy management, is proposed for use by EV charging stations to alleviate the impact on the public grid, while reducing the costs of electricity provided by the grid. The proposed SPVA can determine the optimal charging/discharging start time for an EV, taking into account a number of factors including the initial SOC, charging modes, arrival time, departure time, and peak periods. Simulation results show the effectiveness of the proposed SPVA, which can ensure balance within the public grid while satisfying the charging demand by EV users and, most importantly, reducing the costs of electricity provided by the grid.

### *3.2.1 Introduction*

Due to the advantages of no noise, low environmental pollution, high efficiency of energy use, and simple structure, EVs have received widespread attention [1, 2]. With the development and popularization of EVs, large-scale EVs will be connected to the public grid for charging in the future [3, 4]. The EV distribution in time and space has great randomness and uncertainty [5, 6], thus, a large number of random and unmanaged EVs access to the public grid may have a serious impact on the public grid: load growth, increased difficulty in public grid operations control, and the necessity for a large number of power distribution network upgrades [7, 8]. Therefore, how to coordinate the control of the energy flow between EVs and the public grid is a key issue.

In order to reduce the peak loads, the paper [9] proposes a real-time dynamic pricing model for EVs charging/discharging service and building energy management. In practice, many EVs are traveling on the road for only 4-5% of the day, while they are parked for the rest of the time [10]. Research on bidirectional on-board chargers will make EV discharge possible [11]. EVs can discharge to the public grid during its "*peak*" periods and can be charged during its "valley" periods to achieve peak shaving and valley filling [12]. When EVs need energy supply, they are connected to the public grid as charging loads; when EVs are idle, i.e. EV are seen as distributed power sources, EV battery energy can be injected into the public grid. This is the V2G operation. Thus, V2G technology makes it possible for EVs to have a mobile battery function [13]. Moreover, compared with common loads, EVs

[4] This chapter is based on the following publication: D. Wang, M. Sechilariu, F. Locment: "PV-powered charging station for electric vehicles: power management with integrated V2G", Applied Sciences, vol. 10, no.6, pp 6500, 2020, https://doi:10.3390/app10186500

have greater flexibility and dispatchability. When reasonable scheduling strategies for V2G technology are designed, and the charging/discharging behavior of EVs is planned, EV charging costs will be reduced, most importantly, the load curve of the public grid will be improved. The paper [14] proposes a time-based charging group dispatching approach to schedule the charging of numerous EVs, which enables EVs to play an important role in peak shaving and valley filling, meanwhile solves the stability problem of MG systems caused by the significant penetration of renewable energy.

EV batteries and related power electronics can be used to mitigate PV sources' impact and support the public grid with appropriate control strategies. The paper [15] develops a controllable charge/discharge pattern to optimize the limitation of EV battery capacity and the impacts of PV sources. Most importantly, EVs can provide instant power, much faster than starting a standby power source. So, V2G technology enables EVs to act as emergency power sources in the event of a power outage [16, 17]. V2G can bring economic benefits to EV users, offset part of the EV costs, and enable communication between the public grid and EVs. V2G services are important for reducing environmental pollution, mainly the emissions of $CO_2$ [18].

With the continuous development of renewable energy, such as PV sources, more and more renewable energy is being integrated into the power system. Considering the intermittency and distribution of PV sources, MGs are proposed to achieve small-scale renewable energy penetration while reducing the public grid stress [19, 20]. Surveys show that most EV users can accept the intelligent EV charging station based on a MG [21, 22]. The paper [23] proposes the model for an EV charging station. Traditional V2G technology mainly refers to EVs directly connected to the public grid for the energy exchange. Generally, two types of control exist in systems: centralized control and decentralized control [24]. The former needs high construction costs, while the latter is more difficult to control.

Therefore, the V2G based on a DC MG control mode is proposed, which makes EVs connect to the public grid through a DC MG. Moreover, it effectively integrates renewable energy, while it saves the cost of buying electricity from the public grid. V2G based on MG is used for multi-objective optimization coordination between EVs and public grid to minimum grid load fluctuation, maximum renewable energy utilization, and maximum benefits for the EV users [25]. The paper [26] proposed a centralized model to co-optimize the transformer loss-of-life with the benefits for EV users on charging/discharging management. As an optimal energy cost solution, cyber insurance was introduced to guarantee the best price for charging/discharging, which is effective not only in dealing with cyber risks but also in maximizing revenue for EV users [10]. The paper [27] develops a model predictive control-based approach to address joint EV charging scheduling and power control to minimize both EV charging cost and energy generation costs in meeting both residential and EV power demands.

In addition, V2G was characterized as a comparatively advantageous means of peak load shaving [10]. The paper [24] proposes an optimal logic control algorithm based on V2G to reduce the average charging cost of EVs, which is dedicated to the French energy billing system within the peak/base hour's contract. The algorithm can minimize the EV charging cost and maximize energy selling by using Daily Energy Price profiles, considering constraints and disrupt: EV arrival/departure times, and the desired SOC ( $soc_{EV}$ ) for the next use. However, this algorithm has not yet involved PVCS and research in MG field.

In a V2G system, the EV charging station can obtain the optimal charging/discharging start time by reading the EV's arrival time, departure time, initial SOC namely $soc_{\mathrm{EV\_in}}$ , and the SOC limit at the time of departure, namely $soc_{EV\_final\_\mathrm{lim}}$ . Based on the above, this work proposes an EV charging station management with integrated V2G, in which the optimal charging/discharging start time for EVs can be determined. This allows for peak shaving and valley filling through a dynamic SPVA. Compared with the power limit of the public grid in the "valley" period, the power limit of the public grid absorbed from the MG is larger, while the power limit of the public grid released to the MG is smaller during the "*peak*" period. Therefore, when EVs connect to discharge, the charging station will select a time point near the "*peak*" periods for EVs; when EVs connect to charge, the charging station will choose a time point far away from the "*peak*" periods, which can not only relieve the pressure on the public grid but also reduce unnecessary charging costs.

In order to protect the stability of the public grid, the energy injected into the public grid needs to be limited, which will be done through the self-protection mechanism of the public grid. In order to better ensure the stability of the public grid, the power limit of the power grid is set to different values according to the “peak” periods and “valley” periods.

This chapter studies the power management of a PV-powered charging station with integrated V2G from two aspects of energy scheduling and real-time control. The main contributions of this work are:

(1) An EV charging station model combined with V2G based on a DC MG is proposed, which consists of four parts: PV sources, a storage system, a public grid connection, and EVs. This model makes full use of EV's “load-source” character to bring benefits to users while meeting user needs.

(2) A suitable power management strategy for the EV charging station with integrated V2G is proposed. In the strategy, the priority order for charging EVs is PV sources, the storage system, the public grid. During the “*peak*” periods of the public grid, the DC MG injects to the public grid, and the priority order is PV sources and then the EVs.

(3) The SPVA will calculate the optimal charging/discharging start time of EVs to achieve the effect of peak shaving and valley filling, while meeting the charging requirements of EVs, taking into account the EV arrival time, departure time, $soc_{EV}$ , and $soc_{EV\_final\_\lim}$ . Most importantly, it reduces the cost of the public grid, which is beneficial to the public grid and EV users.

(4) A reasonable electricity price mechanism is set which provides the possibility for SPVA. In order to protect the stability of the public grid, the charge/discharge power limits are different for the “peak” periods and “valley” periods of the public grid.

### 3.2.2 DC microgrid structure with integrated V2G

A MG plays an important role in the realization of smart grid, which can realize the integrated operation of multiple power sources and loads, can coordinately control with the public grid, and can meet users' requirements for power quality, power reliability and safety.

A MG based on DC common bus is considered due to its superior better current control because there is no negative and zero sequence currents [28]. The design of EV charging station including V2G is based on DC MG. As shown in Figure 3.2-1, the DC MG is composed of four parts: PV sources, a storage system, a public grid connection, and EVs.

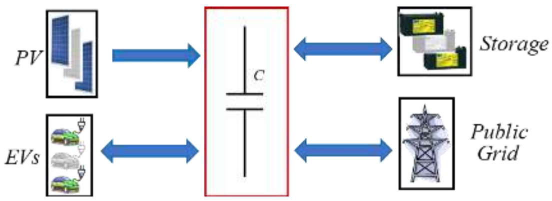


**Figure 3.2-1 DC microgrid with integrated V2G**

DC MG power flow is shown in Figure 3.2-2: ‘PV’ represents PV sources, ‘PG’ represents the public grid, ‘S’ represents the storage system, ‘EV’ represents EVs. The real-time power priority is shown by the arrow. For example, PV sources firstly support EVs, secondly charge storage, then thirdly inject to the public grid.

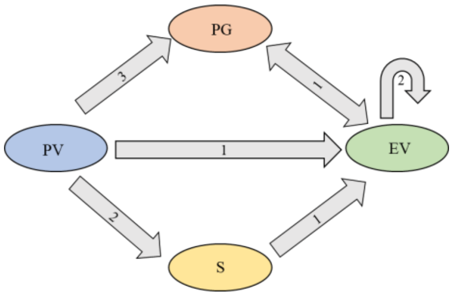


**Figure 3.2-2 DC microgrid power flow**

According to the "*peak*" periods and "valley" periods of the public grid, the energy flow of the DC MG can be divided into two cases. During the "valley" periods of the public grid, the electricity produced by PV sources is first used to charge EVs. Storage is the second-ranked energy source for charging EVs; in addition, it is also used to absorb excess energy produced by PV sources. The public grid is the third-ranked energy source for charging EVs, and it can buy excessive energy from PV sources. During the "peak" periods of the public grid, the order of charging EVs is the same as the "valley" periods of the public grid, and the difference is that V2G is achievable during this period. If the energy produced by PV sources is still in surplus after having supplied the EVs, in order to adjust the peak-valley difference of the public grid, PV sources can inject excess energy in the public grid. In addition, the energy released by EVs can be injected in the public grid. Considering the energy costs, the order of injecting energy into the public grid is PV sources firstly, then EVs batteries.

During the period of V2G, in order to ensure the power balance of the public grid, the energy injected into the public grid, namely $p_{inject\_G}$, should be limited. It may be assumed that the maximum power injected into the public grid cannot exceed the estimated PV power under STC, namely $P_{PV\_STC}$, which is shown in Equation (3.2-1), where $p_{PV}$ is PV power that can be injected into the public grid, $p_{EV\_total}$ is the power that EVs can output, $c_{EV}$ is the coefficient of PV power, and $c_{EV}$ is the coefficient of the energy that EVs can release.

$$p_{inject\_G}=P_{PV\_STC}=c_{PV}\,p_{PV}+c_{EV}\,p_{EV\_total}\ ,\ with\ c_{PV},c_{EV}\in[0,1] \quad (3.2\text{-}1)$$

### 3.2.3 Power flow management: G2V and V2G algorithm

According to users' wishes and the actual situation of EVs batteries, EVs can be divided into two types, only accept to charge, i.e. G2V, and only accept to discharge, i.e. V2G. The stored energy of the EV battery is $E$, the maximum energy that EVs can discharge is $E_{discharge}$, and the maximum energy that EVs can be charged is $E_{charge}$, which can be calculated by Equation (3.2-2) and Equation (3.2-3), respectively:

$$\begin{cases} E_{charge}=E\cdot(SOC_{EV\_final\_\lim}-SOC_{EV\_in}) & \text{if } SOC_{EV\_in}<SOC_{EV\_final\_\lim} \\ 0 & \text{if } SOC_{EV\_in}=SOC_{EV\_final\_\lim} \end{cases} \quad (3.2\text{-}2)$$

$$\begin{cases} E_{discharge}=E\cdot(SOC_{EV\_in}-SOC_{EV\_final\_\lim}) & \text{if } SOC_{EV\_in}>SOC_{EV\_final\_\lim} \\ 0 & \text{if } SOC_{EV\_in}=SOC_{EV\_final\_\lim} \end{cases} \quad (3.2\text{-}3)$$

This part presents two algorithms for power flow management of G2V and V2G, which are demonstrated within an EV charging station to simultaneously support multiple EVs.

#### *3.2.3.1 Immediate charge/discharge algorithm*

Immediate charge/discharge algorithm (ICDA) means that after the EV is successfully connected to the charger, as long as the EV operating power is within the EV power limit, the EV can be charged/discharge immediately, without considering other restrictions. The flow chart of ICDA is shown in Figure 3.2-3.

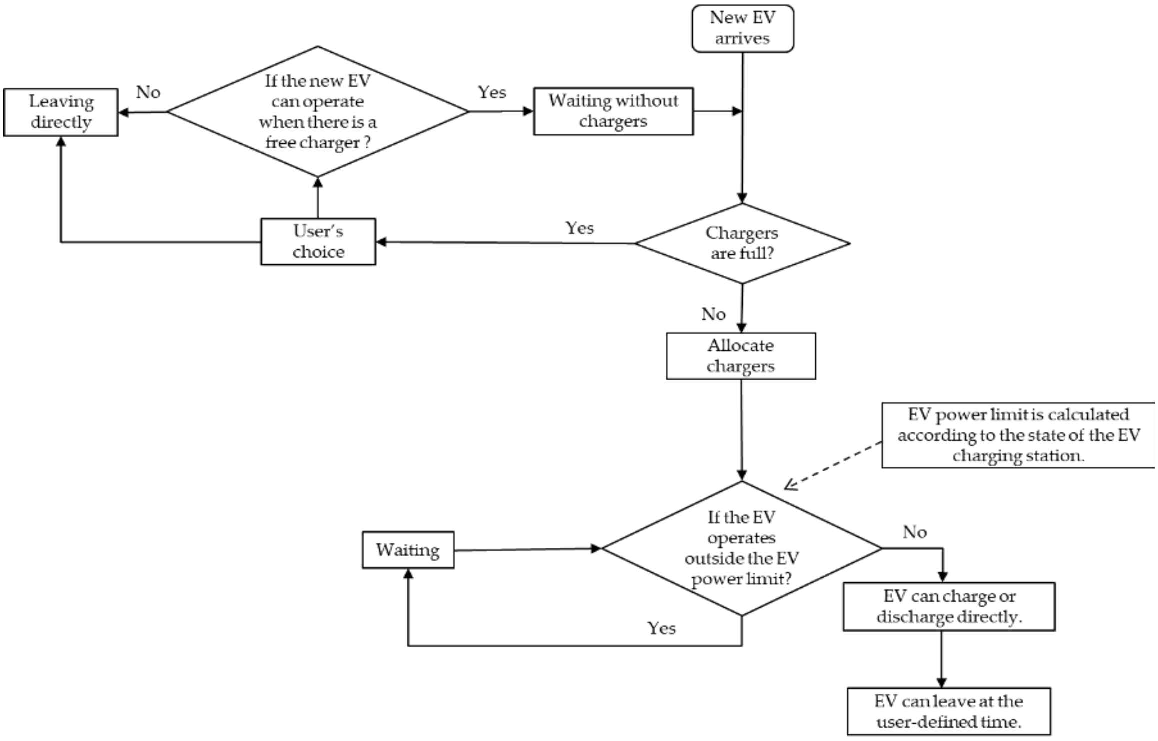


**Figure 3.2-3 Flow chart of ICDA**

When a new EV arrives, if there is a free charger, the charger is directly allocated to the EV. By comparing the EV operating power with the power limit of the EV charging station, it is determined whether the EV enters the waiting state or can be directly charged/discharge until $SOC_{EV\_final\_\lim}$ is reached, and finally, the EV leaves the EV charging station at the time set by the user. The EV power limit is calculated according to the state of the EV charging station. If there are no free chargers when the EV arrives, the EV can choose to leave directly or wait until a free charger becomes available.

### *3.2.3.2 Dynamic SPVA*

The method to estimate the optimal start operating time is shown in Figure 3.2-4. As shown in Figure 3.2-4, the EV estimator is the related function of EV information and grid power information. The purpose of SPVA is to estimate the optimal start operating time of EVs by searching the "*peak*" periods and "*valley*" periods of the public grid.

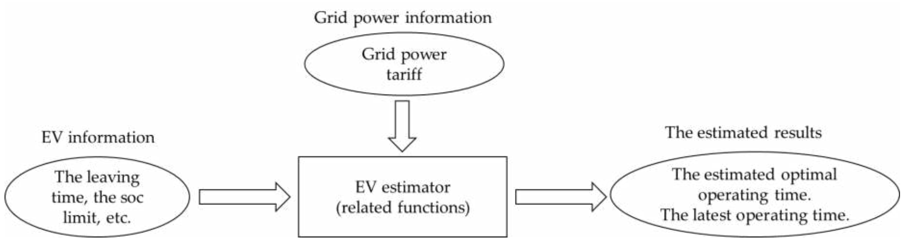


**Figure 3.2-4 Method to estimate the optimal start operating time**

The flow chart of SPVA is shown in Figure 3.2-5. When a new EV arrives, the EV estimator calculates the optimal operating time of EVs. After the EV is connected to the charger, the EV will wait until the optimal operation time appears.

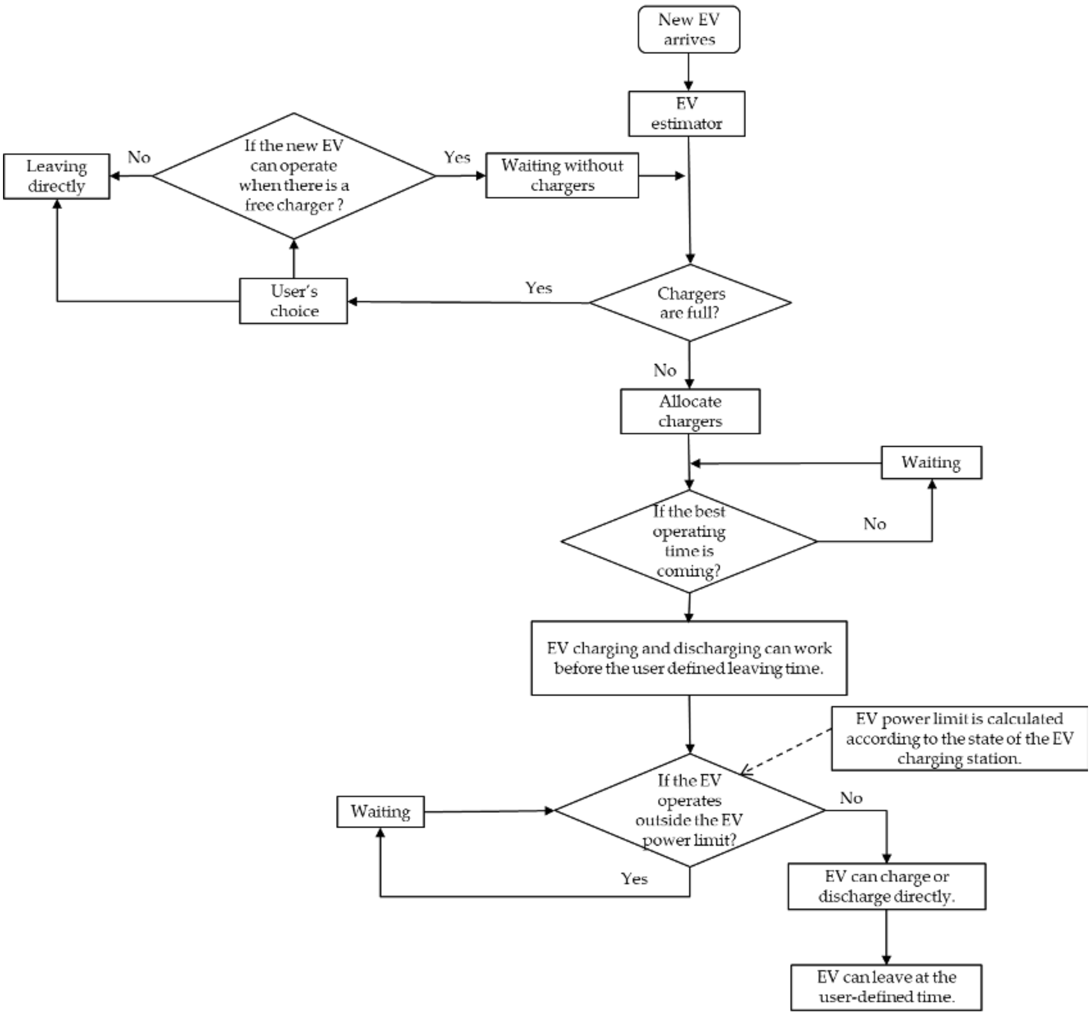


**Figure 3.2-5 Flow chart of SPVA**

## 3.2.4 Simulation results and analyses

In the DC MG system, PV sources include 400 PV panels (40 in parallel and 10 in series), and its power under standard conditions is 100 kW [29]. The storage voltage and capacity are 300 V and 300 Ah, respectively. The public grid is a low-voltage three-phase network with a frequency of 50 Hz. The charging method of lithium-ion batteries in EVs is constant current / constant voltage, while the discharge is constant power. The battery energy of EV is about 24 kWh, namely $J_{EV\_ERF}$ . There are three charging modes in the charging station: fast mode whose maximal charging power is 83 kW, namely $P_{FAST\_MAX}$ ; average mode whose maximal charging power is 27 kW, namely $P_{AVER\_MAX}$ ; and slow mode whose maximal charging power is 7 kW, namely $P_{SLOW\_MAX}$ .

### *3.2.4.1 Simulation conditions and assumptions*

In order to ensure the validity of the simulation, it is assumed that all EVs have the same battery characteristics. Figure 3.2-6 shows the real solar irradiance and PV cell temperature from 8:00 to 22:00 hours on May 28 2019 at Compiegne, France.

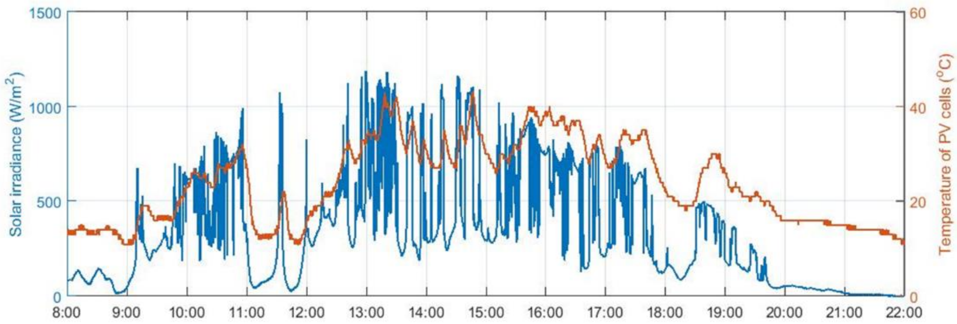


**Figure 3.2-6 Solar irradiance and PV cell temperature**

Figure 3.2-7 shows the tariff of the public grid from 8:00 to 22:00 hours. It exists two grid "*peak*" periods 11:00-13:00 hours and 18:00-20:00 hours, and the tariff is fixed during the two time-periods. The closer the time point to these two time-periods, the higher the tariff to absorb power from the public grid.

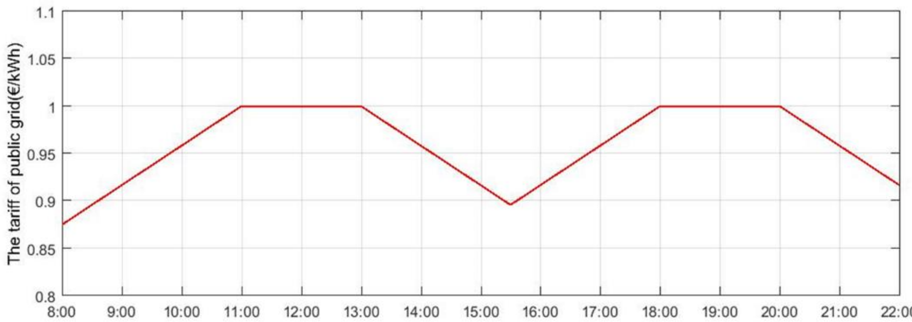


**Figure 3.2-7 Energy tariff of the public grid**

The simulation parameters of the system are detailed in Table 3.2-1 [29], where $P_{DIS}$ is the constant discharge power, which was chosen 89,6 kW, $I_{S\_MAX}$ is the storage current limitation, $SOC_{MIN}$ and $SOC_{MAX}$ are the $soc$ lower limit and the $soc$ upper limit, respectively, $C_{ERF}$ is the capacity of the storage, and $v_{C\_REF}$ is the rated voltage of DC bus.

**Table 3.2-1 Simulation parameters of the system**

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $P_{FAST\_MAX}$ | 83 kW | $I_{S\_MAX}$ | 115 A |
| $P_{AVER\_MAX}$ | 27 kW | $SOC_{MIN}$ | 20% |
| $P_{SLOW\_MAX}$ | 7 kW | $SOC_{MAX}$ | 80% |
| $P_{DIS}$ | 89,6 kW | $C_{ERF}$ | 300 Ah |
| Number of chargers | 5 | $v_{C\_REF}$ | 400 V |
| $J_{EV\_ERF}$ | 24 kWh | $P_{PV\_STC}$ | 100 kW |

The power limits of the point of common coupling of the EV charging station with the public grid are shown in Table 3.2-2. Since loads of the public grid are different according to different periods, the power limits are set accordingly to ensure the stability of the public grid. There are two types of power limits: grid injection power limit and grid supply power limit. In the "*peak*" periods of the public grid, the injection power limit is 100 kW, the supply power limit is -10 kW, and in other periods, the injection power limit is 50 kW, and the supply power limit is -50 kW.

**Table 3.2-2 Power limits of the public grid**

| Period | 8:00-11:00 | 11:00-13:00 | 13:00-18: 00 | 18:00-20:00 | 20:00-22:00 |
|---|---|---|---|---|---|
| Grid injection power limit (kW) | 50 | 100 | 50 | 100 | 50 |
| Grid supply power limit (kW) | -50 | -10 | -50 | -10 | -50 |

The simulation parameters of EVs are shown in Table 3.2-3. The three charging modes for EVs, i.e. fast mode, average mode, and slow mode, are considered. When a new EV arrives, the user can choose waiting or departure if there is no free charger. 'CH' represents 'charge', 'DCH' represents 'discharge', 'F' represents 'fast mode', 'A' represents 'average mode', 'S' represents 'slow mode', 'W' represents 'waiting', and 'D' represents 'departure'. *Ordinal*$_{EV}$ represents the ordinal number of EVs.

**Table 3.2-3 Simulation parameters of EVs**

| *Ordinal*$_{EV}$ | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th |
|---|---|---|---|---|---|---|---|---|
| $T_{arrive}(100s)$ | 17 | 20 | 87 | 198 | 213 | 331 | 336 | 343 |
| $T_{depart}(100s)$ | 42 | 75 | 204 | 311 | 222 | 388 | 405 | 400 |
| $SOC_{EV\_in}(\%)$ | 66 | 87 | 47 | 21 | 49 | 37 | 12 | 44 |
| $SOC_{EV\_final\_\lim}(\%)$ | 11 | 97 | 1 | 78 | 82 | 87 | 9 | 40 |
| Type | DCH | CH(F) | DCH | CH(S) | CH(A) | CH(A) | DCH | DCH |
| Choice | W | W | W | D | D | W | D | W |

**Table 3.2-4 Simulation parameters of EVs** (continuation)

| Ordinal$_{EV}$ | 9th | 10th | 11th | 12th | 13th | 14th | 15th | 16th |
|---|---|---|---|---|---|---|---|---|
| $T_{arrive}(100s)$ | 356 | 375 | 382 | 398 | 428 | 462 | 471 | 484 |
| $T_{depart}(100s)$ | 449 | 464 | 423 | 460 | 431 | 601 | 495 | 499 |
| $SOC_{EV\_in}(\%)$ | 48 | 38 | 41 | 40 | 26 | 37 | 17 | 66 |
| $SOC_{EV\_final\_\lim}(\%)$ | 26 | 81 | 44 | 92 | 19 | 27 | 65 | 80 |
| Type | DCH | CH(S) | CH(A) | CH(A) | DCH | DCH | CH(S) | CH(F) |
| Choice | W | W | D | D | W | W | W | D |

In this case, in order to reflect the effectiveness of the algorithm, the EV number is randomly given 16, and 'Type' and 'Choice' are randomly generated by an algorithm. $T_{arrive}$ represents the time each EV arrives at the charging station. $T_{depart}$ represents the time each EV leaves the charging station. $SOC_{EV\_in}$ represents the initial $soc_{EV}$, $SOC_{EV\_final\_\lim}$ represents the limit value of $soc_{EV}$ when the EV departures that set by users. According to the objective of users, EVs come to charging stations for two purposes: chaging and discharging.

*3.2.4.2 Simulation results under ICDA*

The first simulation case works under ICDA and the EV can directly be charged/discharge within the EV power limit. As shown in Figure 3.2-8, the steady DC bus voltage is 400 V within the simulation period, which proves that the power management strategy works well to balance the powers under ICDA.

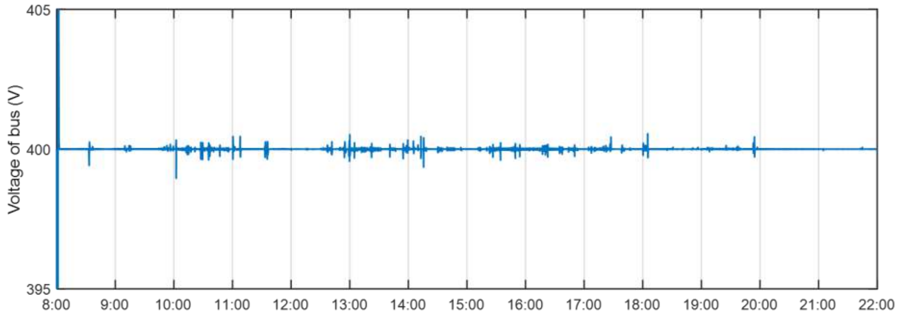


**Figure 3.2-8 DC bus voltage evolution under ICDA**

Figure 3.2-9 shows the storage $soc$ and distribution coefficient $k$ under ICDA. The $soc$ of storage is limited between 20% and 80% to extend storage life. $k=1$ means only the storage is working and $k=0$ means only the public grid is working. $0<k<1$ means the storage and the public grid are working simultaneously.

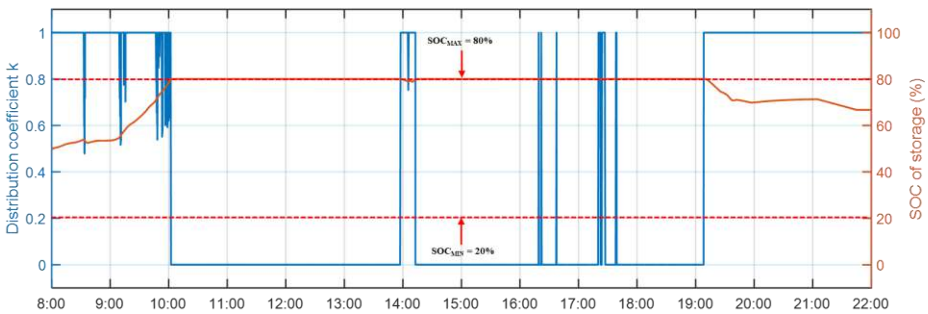


**Figure 3.2-9 Storage $soc$ and distribution coefficient $k$ under ICDA**

Storage current evolution under ICDA is shown in Figure 3.2-10. The storage current is between -115 A and 115 A to prolong the life cycle of the storage. The value -115 A is the maximum discharge current of batteries, while the value 115 A is the maximum current for batteries to be charged. The simulation result shows that the current is successfully limited.

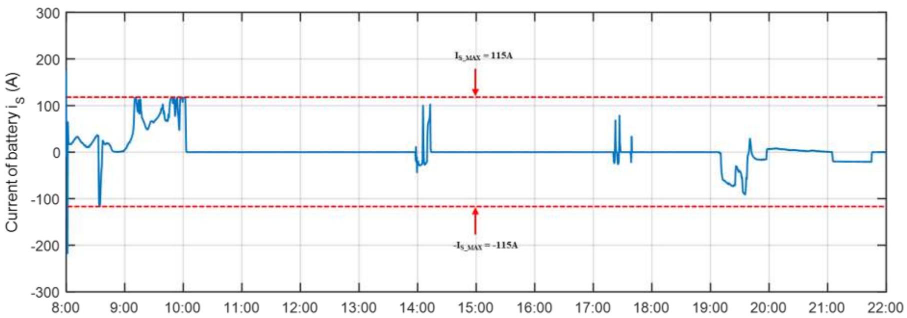


**Figure 3.2-10 Storage current evolution under ICDA**

The power flow of DC microgrid under ICDA is shown in Figure 3.2-11. The PV source can switch freely between PV-constrained production control and PV-MPPT control [30]. The power $p_{EVs}<0$ means that EVs show a total tendency to discharge, $p_{EVs} > 0$ means that EVs show a total tendency to be charged. During the "*peak*" periods of the public grid: 11:00-13:00 hours and 18:00-20:00 hours, the injection power limit is 100 kW, and the supply power limit is -10 kW to prevent the public grid from overloading. During the "valley" periods of the public grid, the injection power limit is 50 kW, and the supply power limit is -50 W. Setting different power limits according to the "peak" periods and "valley" periods of the public grid is beneficial to improve the stability of the public grid, which also respects the power flow given in Figure 3.2-2.

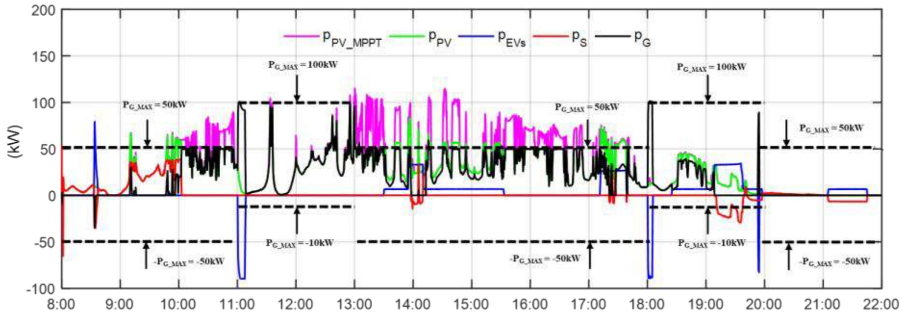


**Figure 3.2-11 Power flow of DC microgrid under ICDA**

Figure 3.2-12 shows the parking periods of EVs. The parking periods of EVs are different according to the willingness of users. From EV_charger_1 to EV_charger_5 represent EVs connected to chargers 1 to 5, respectively, e.g. EV_charger_1 represents the ordinal number and parking periods of the EVs connected to the charger 1.

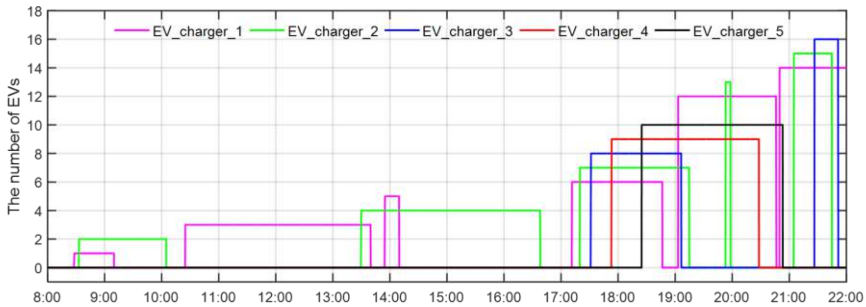


**Figure 3.2-12 Parking periods of EVs at each charger**

The power evolutions of EVs under ICDA are shown in Figure 3.2-13. If the power is positive, it means that the EV is being charged; if it is negative, it means that the EV discharges. Figure 3.2-14 shows the $soc_{EV}$ evolutions under ICDA.

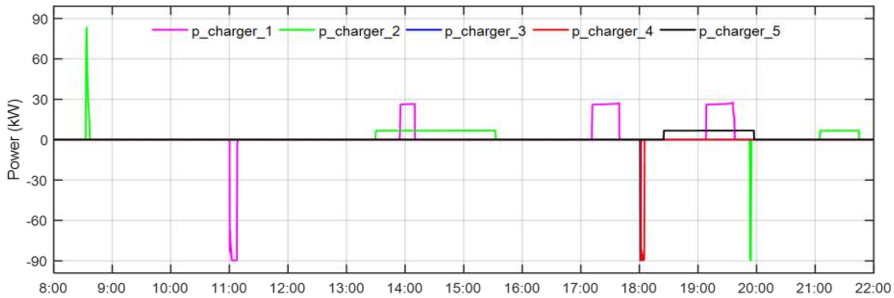


**Figure 3.2-13 Power evolutions under ICDA**

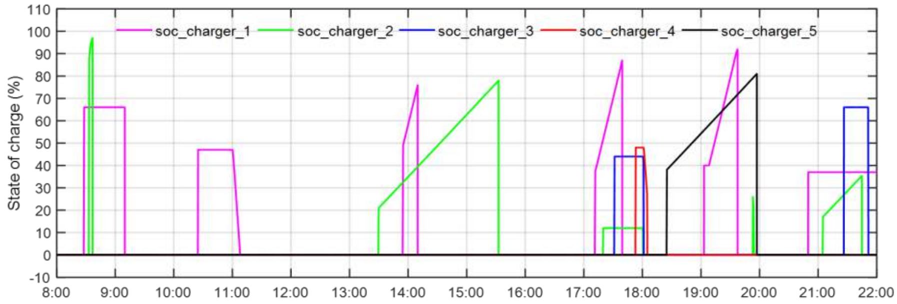

**Figure 3.2-14 State of charge $soc_{EV}$ evolutions under ICDA**

The operating time of EVs connected to charger 1 is shown in Figure 3.2-15. $t_{EV\_charger\_1}$ represents parking periods of EVs connected to charger 1. $t_{EV\_operate}$ represents the start operating time of EVs. $t_{EV\_arrive}$ represents the arrival time of EVs. $t_{EV\_depart}$ represents the departure time of EVs.

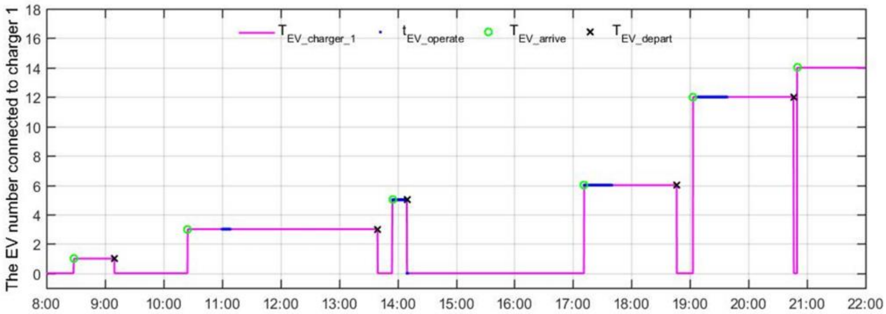

**Figure 3.2-15 Operating time of EVs connected to charger 1 under ICDA**

As shown in Figure 3.2-15, EVs connected to the charger 1 in chronological order are 1st, 3rd, 5th, 6th, 12th, 14th. After an EV arrives at the charging station, when the power is met, the charging/discharging operation begins. EVs that immediately start charging/discharging operations after arriving at the charging station are 5th, 6th, 12th, while the 3rd EV enters the waiting state after arriving at the charging station, then discharges when power is met. Moreover, the 1st and 14th did not discharge until they left because of unsatisfactory power availability.

The operating time of EVs connected to charger 2 is shown in Figure 3.2-16. As shown in Figure 3.2-16, EVs connected to the charger 2 in chronological order are 2nd, 4th, 7th, 13th, 15th. EVs that immediately start charging/discharging operations after arriving at the charging station are the 2nd, the 4th, the 13th, the 15th EVs, while the 7th EV enter the waiting state after arriving at the charging station, then discharges when power is met.

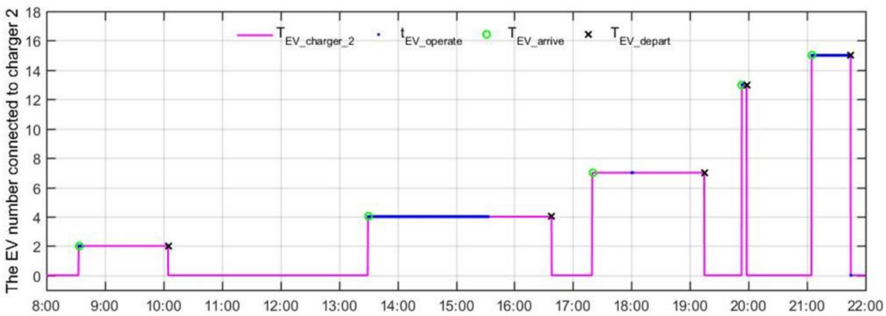

**Figure 3.2-16 The operating time of EVs connected to charger 2 under ICDA**

The operating time of EVs connected to charger 3 is shown in Figure 3.2-17. As shown in Figure 3.2-17, EVs connected to the charger 3 in chronological order are the 8th and the 16th EVs. The 8th EV enters the waiting state after arriving at the charging station, then discharges when power is met, while the 16th EV did not charge until it left because of unsatisfactory power availability.

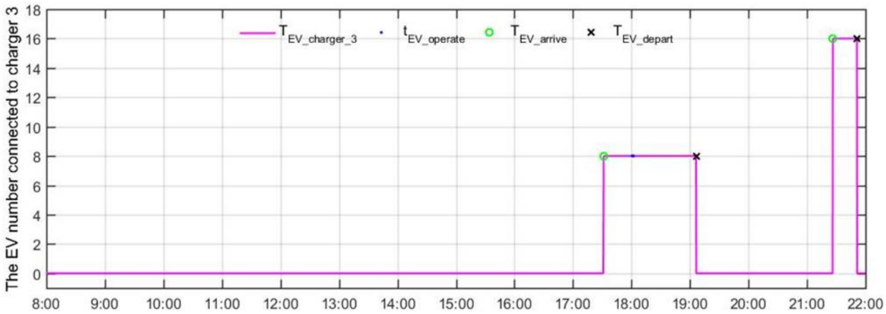


**Figure 3.2-17 The operating time of EVs connected to charger 3 under ICDA**

The operating time of EVs connected to charger 4 is shown in Figure 3.2-18. As shown in Figure 3.2-18, EV connected to charger 4 is 9th EV. The 9th EV enters the waiting state after arriving at the charging station, then discharges when the power level is met.

The operating time of EVs connected to charger 5 is shown in Figure 3.2-19. The EV connected to the charger 5 is the 10th EV, which immediately starts charging/discharging operations after arriving at the charging station.

The recording of EV charging under ICDA is shown in Figure 3.2-20.

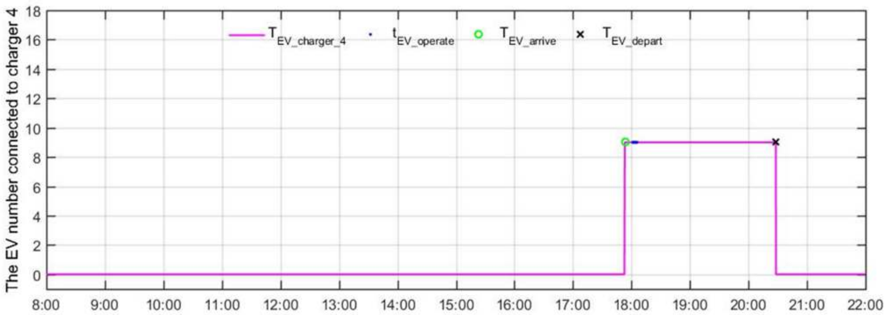


**Figure 3.2-18 The operating time of EVs connected to charger 4 under ICDA**

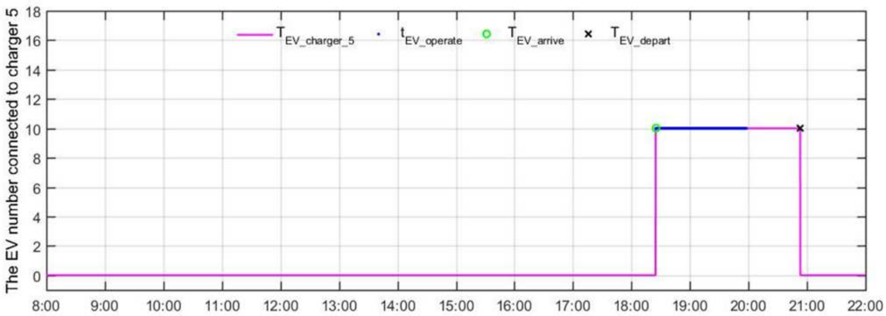


**Figure 3.2-19 The operating time of EVs connected to charger 5 under ICDA**

The ratings arrive_N1, park_N2, finish_N3, not_finish_N4, and depart_N5 are respectively the number of EVs arrived at the charging station, the number of EVs parking at the charging station, the number of EVs that have completed operations, the number that have not completed operations, and the number of EVs leaving directly. The rating arrive_N1 is expressed by Equation (3.2-4):

$$arrive\_N1 = park\_N2 + finish\_N3 + not\_finish\_N4 + depart\_N5 \tag{3.2-4}$$

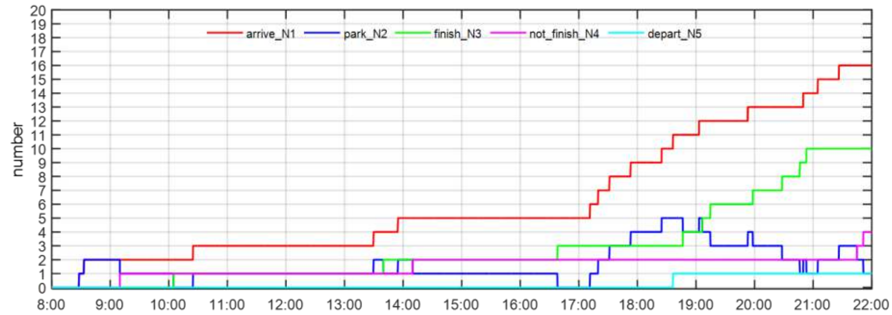


**Figure 3.2-20 Recording of EV charging under ICDA**

### *3.2.4.3 Simulation results under SPVA*

The second simulation works under SPVA and the EV cannot be charged/discharged until the estimated optimal start operating time of EVs is given by searching the “peak” periods and “valley” periods of the public grid; $t_{EV\_best\_st}$ represents the optimal start operating time, and $t_{EV\_latest\_st}$ represents the estimated latest operating time.

As shown in Figure 3.2-21, the steady DC bus voltage is 400 V within the simulation period, which proves that the power management strategy works well to balance the powers under SPVA.

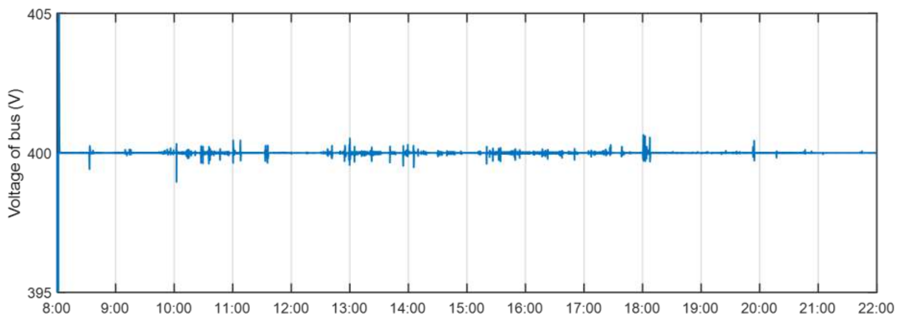


**Figure 3.2-21 DC bus voltage evolution under SPVA**

Figure 3.2-22 shows the storage $soc$ and distribution coefficient $k$ under SPVA. The evolutions of the $soc$ and distribution coefficient $k$ show the feasibility of SPVA and respect the power flow given in Figure 3.2-2.

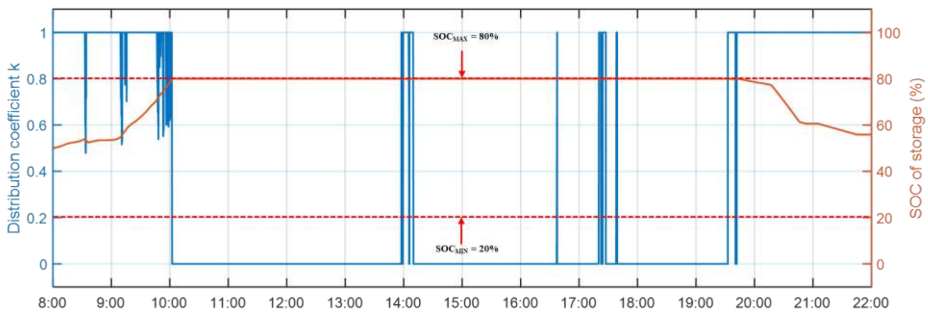

**Figure 3.2-22 Storage $soc$ and distribution coefficient $k$ under SPVA**

Storage current evolution under SPVA is shown in Figure 3.2-23. As already mentioned, the absolute value of the storage current is limited to 115 A, and the simulation result shows that the current is successfully limited.

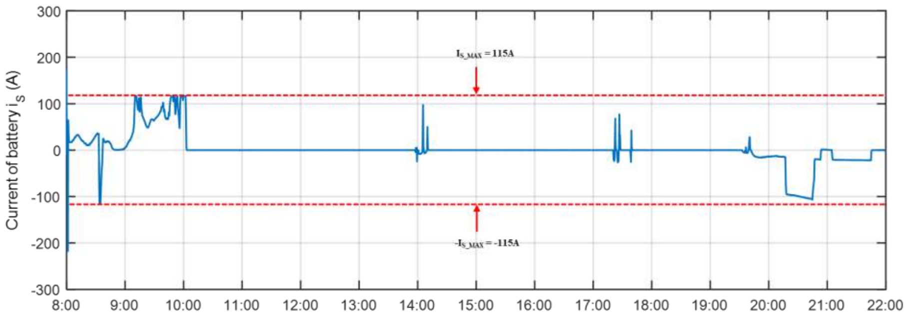


**Figure 3.2-23 Storage current evolution under SPVA**

The power flow of DC MG under SPVA is shown in Figure 3.2-24. The grid power is within the imposed power limits during the simulation period, respecting the power flow given in Figure 3.2-2. Setting different power limits of the public grid in the "*valley*" period and the "*peak*" period provides a guarantee for the stability of the public grid.

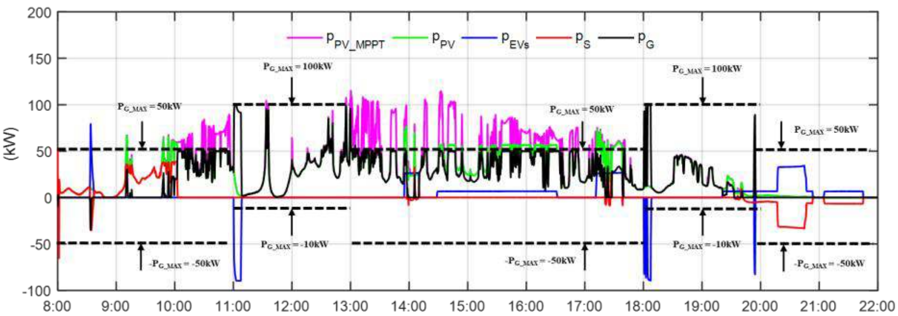


**Figure 3.2-24 Power flow of DC microgrid under SPVA**

Figure 3.2-25 shows the parking periods of EVs. In order to compare the two algorithms, all the information about EVs in case 1 and case 2 are the same.

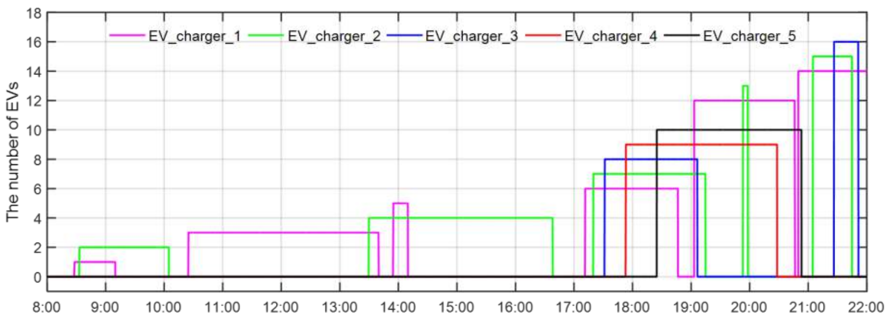


**Figure 3.2-25 Parking periods of EVs at each charger**

The theoretical optimal start operating time and latest start operating time of EVs are shown in Table 3.2-5, which can be calculated by the EV charging station based on $T_{arrive}$, $T_{depart}$, $SOC_{EV\_in}$, $SOC_{EV\_final\_lim}$, charging modes, and discharge power.

**Table 3.2-5 Theoretical optimal start operating time and latest start operating time of EVs**

| *Ordinal*$_{EV}$ | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th |
|---|---|---|---|---|---|---|---|---|
| $t_{EV\_best\_st}(100s)$ | 36,69 | 20,00 | 108,00 | 233,15 | 213,00 | 331,00 | 360,01 | 360,01 |
| $t_{EV\_best\_st}(100s)$ | 36,70 | 72,83 | 199,56 | 237,28 | 213,00 | 371,33 | 404,71 | 399,61 |

**Table 3.2-6 Theoretical optimal start operating time and latest start operating time of EVs** (continuation)

| *Ordinal*$_{EV}$ | 9th | 10th | 11th | 12th | 13th | 14th | 15th | 16th |
|---|---|---|---|---|---|---|---|---|
| $t_{EV\_best\_st}(100s)$ | 360,01 | 408,56 | 382,00 | 442,40 | 428,00 | 462,00 | 471,00 | 497,42 |
| $t_{EV\_best\_st}(100s)$ | 446,88 | 408,56 | 421,99 | 442,41 | 430,33 | 600,04 | 471,00 | 497,43 |

The power evolutions under SPVA are shown in Figure 3.2-26. Compared with Figure 3.2-13, the 4th and the 10th EVs are farther away from the "*peak*" periods of the public grid, while the 12th EV directly avoids the "*peak*" periods of the public grid, thereby preventing public grid from overloading, meanwhile reducing charging costs, which proves the effectiveness of SPVA. Figure 3.2-27 shows the $soc_{EV}$ evolutions under SPVA.


**Figure 3.2-26 Power evolutions under SPVA**

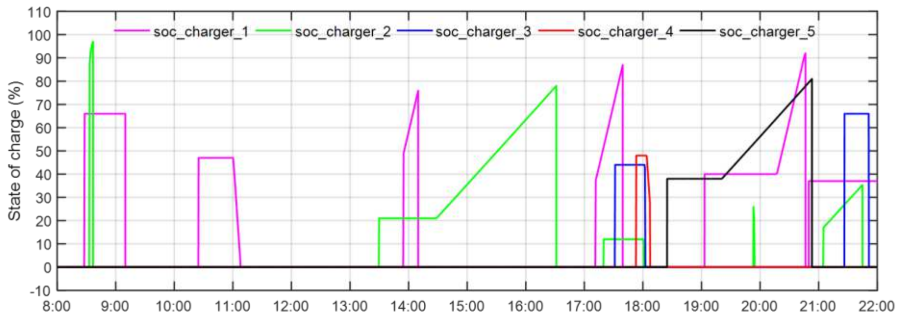


**Figure 3.2-27 State of charge $soc_{EV}$ evolutions under SPVA**

The operating time of EVs connected to charger 1 is shown in Figure 3.2-28. Compared with Figure 3.2-15, due to SPVA, the 12th EV did not choose to be charged immediately after arrival but waited for the optimal start operating time, which saved the user's charging costs and avoided adding peak loads to the public grid.

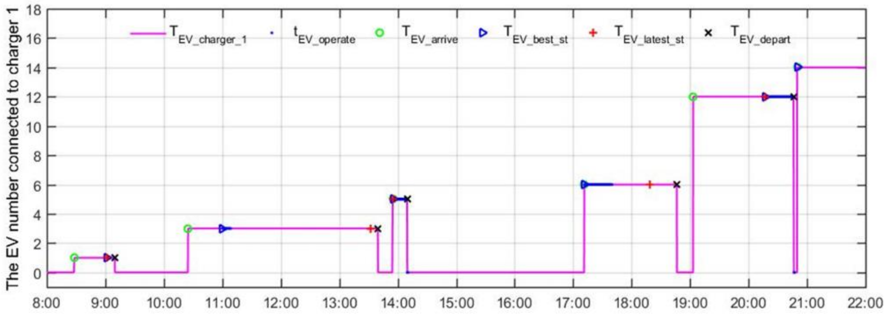


**Figure 3.2-28 Operating time of EVs connected to charger 1 under SPVA**

The operating time of EVs connected to charger 2 is shown in Figure 3.2-29. Compared with Figure 3.2-16, due to SPVA, the 4th EV did not choose to be charged immediately after arrival but waited for the optimal start operating time.

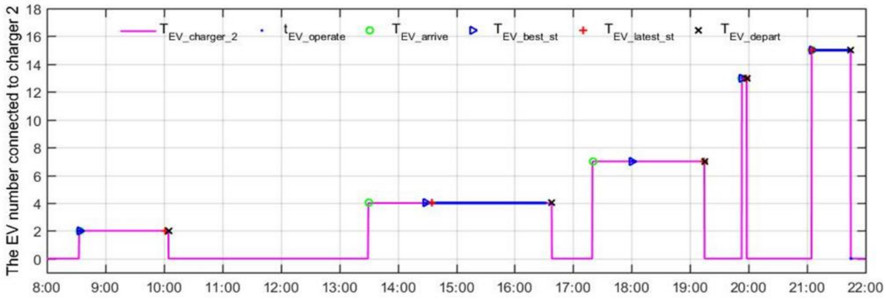


**Figure 3.2-29 Operating time of EVs connected to charger 2 under SPVA**

The operating time of EVs connected to charger 3 is shown in Figure 3.2-30, and the 8th and the 16th EVs have the same operation results as Figure 3.2-17.

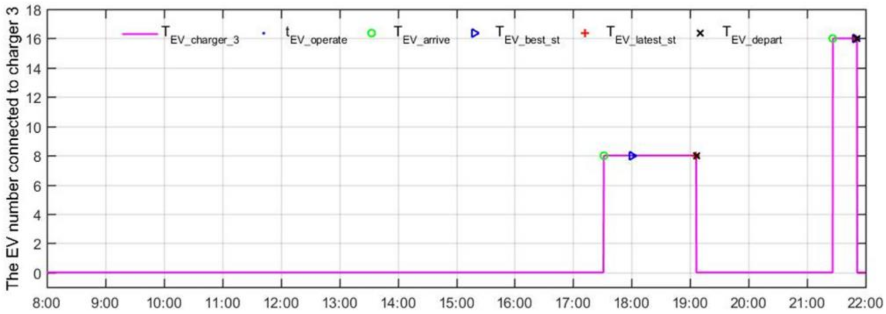


**Figure 3.2-30 Operating time of EVs connected to charger 3 under SPVA**

The operating time of EVs connected to charger 4 is shown in Figure 3.2-31. The operating time of EVs connected to charger 5 is shown in Figure 3.2-32 and the 9th EV has the same operation result as Figure 3.2-18. Compared with Figure 3.2-19, due to SPVA, the 10th EV did not choose to be charged immediately after arrival but waited for the optimal start operating time.

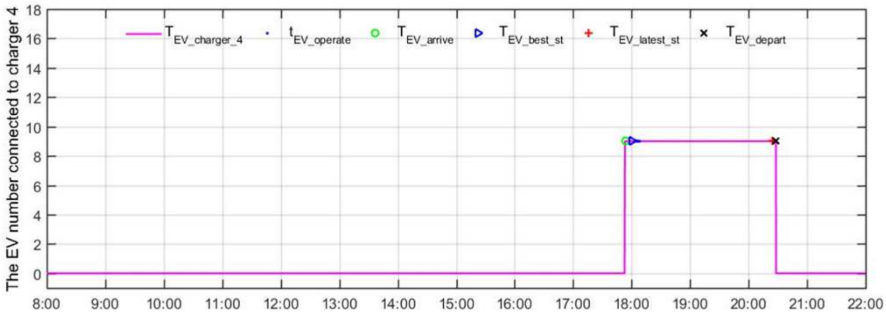


**Figure 3.2-31 Operating time of EVs connected to charger 4 under SPVA**

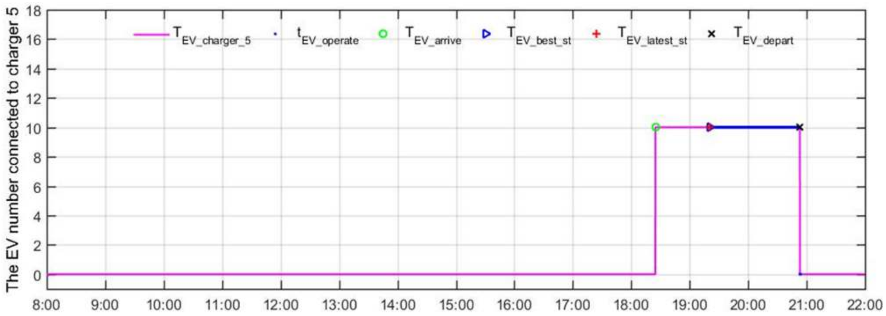


**Figure 3.2-32 Operating time of EVs connected to charger 5 under SPVA**

The recording of EV charging under SPVA is shown in Figure 3.2-33, which respects to the Equation (3.2-4).

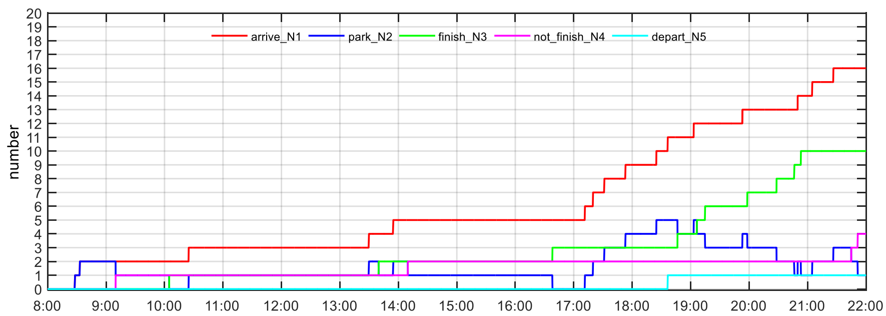


**Figure 3.2-33 Recording of EV charging under SPVA**

*3.2.4.4 Comparison and analyze of the two simulation cases*

**The simulation results of ICDA and SPVA are shown in**

Table 3.2-7, where $D_{cp}$ represents the completion degree of EVs, calculated by Equation (3.2-5):

$$D_{cp} = \left| \frac{soc_{EV\_final} - SOC_{EV\_in}}{SOC_{EV\_final\_lim} - SOC_{EV\_in}} \right| * 100\% \qquad (3.2\text{-}5)$$

The parameter $soc_{EV\_final}$ represents the $soc_{EV}$ when EVs leave the charging station. $D_{cp}(1)$ and $D_{cp}(2)$ are the completion degree of EVs under ICDA and SPVA, respectively.

Under the two algorithms, the completion degree of EVs is the same under ICDA and SPVA, as shown in

Table 3.2-7 and Table 3.2-9.

**Table 3.2-7 Simulation results of ICDA and SPVA**

| Ordinal$_{EV}$ | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th |
|---|---|---|---|---|---|---|---|---|
| Type (1) | DCH | CH | DCH | CH | CH | CH | DCH | DCH |
| $D_{cp}(1)$ | 0% | 100% | 100% | 100% | 81,65% | 100% | 100% | 100% |
| Type (2) | DCH | CH | DCH | CH | CH | CH | DCH | DCH |
| $D_{cp}(2)$ | 0% | 100% | 100% | 100% | 81,65% | 100% | 100% | 100% |

**Table 3.2-8 Simulation results of ICDA and SPVA** (continuation)

| Ordinal$_{EV}$ | 9th | 10th | 11th | 12th | 13th | 14th | 15th | 16th |
|---|---|---|---|---|---|---|---|---|
| Type (1) | DCH | CH | CH | CH | DCH | DCH | CH | CH |
| $D_{cp}(1)$ | 100% | 100% | 0% | 100% | 100% | 0% | 38,33% | 0% |
| Type (2) | DCH | CH | CH | CH | DCH | DCH | CH | CH |
| $D_{cp}(2)$ | 100% | 100% | 0% | 100% | 100% | 0% | 38,33% | 0% |

One note that there are 11 EVs with a completion degree of 100%, the 1st, the 11th, the 14th, and the 16th EV with a completion degree of 0%, among which, the 11th EV directly left after arriving at the charging station because the charging station could not meet the user needs. The 5th EV with a completion degree of 81,65%, and the 15th EV with a completion degree of 38,33%.

**Table 3.2-9 Results comparison of ICDA and SPVA**

| Algorithms | ICDA | SPVA |
|---|---|---|
| EV number | 16 | 16 |
| Number of finishing CH or DCH | 11 | 11 |
| Energy cost of public grid power (c€) | -280,4216 | -294,1568 |

The comparison between the two algorithms highlights that energy costs of public grid under ICDA are higher than those under SPVA. Thus, the power management strategy can run well under SPVA, ease the pressure on the public grid at the "*peak*" periods and reduce the costs of energy from the public grid.

## *3.2.5 Conclusions*

This chapter presents a power management strategy with integrated V2G to reduce the peak pressure of the public grid while meeting the needs of users. In the strategy, PV sources, battery storage, and the public grid are used to charge EVs in sequence; at the "peak" periods of the public grid, PV sources and EVs are discharged to the public grid one after another to play the role of V2G. The SPVA defines the optimal charging/discharging start time of EVs, through its arrival time, departure time, $soc_{EV\_in}$, and $soc_{EV\_final\_lim}$, to achieve peak shaving and valley filling while reducing the costs of energy from the public grid. In addition, in order to better maintain the stability of the public grid, the "peak" periods and "valley" periods of the public grid correspond to different power limits. Simulation results show that the charging station based on a DC MG can well operate considering the EV charging/discharging behaviors. The proposed SPVA is highly effective in reducing the cost of the public grid by calculated the optimal start operating time of EVs, meanwhile ensuring the stability of the public grid.

With the growing popularity of EVs, there will be certain rules for EVs arriving at the charging station every day, thus, the EV prediction system will be designed which can predict the current situation of EVs based on the EV data of the past few days. In addition, PV data can be predicted based on the weather forecast. With these two predictions, EV charging stations will have predictions about the usage of the public grid and batteries, which can better control the system and improve the stability of the system, laying a solid foundation for the realization of fully intelligent EV charging stations in the future.

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# 4 SOCIETAL IMPACT AND SOCIAL ACCEPTANCE OF PV-POWERED INFRASTRUCTURE FOR EV CHARGING AND NEW SERVICES

Before setting up a PV infrastructure for EV charging, a study on the societal impact and social acceptability of the infrastructure and the new associated services is an important preliminary step. The present chapter looks at the societal impact and social acceptance of PV-powered infrastructure for EV charging and new associated services that will go beyond early adopters and urban users. This chapter is divided into three sections. The first presents a case study in France based on a survey on the social acceptance of PV-powered infrastructure and new services. This survey had three components: a marketing and societal survey, a qualitative survey, and a quantitative survey. Results indicate that PV-powered charging stations are socially acceptable to a large majority, although some aspects such as location, business model and design require careful consideration, especially for stations in an urban environment.

PV technology can help to improve electric mobility systems in regard to product aesthetics and user experience. The second section in this chapter presents the results of a design study on conceptual PV applications for electric mobility systems, covering the regulatory, user, aesthetic, and technical aspects. This study includes as case studies four conceptual designs, namely a solar bus terminal, a solar train stop, a solar mobile charger, and a solar luggage vehicle. The contribution of PV-produced electricity to meet the charging demand by EVs varies considerably depending on the design. The main design limitations found in this study were lack of available space for installing PV cells, problems in communicating the concept's intended operation in an effective visual way, and technical limitations inherent in some of the proposed charging methods.

To increase people's willingness to adopt the use of PV systems for electric mobility in the near future, exploratory studies on the perceived advantages and limitations of this type of applications from the perspective of their users must be carried out. The exploratory user study for PV-powered mobility applications presented in the third section of this chapter aims to identify what potential users of these applications perceive as benefits or barriers to their adoption, and to assess the impact on these perceptions of factors such as previous experience with EVs, residential PV ownership, and pro-environmental attitudes. Results give some initial insights into user needs and motivations regarding solar-powered mobility applications in an international context. While respondents tend to have a positive perception of the presented PV-powered mobility applications, the likelihood that they will adopt them in the near future appears to be relatively low.

## 4.1 Case study in France: survey on the social acceptance of PV-powered infrastructure and new services

The electromobility requires installing recharging infrastructures for EVs in urban areas. However, social acceptance is an important issue to increase public awareness on EVs recharging infrastructures and have to be studied simultaneously with the technical project. This chapter[5] aims at presenting the social acceptance study of an innovative energy system based on renewable energy, *i.e.* an EV charging station powered by a MG. The proposed energy system consists of three components: an intelligent infrastructure for recharging EVs (IIREVs) powered by MG, a heterogeneous fleet of EVs, and a building with a connection to IIREVs. The MG optimizes the power flows in accordance with the requirements of the EVs users and the public power grid. This MG contains PV sources and takes into account the following strategies: V2G, V2B, and IIREVs to building (energy generated by the IIREVs and not used by the EVs directly is used to power a building). The social acceptance survey show that a large majority accepts the IIREVs while some imperatives have to be considered in certain urban cases' implementations. According to respondents' expectations, an action plan is highlighted in order to best fit IIREVs in urban areas.

### *4.1.1 Introduction*

This chapter aims at presenting the social acceptance study of an innovative energy system based on renewable energy, i.e. EVs charging station powered by a MG. The proposed energy system consists of three components: an IIREVs powered by MG, a heterogeneous fleet of EVs, and a building/home with a connection to IIREVs. The preliminary study of the social acceptance of uses and innovative services related to electromobility in the city, using IIRVEs coupled to the production and consumption of renewable energy, emphasises the following questions:

- What is the current state of mind of city dwellers about electromobility and what are their travel habits?
- What innovative scenarios for the IIRVEs can be integrated into the urban space?
- Are city dwellers ready to accept an innovative electromobility scenario in their city and rethink new consumption and renewable energy sharing practices?

The realization of the social acceptance survey follows three phases [1]: marketing and societal survey, qualitative survey, and quantitative survey. The survey results show that the IIREVs are accepted socially by a large majority

[5] This chapter is based on the following publication: M. Sechilariu, F. Locment, N. Darene : "Social Acceptance of Microgrids Dedicated to Electric Vehicle Charging Stations", IEEE 7th International Conference on Renewable Energy Research and Applications (IEEE-ICRERA 2018), pp. 1374-1379, Paris, France, October 14-17, 2018, DOI: 10.1109/ICRERA.2018.8566787

while some imperatives have to be considered in some urban cases implementations. According to users' expectations, an action plan is highlighted in order to best fitting IIREVs in urban areas.

The Section 4.1.2 introduces the MG powered charging station for EVs while the Section 4.1.3 and 4.1.4 presents the social acceptance survey and the obtained results.

An action plan to best fit IIREVs in urban areas is highlighted in Section 4.1.5. Conclusion and further works are given in the last section.

### *4.1.2 EVs charging station powered by MG*

Defined as a set of objects (IIREVs powered by MG, EVs, and a building/home connected to the IIREVs), the innovative energy system and its interactions are represented in the Figure 4.1-1. The IIREVs main objective is to facilitate interactions between IIREVs, the public grid, users of EVs, and nearby buildings. The IIREVs optimizes the power flows in accordance with the requirements of the EVs users, building/home owner, and the public power grid. The MG is based on PV sources and takes into account the following strategies: V2G, discharge of EVs batteries into the public grid; V2H, discharge of EVs batteries into building; infrastructure-to-Home (I2H), electrical supply of building by IIREVs, *i.e.* energy generated by the IIREVs and not used by the EVs directly feeds the building/home. Figure 4.1-1 presents these interactions.

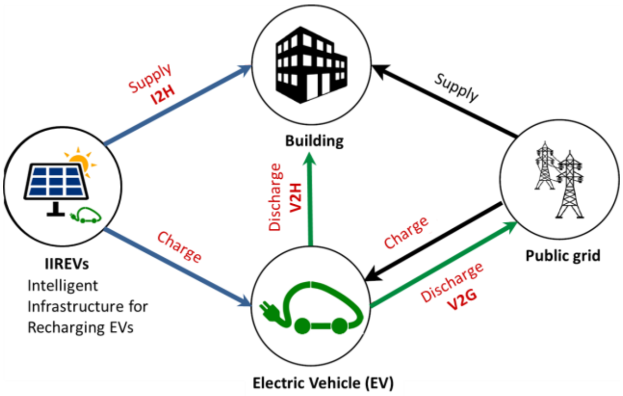


**Figure 4.1-1 Innovative energy system and its objects interactions**

The strategy V2G smooths the peaks of consumption at the power grid level, while V2H smooths the peaks of consumption at the building level and secures the building supply during an electrical cut-off. The new strategy I2H implies that an IIREV supplies the building if no EV needs energy. One of the solutions can be the MG integrated in the car parking where PV panels are installed on sun-shading roofs as shown in Figure 4.1-2. This MG contains PV sources, electrochemical storage, supercapacitors, connection to the surrounding building, and connection to the public grid [2].

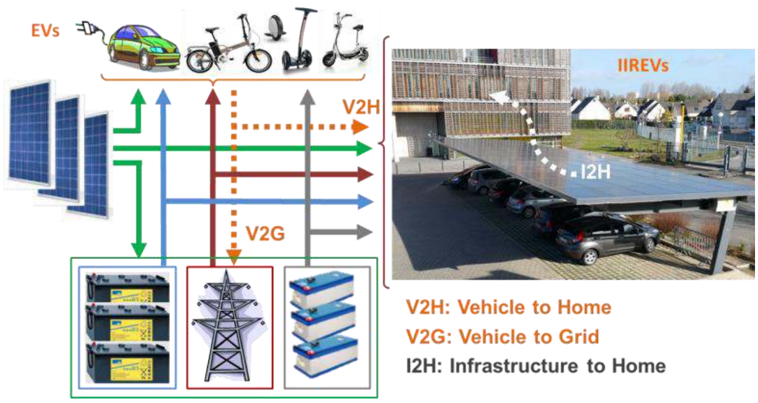

**Figure 4.1-2 IIREVs of UTC [2]**

The existing PV integrated car parking shades inject the total produced energy into the public grid. On the other hand, within the limit of the possible discharge threshold, EV is seen as a conventional energy reservoir for setting the public grid frequency. Although several works deal with the possibility of using the V2G mode to participate in ancillary services, the strategy V2G is not yet implemented, except for some experimental sites. Concerning the EVs charging stations' terminals the control does not take into consideration constraints related to the use of the power grid, the EV users' needs, and the supply of a building. However, in the absence of a proposal of a smart MG dedicated to the EVs recharging, the I2H strategy is not proposed. Furthermore, publications reveal more the use of EVs connected to charging stations related to the whole city or larger areas and less often to a specific urban neighborhood or defined local urban area. In this situation, the proposed IIREVs is an innovative charging station and new services at the urban level may be proposed.

### *4.1.3 Social acceptance preliminary studies*

The realization of the social acceptance survey follows three phases [2]: marketing and societal survey, qualitative survey, and quantitative survey. As a first step, the marketing and societal survey defines the product IIREVs, the market, and the actors [3]. In a second step, the qualitative survey, carried out on a limited sample of respondents, reveals their reflections on the IIREVs. This part presents these two preliminary studies.

#### *4.1.3.1 Marketing and societal survey*

The marketing and societal survey defines the nature of the product IIREVs, the market, and the actors that can be implied.

In order to produce an adequate questionnaire and, thus, to obtain data allowing reflection on the IIREVs and its feasibility, the typology of the innovation has to be defined. Concerning the IIREVs, two innovations can be distinguished: the charging of EVs using PV energy and the V2G / V2H strategies. The MG based on PV sources, which supplies the EVs charging station, is defined as a technology-push and a market-pull innovation [3], [4]. This consideration implies that the IIREVs is a new innovation, both pushed through technology (i.e. without consideration of whether or not it satisfies a user need) and based upon market-pull or demand-pull (i.e. in response to an identified market need). The IIREVs represents an incremental innovation in relation to a range of existing PV-integrated car parking sheds or to a gas station for fossil fuel vehicles. In contrast, the V2G / V2H strategies represent disruptive technologies.

Regarding the electromobility market, various factors favorable to its development have been identified:

- political: incentive policies increase the development of the electromobility market (EVs, charging infrastructure);
- economic: the EV market is growing;
- socio-cultural: citizens' ecological consciousness and their initiatives in favour of sustainable development increase and may lead to a good acceptance of electromobility;
- technologic: the charging stations technology and related services have been developed and have been marketed on a large scale;
- environmental: renewable energies awareness is a very favourable factor for the IIREVs development;
- legislative: regulations are favourable to electromobility, but there is still a lack of standardization of the products and services offered.

One notes that the IIREVs connects a multitude of actors (automobile manufacturers, the electrical industry, energy suppliers/grid operators, technical associations, and public authorities) and stakeholders. In addition, the study highlights the existence of a triple consumer, i.e. EV user, building/home owner, and public grid, whose opinion is assessed in the rest of this work.

#### 4.1.3.2 *Qualitative survey*

The qualitative survey is based on an open-ended questionnaire addressed to a panel of respondents that can be representative of the population [1]. The used methodology to obtain this panel is based on three hierarchical criteria (from most to least important): age, socio-economic classification (SEC), and type of used vehicle (fossil fuel or electric).

The qualitative survey conducted on a limited sample of respondents highlights their considerations on IIRVEs. It was based on the completion of an open-ended questionnaire in order to make the respondents talk about their own practices and to become familiar with certain trends to analyze without influencing the answers. It was not only about knowing how to talk to people but also about being sensitive to how they could describe their activities. This qualitative inquiry was also necessary to allow unexpected terminologies to be expressed and to identify points of view. Furthermore, the questionnaire was made in two versions: a first one for the potential users and a second one, with two additional questions, for the institutional actors. This distinction was important insofar as the institutions could provide more details on the installation and management of infrastructures according to their activity.

Following these qualitative interviews, a critical feedback allowed to build a quantitative questionnaire limiting the sources of misunderstanding on the part of the respondents. To do this, special attention was given to vocabulary and expressions used by respondents to be inspired during the construction of the quantitative questionnaire. In addition, this qualitative survey aimed to better identify the expectations of potential users and to highlight trends.

### 4.1.4 *Social acceptance quantitative survey*

The quantitative questionnaire aims to obtain a large amount of opinion on the IIREVs project [1]. To formalize the quantitative questionnaire, the formulation of the social acceptance, the marketing and societal approaches, and the answers to the qualitative questionnaire were deeply analysed [4]. The main points taken into account for the quantitative questionnaire writing are: travel habits of respondents; current obstacles to the electromobility development, influence of ecology on the project acceptance, main expectations of respondents regarding IIREVs, strategic locations for IIREVs, public institutions or private companies that should own the IIREVs, respondents opinion about the potential partial EVs discharge, respondents opinion about the recharge by PV energy, respondents opinion about the car parking shades in urban areas including their visual urban landscape integration.

From these points, a closed-ended questionnaire, based on 33 questions, was written. For each question, the most appropriate and relevant types of responses for the subsequent exploitation of the results were determined. Thanks to the feedback obtained by the qualitative open-ended questionnaire, the quantitative survey has been refocused more on the EV charging terminal than on the PV energy since it is indeed the central element of the IIREVs.

In the first part of the questionnaire, the subject is explained in a simple and concise way to facilitate the understanding of IIREVs and the questions. General questions related to the respondent profile are addressed at the beginning. Then, questions about the IIREVs and the discharge-recharge system follow. Finally, the questionnaire ends with the PV energy for the EVs charge and the urban implementation of the car parking shades.

The French diffusion of the questionnaire was carried out by the following means of communication: weekly newspaper of UTC, Tremplin UTC, social networks such as LinkedIn, Twitter, Facebook, and personal emailing. The town council of Compiègne and its suburbs distributed the survey among the inhabitants by publishing the link on their Facebook account. Within two weeks, 629 answers were obtained.

#### 4.1.4.1 *Profile of the respondents*

According to Figure 4.1-3, the respondents' profile analysis reveals a diverse SEC. However, the 15-25 age group (Figure 4.1-4(a)) and the "student" SEC (Figure 4.1-3) are overrepresented due mainly to the dissemination of the quantitative questionnaire.

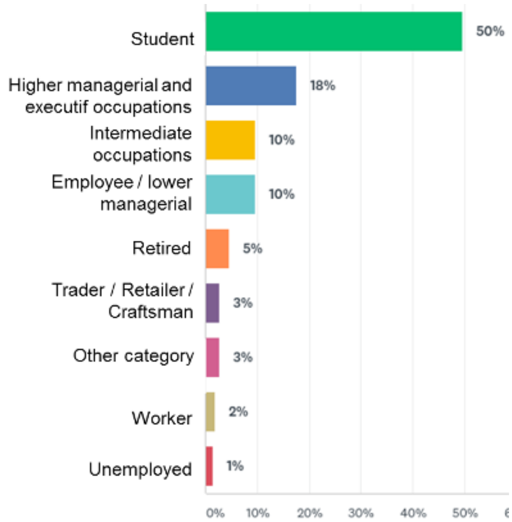


**Figure 4.1-3 Socio-economic respondents' classification**

Nevertheless, the "student" and 15-25 age group overrepresentation are not problematic in this study because it allows knowing the positioning of potential future IIREVs users. Otherwise, Figure 4.1-4(b) shows a fairly gender-balanced panel.

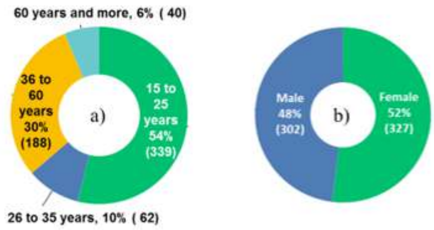


**Figure 4.1-4 Age ranges for survey (a); Gender representation (b)**

Figure 4.1-5 shows that approximately 50% of respondents travel by fossil fuel vehicle to work and leisure locations. There are few differences between the modes of travel for work (Figure 4.1-5(a)) and leisure (Figure 4.1-5(b)).

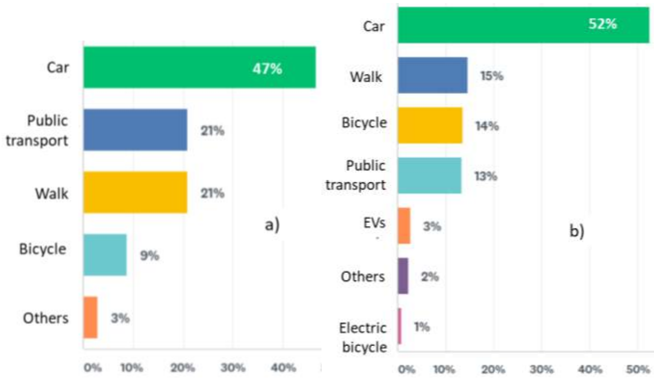


**Figure 4.1-5 Travel mode for work (a); Travel mode for leisure (b)**

In addition, 76% of respondents do not change the mode of travel for their various activities. In addition, crossing this question with the criterion of the place of life, one notes that the respondents residing in the countryside move mainly by car, while respondents living in a small city also use public transportation. To better estimate future EV users' recharge needs, the average daily distance travelled was also questioned. Therefore, the results shown that

45% of respondents travel between 0 to 10 km, 30% between 11 and 30 km, 13% between 31 to 50 km, 11% between 51 to 100 km, and 2% travel over 100 km.

#### *4.1.4.2 IIREVs system discharge-recharge*

This part of the quantitative questionnaire analyses the respondents' opinion on the characteristics of a charging station with an integrated discharge-recharge system, i.e. V2G and V2H. The emerging trends address the following issues:

- Under what conditions the respondents are ready to regularly use a discharge-recharge system?
- What type of system, profit / non-profit, is most appropriate?
- What should the characteristics of each terminal be? What services should each terminal offer?

The results show that the general trend seems to be favourable to the discharge through the V2G/V2H strategies: 84% of respondents answered "Yes" (19%) or "Yes but under certain conditions" (65%). However, 16% of respondents expressed a real refusal, which is not negligible. This question was intended to obtain a spontaneous reaction of the respondents without any preliminary explanation on the modalities of the discharge.

The responses show that respondents do not seem, *a priori*, reluctant to discharge their EV battery. Nevertheless, this acceptance still depends on the terms of the discharge. The significant results are: 55% of the respondents expressed that the EV discharge-recharge process must go unnoticed financially, 26% desire to set up a profit system, and 4% of people agreed V2G/V2H strategies without any payment or compensation.

Respondents having answered that they accepted the discharge-recharge under the condition of making profit, were then asked to indicate the type of profit that could be imagined (three answers maximum). Balancing the electricity invoice is considered by 74% of respondents as the most appropriate measure. In second position comes the income tax deduction, chosen by 37% of respondents. Finally, one notes that 43% of respondents chose a simple financial remuneration as counterpart. The second noteworthy point in the answers concerns the free car parking when connected to the terminal. This type of advantage could serve as a lever allowing for a faster transition towards the deployment of V2X EVs.

Concerning the characteristics of each terminal, the location and availability of a terminal are the main expectations of respondents, followed by the speed of recharge. The speed of recharging is a priority for 27% of respondents, which is not negligible. It would be interesting to consider this criterion to adapt the technology to the expectations of the future market. For older people the ease of use is essential, while for the youngest the speed of the recharging takes precedence. Subsequently, the respondents mentioned the main places in which they want to find the IIREVs (Figure 4.1-6).

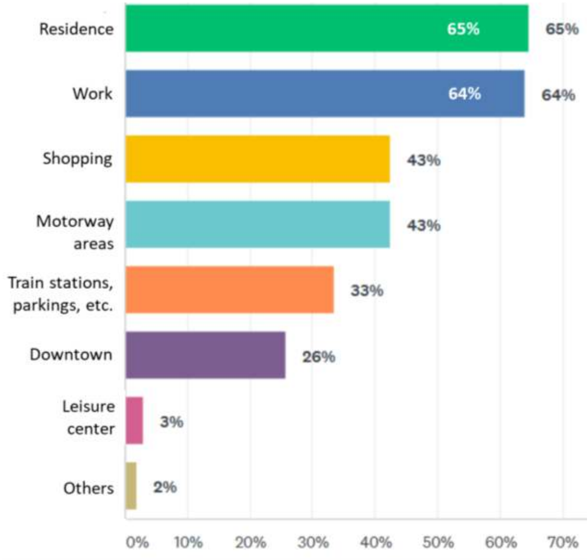


**Figure 4.1-6 Results obtained with the question: "Where would you prefer to find the charging stations (3 answers maximum)?"**

#### *4.1.4.3 PV energy for EV charge and car parking shades implementation*

This section investigates different ideas that are divided into three paragraphs answering the problems:

- Are respondents reluctant to use PV energy to recharge their EVs?
- What disturbs them most in this type of energy generation?
- Does the setting up of a car parking shed with integrated PV sources disturb the people questioned?

For 80% of respondents, the use of renewable energy influences their adhesion to IIREVs. Whatever the age group studied, the distribution of answers to this question is relatively homogeneous. One notes that the percentage of respondents influenced by the use of renewable energy for this project increases with the size of the urban area.

Concerning the EV charging by PV energy, the following questions were addressed: "Would you like your EV to be recharged by PV panels' energy?" and "What could be the main impediments to using PV panels energy for the EVs charging station (two answers maximum)?". To sum up, 96% of respondents agree the EVs charging by PV sources. This proportion is much higher than for the qualitative survey in which the results on this question were more contrasted. This can be explained by the order of the questions that can influence the level of the reflection. However, Figure 4.1-7 presents the impediments to using PV panels for the EVs charging station. There are four main impediments: efficiency and yield, environmental impact during the PV panels' production, PV panels recycling, and lifetime of PV panels. Nonetheless, there are some variations depending on age. In fact, young people are more sensitive to the environmental impact during the PV panels' production while older people attach more importance to their lifespan.

Regarding the setting up of a car parking shed with PV sources integrated the study focuses on its design and its location, as potential factors influencing the adhesion to the IIREVS project. To know where respondents would like to find this infrastructure, the results of the following questions were analysed: "Does the use of a car parking shed constitute a negative factor on your adhesion to the project?", "In what places would it bother you to find a car parking shed?", "Would you be more favourable to the installation of the car parking shed if you were asked for its installation?". One notes that 97% of respondents do not consider the car parking shed a negative factor to the project. Among the respondents (3%), for whom the car parking shades are a negative factor to their project adhesion, 57% of them would be more favourable to the project implementation if they would be consulted before. Consultations would seem to help change their minds.

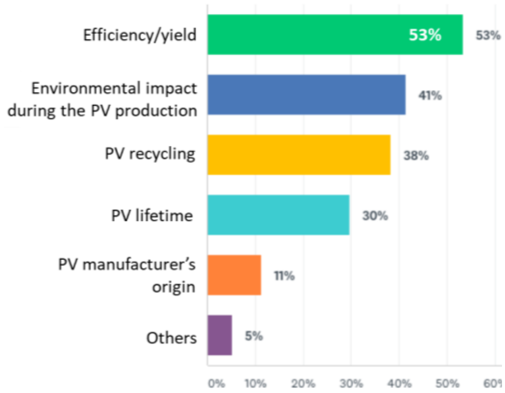


**Figure 4.1-7 Impediments to using PV panels for the charging station**

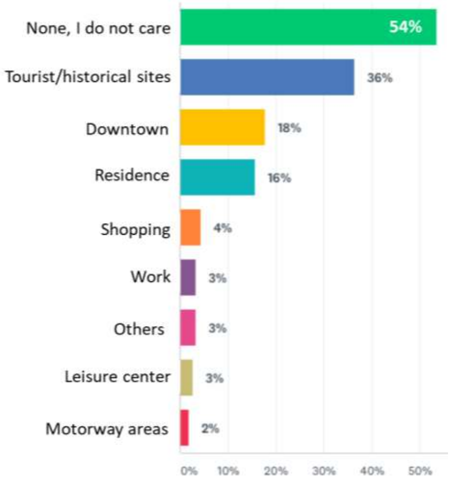


**Figure 4.1-8 Results obtained at the question: "In what places would it bother you to find a shed?"**

Conversely, it was found that some respondents consider that the integration of the car parking shed in specific places may be one of the project limitations. The main obtained results are given in Figure 4.1-8. The majority of users do not express a place where the shed can disturb them. However, the other part believes that the integration of the car parking shed would be disturbing on tourist sites, classified or historical, downtown, and residential neighbourhoods. Otherwise, older people are more reluctant to install these car parking shades at their place of residence.

*4.1.4.4 Global Trend of the social acceptance*

The quantitative survey results allow to conclude that the global trend is favorable to the IIREVs project but with some hesitations to be lifted. It can be noted that 84% of respondents are in favor of the principle of discharge-recharge of their EV (Figure 4.1-9(a)) and 97% do not mind that their EV is recharged by PV (Figure 4.1-9(b)). In addition, 96% of respondents are not opposed to the installation of the car parking shades as a support to place PV panels. Both innovations, EV discharge and PV energy use, therefore, seem to be accepted by many current and future EV users. However, 64% of the respondents accept the discharge-recharge but under certain conditions. One of the conditions for respondents is to ensure a financial balance.

The majority does not desire to incur additional costs when using such an infrastructure, and some even see it as a financial incentive to gain some profit in sharing their energy.

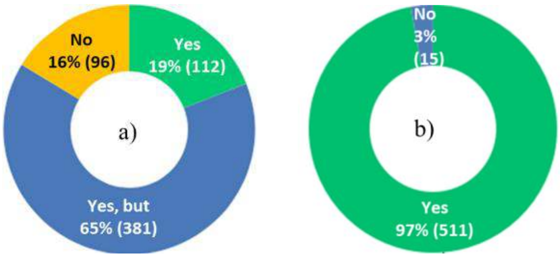


**Figure 4.1-9 General trend to the discharge acceptance (a); General trend to the recharge of EVs by PV panels (b)**

The compensation that comes out the most is an indirect compensation such as a deduction on their electricity bill and/or free parking. A second condition is that a majority of respondents prefers to make their EV's battery energy available to home use or public use, but would be less inclined to share their energy for the private use of a business. In addition, according to respondents, the local authorities should have the largest role to play in the IIREVs implementation and management. A last condition relates to habits: respondents would like that the discharge affects as little as possible their electric mobility. They would also prefer to have a safety margin on the autonomy of their EV. In addition, they find it somewhat important to know the destination of the discharged energy from their battery. They also expect an access to information on the autonomy and recharge time of their battery. These conditions highlight the importance of defining a suitable business model, which seems to be one of the factors determining the development of IIREVs on a large scale.

### *4.1.5 Limits and action plan for the IIREVs project*

Concerning the possible project's limits, it was proposed a multiple choice of answers following the interrogations of the qualitative questionnaire. Figure 4.1-10 presents the results. For 51% of respondents the investment and the costs are too important to develop, build, install, and maintain these facilities; these are the most important limits. The low efficiency of PV and the ecological benefits also appears to be project's limitations, because of the environmental impact of the PV panels' production and the increase of the indirect pollution obtained during the EVs batteries charging. Thanks to an adequate question, one estimated that the entire panel generally understood the project. Indeed, during their self-assessment on the subject's understanding, the respondents gave themselves an average score of 4 out of 5. Finally, the last question allowed respondents to express themselves freely. Although some hesitations have appeared, especially on the use of "all electric" or just on the future of individual cars, overall, there is a very positive and encouraging trend for the project.

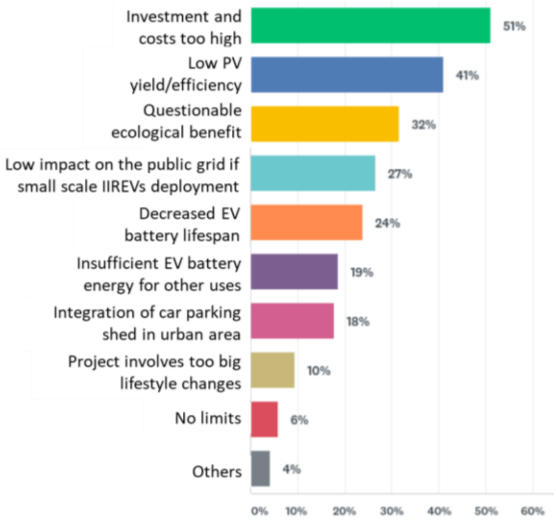


**Figure 4.1-10 IIREVs project limits general trends**

After the survey analysis, an action plan to improve acceptance of the IIREVS project may be proposed. According to user expectations, there are three main actions to carry out:

- to build an appropriate interface to control its battery;
- to be attentive to improved PV technologies;
- to design the car parking shades for good integration into the urban environment.

The suggested actions are interesting and could be the subject of a full-fledged study with the goal of adapting the IIREVs to real needs (e.g. by type of displacement, by type of activity...).

### *4.1.6 Conclusions*

This chapter has focused on social acceptance of an innovative energy system based on MG powered EVs charging stations. The survey results show that the IIREVs are socially accepted by a large majority while some imperatives have to be considered especially for stations in an urban environment. According to respondents' expectations, an action plan was proposed in order to best fit IIREVs in urban areas.

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## 4.2 Innovative design of applications for EV charging infrastructure

In the context of this report, this section focuses on the design of new innovative conceptual PV applications for electric mobility systems. This is a relevant topic, because PV technology can help to improve electric mobility systems, not just in terms of functionality, technical aspects and $CO_2$ emissions, but also regarding product aesthetics, user experience and, consequently, user acceptance of new forms of EV charging.

Design, by its very nature, has a multidisciplinary character, and this section describing a design study on solar applications for EV charging[6] therefore covers technical, user, regulatory and aesthetic aspects. Eleven conceptual designs were developed in 2019 as part of a design project at the University of Twente (UT), encompassing solutions for PV-powered charging of EVs, vehicle-integrated PV (VIPV) products and other applications. The concepts focus on various modes of transport beyond passenger cars including public transportation, electric bicycles and utility vehicles, in some cases applying alternative charging technologies such as battery swapping and induction charging in their design.

Here, some of these conceptual designs are presented as case studies, showing their multidisciplinary focus as well as parts of the design process behind their development. An evaluation of these conceptual designs reveals several design challenges that need to be addressed in their development, including the limited space available for integrating PV cells, technical limitations associated with some of the proposed charging methods, and difficulties in communicating of the concept's intended operation visually.

### *4.2.1 Introduction*

#### *4.2.1.1 A solar revolution in design*

Many international and national agreements state that PV energy technologies will be one of the main contributors to achieve a prospective 100% renewable energy supply [1], and both societal acceptance and technology development will be key to realize this goal. The interdisciplinary field of design can bring these two aspects together through the creation of products or systems which people like to use [2,3], and in this chapter it will be explained why Industrial Design Engineering is a useful approach for enhancing solar applications in mobility.

The idea of integrating solar technology into objects such as products, buildings or vehicles (see Figure 4.2-1) is not new. Already in the 1950s researchers and business developers thought about integrating solar PV cells into

[6] This chapter is based on the following publication: Sierra, A. and Reinders, A.H.M.E., Designing innovative solutions for solar powered electric mobility applications, Progress in Photovoltaics, 30 December 2020, https://doi.org/10.1002/pip.3385

smaller products that were not connected to the household's mains to let them autonomously generate electricity for these products [2,4,5,6]. In the past 70 years, increasing production volumes have caused cost reductions for silicon PV cells, which together with enhanced solar cell efficiencies and an increased social acceptance of PV technologies have led to a new trend which we call a solar revolution in design [3]. Since the price of solar electricity has become significantly lower, there now exists an opportunity to integrate PV modules and PV systems in vehicles, buildings, and landscapes whether they are urban or rural.

**Figure 4.2-1 Examples of integration of solar technologies in objects. Left: a PV powered building: the Copenhagen International School [7]. Right: a PV powered car, the Sion of Sono Motors [8]**

In this framework, because solar PV modules can be easily observed in the public space, their image and visual appearance is becoming more important and might need changes or new types of applications. Solar PV technologies can become a natural part of our environment, for electricity supply to our buildings and our cars, making it possible to create more diversity in placing and integrating solar cells in terms of orientation and positioning, color, transparency and even flexibility and design. These developments are needed to stimulate the large-scale adaptation of PV technologies in our living environment.

*4.2.1.2 Aspects of interest for designing with PVs*

Despite the situation sketched in the previous section, at present the application of PV solar cells and PV systems beyond primary energy production is still limited. Earlier work revealed that the design potential of PV solar cells and PV systems is often not fully used [9], therefore in this section the opportunities and challenges of designing with PV materials and systems are explored in the context of five aspects that are relevant for successful product design.


**Figure 4.2-2 Innovation flower of industrial product design showing objects that contain integrated solar cells, such as (clockwise from top left) a solar-powered coat park, a PV tracking system, building-integrated PV and a PV powered EV [2,3]**

The five aspects that are relevant for successful product design [2] are: (1) Technologies and Manufacturing, (2) Financial Aspects, (3) Societal Context, (4) Human Factors and (5) Design and Styling, which all together form the so-called “Innovation Flower” shown in Figure 4.2-2. These five aspects will be shortly described below to create a context for the reader in order to better understand the results of this design study.

The aspect ‘Technologies and Manufacturing’ deals with the PV materials and the manufacturing techniques that are used to create PV cells and modules. The electric and electronic equipment that is applied to convert, distribute, monitor and store solar energy plays an important role in this aspect. ‘Financial Aspects’ deal with investments in solar systems and related PV products and the economic value of the energy produced.

The ‘Societal Context’ plays an important role in the realization and acceptance of PV systems within society. Policy, regulations, laws and standards are typically categorized as societal aspects. However, the public opinion on sustainability and the willingness to use PV technologies play important roles as well. The ‘Human Factors’ aspect deals with the use of PV systems; this is especially important in the case of PV systems in in the built environment and product integrated PV where usability, performance and visibility features will determine the appreciation of users [10, 11].

The last aspect, ‘Design & Styling’, deals with the appearance of PV technologies. An interesting and contemporary appearance can have a major influence on the desirability of PV-integrated products, but can also play a role in making PV systems more acceptable by its users or in its environment of use, as is the case for building-integrated PV systems. Well-designed objects tend to encounter less resistance and also have an increased functionality because of a positive and forgiving attitude from the user [12]. Moreover, the communication function of design can help to improve the other four aspects, in particular the ‘Human Factors’ [13] and, hence, also stimulate the acceptance of innovative technologies [14, 15].

Usually in the PV industry, so far, only two out of these five aspects, namely (1) ‘Technologies and Manufacturing’ and (2) ‘Financial Aspects’ are emphasised in product development of PV modules, with ‘Societal Context’ being occasionally taken along in the design process, though at present changes are observed with societally responsible PV applications in the built environment and automotive applications. But, in general, the two remaining aspects (‘Human Factors’ and ‘Design and Styling’) that are also required to create a successful product in the market are usually neglected. This is a serious omission from the product development chain, which potentially can have a negative impact on consumers’ long-term interest in PV products. Therefore, it makes sense to evaluate how we can design with PV instead of just applying the technology [9], and in this scope, Industrial Design Engineering can play an important role.

#### *4.2.1.3 What is Industrial Design?*

Before continuing it would be useful to shortly evaluate the definitions that exist for Industrial Design Engineering. For instance, the World Design Organization (WDO), formerly known as the International Council of Societies of Industrial Design, defines Industrial Design as:

*“a strategic problem-solving process that drives innovation, builds business success, and leads to a better quality of life through innovative products, systems, services, and experiences” [3].*

According to an extended description, Industrial Design:

*“bridges the gap between what is and what’s possible. It is a trans-disciplinary profession that harnesses creativity to resolve problems and co-create solutions with the intent of making a product, system, service, experience or a business, better. At its heart, Industrial Design provides a more optimistic way of looking at the future by reframing problems as opportunities. It links innovation, technology, research, business, and customers to provide new value and competitive advantage across economic, social, and environmental spheres” [3, 16].*

These definitions are very descriptive and rather instrumental. A more meaningful definition of what Industrial Design really can bring is needed to understand its role in the engineering process, which is the “humanization of technologies” or “making technology available for people”. Other important aspects of Industrial Design are creativity and cultural and economic exchange. On a broader level, design can be seen as the human capacity for changing the world around us in a preferable direction:

*“design, stripped to its essence, can be defined as the human capacity to shape and make our environment in ways without precedent in nature, to serve our needs and give meaning to our lives” [17].*

#### *4.2.1.4 PV-powered electric mobility applications*

The current uptake in the use of EVs is expected to lead to a substantial reduction of global $CO_2$ emissions since road vehicles currently account for around 70% of GHG emissions in the transport sector [18]. This reduction, however, greatly depends on the carbon intensity of the electricity used for EV charging. For instance, the $CO_2$ emissions per kilometer driven by an EV in countries with carbon-intensive grid electricity such as Latvia (169 – 234 g $CO_2$ eq/km) and Poland (140 – 195 g $CO_2$ eq/km) could be as high as those of an equivalent ICEV [19]. In order to reduce these emissions, it is of particular interest to charge EVs with renewable energy such as solar PV. According to our previous work [20], which is also represented in chapter 2 section 2.1 of this report, the emission reduction potential of solar-powered EVs can be as high as 60 – 90% compared to grid charging depending on the location and over 90% compared to a gasoline-fueled ICEV (see Table 4.2-1). At present, both applications of VIPV and PV charging stations are being developed with a merely technical scope in order to show that from an energy balance perspective and a PV perspective it will be possible to drive on solar power. In the first technical report of IEA PVPS Task 17, which is fully focused on VIPV, an extensive overview is shown of VIPV applications and in this report. Chapter 1.1 shows many examples of solar charging stations.

**Table 4.2-1 Driving emissions (in g $CO_2$/km) from an EV charged with different energy sources in four locations around the world [20]** (see also chapter 2 section 2.1 of this report for more details)

| Location: | Perth, Australia | São Paulo, Brazil | Amsterdam, The Netherlands |
|---|---|---|---|
| 100% PV Charging | 10 | 11 | 13 |
| 50% PV + 50% Grid Charging | 75 | 24 | 66 |
| Grid Charging | 135 | 30 | 110 |
| Equivalent ICEV | 178 | 178 | 178 |

#### *4.2.1.5 Structure of the chapter*

This chapter is structured as follows: Section 4.2.2 describes the context in which the design study on PV powered electric mobility applications was carried out, including the design brief. Section 4.2.3 presents the results of the study with an overview of the developed conceptual designs followed by a more detailed description of four of these concepts, which are presented as case studies. The concepts are then critically evaluated in Section 4.2.4, encompassing an analysis of the current design limitations, possible improvements and other potential applications for each concept. Finally, Section 4.2.5 will summarize and discuss the findings of this evaluation followed by some conclusions on the design study.

### *4.2.2 Design study description*

#### *4.2.2.1 Context of the design study*

Since there is at present limited experience with the application of PV systems in EVs and their charging infrastructure, a conceptual design study was carried out in 2019 with students of Industrial Design Engineering and Mechanical Engineering at the UT in the Netherlands to explore how innovative PV applications for these technologies could look like in a near-future mobility context. This chapter presents the results of this design study consisting of several innovative conceptual designs for the integration of PV in future electric mobility systems which are critically evaluated regarding their expected benefits, points of improvement and barriers towards implementation in practice. The design study and the evaluation of its results have an interdisciplinary scope by considering the technical, user, regulatory and aesthetic aspects introduced in Section 4.2.1.2. This fits to existing theoretical frameworks for designing with PVs [1,3], which have been developed through the execution of design projects in the past 15 years at the UT [21].

The design study was executed within the framework of the research project ‘PV in Mobility’ [22] and as part of the Master-level course ‘Sources of Innovation’ which is offered to students at the UT. The approach in the ‘Sources of Innovation’ course is twofold: theory is provided on innovation processes and innovation methods, and this knowledge is simultaneously applied in a design project [23]. The innovation process is studied from different points of view such as diffusion of innovations, industry dynamics and strategy. The design projects then focus in the use of innovative product design for an emerging technology, and the final result should be an innovative technology-based product concept which is well-suited for a future market. This approach has been successfully applied in the past to other projects aimed at designing with concentrator PVs, luminescent solar concentrators, smart grid technologies and other PV applications [9,24].

During the period of September to November 2019, students were tasked with designing a conceptual product-service combination for solar PV powered EV charging solutions with a focus on increasing their adoption potential by future users. The design projects took place in a period of ten weeks and involved a specialist lecture introducing the students to the topic as well as the application of several industrial design methodologies. These innovation methods are commonly used in industrial design for the development of an innovation strategy focusing on the design of technology-based products. The course was completed by a poster presentation of the final concepts and written reports from each project team.

*4.2.2.2 Design brief*

The design assignment required the student teams to "*develop the conceptual design of a product-service combination for solar PV powered EV charging solution which will have a better adoption potential*". This conceptual design should cover five features which are key for designing with PV technologies: technical aspects, human factors, financial feasibility, product styling and societal context (see Figure 4.2-2). The PV-powered mobility solution should be suitable for the Netherlands as well as other international locations of the students' choice such as China, India and the United States.

To provide a realistic context and to stimulate creativity ("ideation"), students were asked to imagine being part of the design team of one of three companies participating in the PV in Mobility project: Lightyear [25], IM Efficiency [26], which develops solar powered trailers for trucks, and Trens Solar Trains [27] that is a developer and manufacture of public transportation with integrated. Students were also required to apply innovation methods in the development of their concept. These methods include the Innovation Phase Model [28], the Russian technical problem-solving method TRIZ [29] and Platform-driven Product Development [30], among others.

### 4.2.3 Results

A total of eleven different conceptual designs were created by the student teams as part of the 'Sources of Innovation' course, covering a wide range of application purposes and vehicle types (see Figure 4.2-3). A short description of each of these designs can be found in Table 4.2-2.

**Table 4.2-2 Conceptual designs created in the 'Sources of Innovation' course**

| Concept Name | Description |
|---|---|
| Solar Mobile Charger | A van with an extendable PV array, which acts as a mobile charge unit for charging EVs upon request. |
| Robot Charger | A robot arm able to plug in and perform ultra-fast charging for any type of EV, in particular EVs that can drive autonomously. |
| SolarShare+ | An energy sharing platform connecting EV users and residential PV owners, also including a simple PV-powered charge point for users of this platform. |
| Zun | A van with rotating PV panels integrated to the vehicle sides and roof, which can be used to recharge EVs in areas where no charging infrastructure is available. |
| CoolSun | A city bus with an integrated PV roof which informs passengers on the amount of PV energy used and $CO_2$ emissions saved by the vehicle through a set of displays. |
| Solar Bus Terminal | A station for city buses with a PV array which charges battery packs that can recharge the buses through a battery swapping process. |
| Extendable CPV Car Roof | A modular roof for a passenger EV which uses concentrator PV technology and can be extended to increase energy production. |
| Solar Train Stop | A tree-shaped stop for city trains where integrated PV panels are used for providing shelter to waiting passengers as well as for charging the vehicle through a set of induction charging pads. |
| Solar Luggage Vehicle | A solar-powered autonomously operated vehicle used for loading and unloading luggage in airports. |

| | |
|---|---|
| Lock N' Load | A shed for electric bicycles with an integrated PV system. Induction pads are used to wirelessly charge the bicycles while they are parked. |
| Solar Trains Service | A subscription programme for solar-powered city trains which includes maintenance, remote support and a battery swapping service. |


**Figure 4.2-3 Selected conceptual designs from the 'Sources of Innovation' student projects: (1) Solar Mobile Charger[a], (2) Solar Luggage Vehicle[b], (3) Zun[c], (4) Solar Bus Terminal[d], (5) Lock n'Load shed[e], (6) Solar Train Stop[f], (7) Solar Trains Service[g] and (8) Solarshare+ charge point[h]**

[a]Design by R. den Hertog, S. de Jonge and T. Willems.
[b]Design by J. Liao, N. Pizzigoni and V. Rachmanda.
[c]Design by J. Varghese and O. Martínez.
[d]Design by M. Dijkstra, A. Suresh and S.V. Ramana.
[e]Design by D. Nguyen, D. Schmidt and M. Vos.
[f]Design by S. Elango, U. Parvangada and G. Ribeiro.
[g]Design by J. Kaal, H. Reuvekamp and L. Téxier.
[h]Design by A. Reus, J. Schutte and E. van Steenis.

Figure 4.2-4 presents an overview of the design features selected for the developed concepts. Designs mostly focused on either PV-powered charging infrastructure (7 concepts) or VIPV systems (5 concepts), with two projects combining both applications in the form of a mobile charging unit for recharging passenger EVs. Additionally, one project offered a product-service combination where a residential PV charger is coupled with an energy sharing platform, while another project proposed a service-only solution aimed at solar city trains.

The design projects also proposed PV-powered mobility solutions for different vehicles beyond passenger cars. This type of vehicle was covered in 5 of the eleven designs, with the rest focusing on city buses or trains (4 concepts), vans (2), electric bicycles (1) and utility vehicles (1). Although plug-in charging was the preferred charging technology in the developed designs (4 concepts), several projects involved the application of alternative charging technologies such as battery swapping and inductive charging (2 concepts each). In line with the different vehicle types proposed, the developed concepts covered both public (5 concepts) and private (3) transport as well as vehicles intended for shared use (3). The design teams also considered user interaction as an important component of their solutions, with four projects including the design for a dedicated user interface.

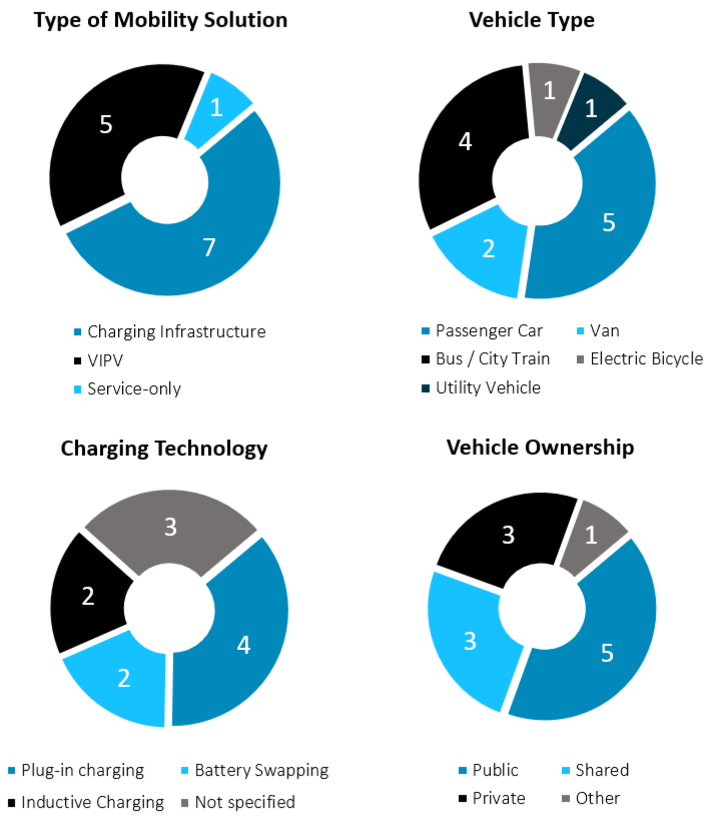


**Figure 4.2-4 Overview of specific features of concepts resulting from the design project: type of mobility solution, vehicle type, ownership and charging modes**

The following sections will introduce two examples of the designs developed by the student teams in further detail as case studies. The concepts presented in sections 4.2.3.1 and 4.2.3.2 focus on PV-powered charging infrastructures.

#### *4.2.3.1 Solar Bus Terminal*

This conceptual design consists of a terminal for electric city buses where a PV system located on top of the structure charges battery packs which are used for recharging the buses while they are parked at the terminal (see Figure 4.2-5). The terminal is connected to the local grid in order to ensure the battery packs are charged even during times of low PV production, and the PV modules can also be fitted with a one-axis tracking system to increase energy production.

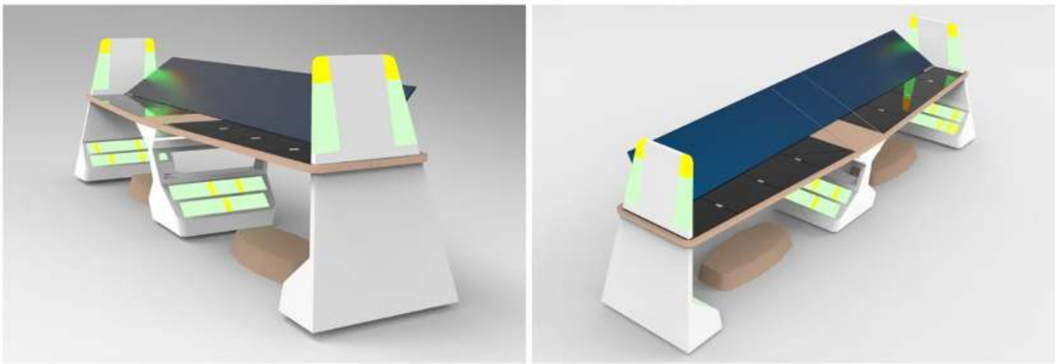

**Figure 4.2-5 Solar Bus Terminal conceptual design. Designers: M. Dijkstra, A. Suresh and S.V. Ramana**

The bus terminal has a series of LED lights in the two pillars located next to the PV system as well as in several panels near the passenger waiting area. The lights can show yellow or green colouring, and the ratio between these two colours is used to indicate how many battery packs have been charged by the PV system at any given moment. This visual feedback, together with a design aesthetic, which highlights the PV modules on top of the structure, is intended to communicate the sustainability-oriented focus of the bus service to its end users.

Table 4.2-3 shows some of the technical specifications for this concept including PV system size, battery capacity and charging speed.

**Table 4.2-3 Technical specifications for the Solar Bus Terminal concept**

| | |
|---|---|
| PV System Size | 10 – 20 kWp |
| Dimensions (L x W x H) | 18 x 4 x 6 m (Terminal Structure)<br>50 x 15 x 30 cm (Battery Packs) |
| Battery Capacity | 200 – 300 kWh (Bus)<br>20 – 25 kWh (Battery Packs) |
| Charging Speed | Battery swapping at periodic intervals |

*4.2.3.2 Solar Train Stop*

In this concept, a small PV system is integrated with a street bench in order to create a stop for city trains, which provides shelter to users while also acting as a local renewable energy source. Figure 4.2-6 shows how this design would operate in combination with an electric train where both the stop and the vehicle have integrated PV cells. This concept has a modular design since the number of benches can be modified depending on the available space and the required PV capacity.

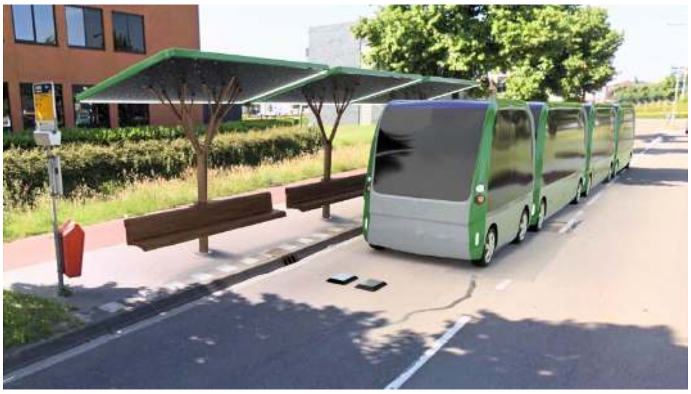

**Figure 4.2-6 Solar Train Stop conceptual design. Designers: S. Elango, U. Parvangada and G. Ribeiro**

The vehicle is charged by using a set of charging pads located on the street, which use induction charging to provide a small amount of charge while the vehicle stops to pick up and drop off passengers. Adequate contact between the train and the charging pads is achieved through a system of sensors and actuators, which uses compressed air and small heaters to clear the pad surface in case of rain or snow. The charging pads are only active when the vehicle is directly above them in order to prevent safety hazards to other vehicles or pedestrians.

The solar train stop concept is intended to provide a comfortable environment for waiting passengers while making the vehicle charging process as unobtrusive as possible from both the driver's and the user's perspective. The station's visual design replicates the shape of a tree in order to help it blend in with the urban environment as well as providing a more pleasant and eco-friendly appearance to users. This distinct appearance is also important for making the station recognisable as part of a sustainable transportation system.

Table 4.2-4 shows some of the technical specifications for this concept including PV system size, battery capacity and charging speed.

**Table 4.2-4 Technical specifications for the Solar Train Stop concept**

| | |
|---|---|
| PV System Size | 1 – 2 kWp |
| Dimensions (L x W x H) | 3,5 x 2 x 2,5 m |
| Battery Capacity | Up to 10 kWh |
| Charging Speed | Inductive charging, 100 – 200 kW [31, 32] |

* Specifications shown are for one bench, total values for a given stop can be scaled depending on the total number of benches used.

### *4.2.4 Conceptual design evaluation*

The conceptual designs introduced in the previous part were presented as conceived by the designers. These designs, however, are still at an early development stage and there are still many factors that need to be considered before they are implemented in practice. This part will therefore evaluate the conceptual designs in order to identify possible design limitations as well as suggesting improvements and alternative applications that could be explored.

#### *4.2.4.1 Solar Bus Terminal*

One of the main limitations of the proposed concept, involves the challenges posed by the battery swapping process which requires drivers to exit the bus for a brief period of time. This could be problematic during peak hours or at times with unfavourable weather conditions, and might also become an inconvenience to passengers as additional waiting time could be required. In addition to this, the assumed energy capacity of the battery packs is relatively high considering the energy density of current lithium-ion batteries (200 – 500 Wh/kg) [33] making the packs too heavy to be carried by a single person. Several smaller small battery packs could be used instead but this would greatly increase the time required for performing the swapping operation. Another possibility involves automating the swapping process, which has already shown positive results in the Chinese EV market [34].

A likely reason for choosing battery swapping as the charging technique for this design is the short amount of time city buses are stationary during their route. However, in order to provide a sufficient amount of charge during this brief period a high charging speed is required which cannot be directly provided by the terminal's PV system. A possible solution to this issue could be replacing the battery packs with a centralised battery storage system, which is able to provide the necessary power for high-speed charging. An additional limitation from this design is the potential self-shading of the PV system due to the pillars located at its sides. This can be corrected by designing less intrusive pillars or removing them altogether. Additional PV cells could also be integrated into other parts of the structure but their location would ultimately depend on the specific location and orientation of each terminal.

This concept for a solar bus terminal can be adapted for similar applications, such as passenger EV or electric bicycle charging in the form of a structure, which also provides sitting areas to users in public spaces such as parks or squares as shown in Figure 4.2-7.

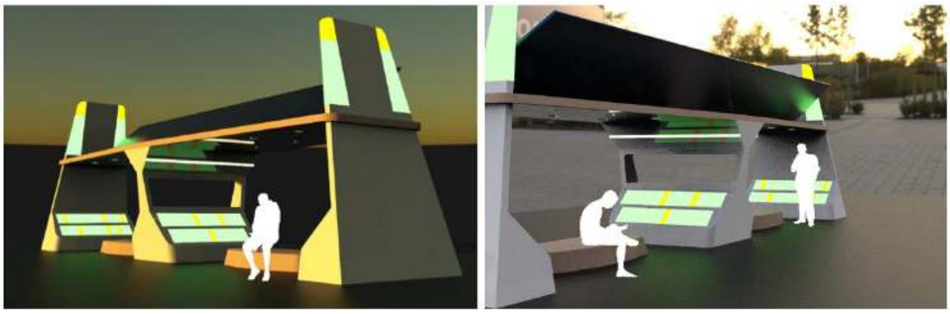

**Figure 4.2-7 Design impression of passengers using the Solar Bus Terminal concept by M. Dijkstra, A. Suresh and S.V. Ramana**

*4.2.4.2 Solar Train Stop*

During its operation, the solar train will only be in front of the stop for several seconds while passengers board or exit the vehicle. This means that a high charging speed is required and, while induction pads are able to provide charging with speeds of up to 200 kW [35], the PV system is not able to directly provide this amount of power to the vehicle. Installing an energy storage system near the train stop or adding a grid connection could enable more power to be transferred to the vehicle but there would still be safety concerns from the use of high-power charging near passengers. Despite this limitation, even if a lower charging speed is used the concept could allow for smaller on-board batteries to be used, reducing vehicle weight and increasing its energy efficiency.

The concept's designers proposed the addition of PV systems in nearby buildings as a way to increase its total PV capacity, but this idea could be further developed for creating a local MG where surplus production from the solar train stop is used to partially cover the electric demand of these buildings. Like the previously introduced Solar Bus Terminal concept, this design can be adapted for charging other types of vehicles such as passenger EVs or electric bicycles in public areas. Similar applications for other objects found in the urban environment such as street signs and lamps could also be developed for charging parked vehicles.

*4.2.4.3 Simulations of EV energy demand and PV production*

In order to quantitatively assess the potential of PV systems for powering the mobility concepts developed in this design project, the approximate share of their energy demand covered by the integrated PV system was calculated applying a simulation model, which has been previously developed and published by the authors [20].

Two representative locations with different yearly irradiance were chosen for this assessment: Amsterdam, The Netherlands (GHI: 1,060 kWh/$m^2$ per year) and Perth, Australia (GHI: 1,960 kWh/$m^2$ per year) [36]. Additionally, two scenarios considering different shading factors (no shading and 30% shading) were defined at both locations in order to determine each concept's expected PV share under different conditions.

Table 4.2-5 below shows the estimated PV shares for all four concepts introduced in section 4.2.3 as well as the technical assumptions considered in each simulated scenario based on the specifications provided in Table 4.2-3–Table 4.2-4.

**Table 4.2-5 Simulated PV shares achieved by the conceptual designs**

| Concept | Input Variables | Energy Demand | PV Share (Amsterdam, NL) | | PV Share (Perth, AU) | |
|---|---|---|---|---|---|---|
| | | | No Shading | 30% shading factor | No shading | 30% shading factor |
| Solar Bus Station | 20 kWp PV installed, 250 kWh EV battery capacity, 50 kWh stationary storage. Drive distance 30 000 km/year, driving efficiency 0,58 kWh/km [37], 2 buses operating per station | 17 400 kWh/year | 50% | 35% | 69% | 51% |
| Solar Train Stop | Train stops consisting of 3 bench modules, each with 2 kWp PV installed. 45 kWh EV battery capacity [32], 10 kWh stationary storage. Drive distance 30,000 km/year, driving efficiency 0.58 kWh/km [38] | 17 400 kWh/year | 32% | 22% | 46% | 32% |

The PV share is defined as in (4.2-1):

$$\mathrm{PV}_{\mathrm{share}} = \frac{E_{PV,year}}{E_{EV,year}} \tag{4.2-1}$$

where $E_{PV,year}$ is the yearly energy production from the PV system (in kWh) and $E_{EV,year}$ is the vehicle's yearly energy demand (in kWh). It is worth noting that these estimations assume that the energy produced by the PV systems is used by the vehicles. This may not always occur in practice as in some situations the on-board or stationary batteries could already be fully charged and thus generated PV energy cannot be stored.

### *4.2.5 Discussion and conclusions*

A total of eleven design solutions were developed in this study, most of which focused on charging infrastructure (7) or on VIPV systems. Designs also included a product-service combination as well as a service-only solution aimed at one of the companies participating in this project. The developed concepts focused on several different vehicle types such as passenger cars, buses and electric bicycles with either public, private or shared ownership.

The extent to which the PV electricity produced by these systems will meet vehicle demand will vary significantly. The share of PV estimated for the four conceptual designs introduced in Section 4.2.3 show that for public transport applications PV systems could supply approximately 22 – 50% of vehicle demand in the Netherlands and 32 – 69% in Australia, while the share of PV for a mobile EV charger depend on how many EVs it needs to charge simultaneously, ranging from 24% and 35% when charging four EVs in Amsterdam and Perth respectively to 98 and 100% when charging only one EV. On the other hand, due to their high daily use airport service vehicles are only likely to obtain around 10 – 15% of their energy demand from an integrated PV system in both locations.

One of the main design limitations found in this chapter was the small area available for installing PV systems, particularly for designs for which PV cells are integrated on vehicles. This was not the case for solar charging in infrastructural contexts and can hence be considered to be an advantage for a wider use of solar charging stations for EV charging.

Designs for PV-powered charging infrastructure, also showed how PV systems can be used for powering a wide range of modes of transportation beyond electric passenger cars. In these cases, as mentioned above, space constraints regarding PV cells, modules or arrays were hardly observed. The use of alternative charging technologies presents an innovative approach; at present significant progress has been made in the development of both battery swapping [34, 39] and inductive charging [40, 41] however it is still unclear when these charging methods will be widely implemented.

Finally, an important aspect of designing these applications is the use of their visual appearance not only for providing an aesthetically pleasing element to the urban environment but also for communicating to users their function and their focus on sustainability. Charging infrastructure has more liberty to achieve this goal than the vehicles themselves although it is still constrained by the limited space available in urban areas, particularly those with high structural density and related shading Remarkably, none of the projects considered changing the colour, transparency, texturing or shape of PV cells, though the authors assume these design features have a great potential to make PV applications for mobility appealing to a broad audience. On the other hand, for this specific design study, the lack of modifications of color, transparency and form giving, could mean that in this premature innovation and product development phase these features are not as relevant to designers as previously assumed, and that the current attributes of PV technologies are already valuable from a design perspective.

It is important to consider that the presented designs were developed at the conceptual stage only and as such it is difficult to evaluate design aspects such as costs, user acceptance and the required balance of system components for each concept. Further development of these concepts is therefore required to better capture and quantify the required design elements for innovative PV-powered mobility solutions before they can be fully implemented in practice.

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## 4.3 An exploratory user study for PV-powered mobility applications

This chapter presents the results of a user survey on several market-ready applications for solar-powered mobility which aims to identify what the potential users for these applications perceive as benefits or barriers to their adoption, as well as the impact of factors such as previous experience with EVs, residential PV ownership and pro-environmental attitudes on these perceptions.

EVs have recently emerged as a promising solution for reducing $CO_2$ emissions in the transport sector, with global vehicle stock for both battery electric and plug-in hybrid cars reaching 7.2 million electric cars in 2020 [1]. This growth has been driven by reduced costs and government incentives aimed at emissions reductions. It is important to consider, however, that the potential for an EV's $CO_2$ emissions reduction is dependent on how the electricity that powers it is produced [2]. A substantial reduction of $CO_2$ emissions from EV usage could be achieved by the development of solutions that rely on PV systems as a primary energy source such as solar-powered EV charging stations or vehicles with integrated PV cells. With the exception of rooftop PV systems being used for charging EVs, there are currently very few applications for solar-powered mobility available on the market or under commercial development. Nevertheless, the potential for solar-powered mobility is enormous and it is important to understand how possible 'lead users' or early adopters perceive these technologies and what aspects they believe are their main advantages and limitations. This information can help to increase the willingness to adopt this type of applications in the near future not just for this specific group of users, but for a larger segment of the future market as well.

In general, the motivations for using a car [3] as well as the key factors behind its adoption have been extensively studied, particularly regarding the adoption of EVs compared to internal combustion engine (ICE) vehicles [4], [5]. While some user studies have been conducted for EVs as well as their charging infrastructure [6], [7], [8], [9], solar-powered applications have not been specifically included so far. Likewise, user studies have been executed on the adoption of renewable and smart energy applications [10], [11], [12], [13] but transport is rarely included in these studies with the notable exception of solar-powered bicycles [14], [15].

The user study presented in this chapter therefore aims to bridge this gap by presenting exploratory findings on the perceived benefits and limitations of existing solar-powered mobility applications from the perspective of their (potential) users, as well as exploring which factors (such as experience with EV use, residential PV ownership and sustainable or pro-environmental attitudes) play a significant role in determining these perceptions.

### *4.3.1 Method*

#### *4.3.1.1 Theoretical Framework*

The selection of variables to be captured by the user study was based on the Unified Theory of Acceptance and Use of Technology (UTAUT) model [16] which is frequently applied for studying the acceptance of new technologies including, among others, new transport modes [17], [18]. UTAUT incorporates elements from previous technology adoption frameworks such as Rogers' Innovation Diffusion Theory (IDT) [19] and the Technology Acceptance Model (TAM) [20], using several variables such as experience, facilitating conditions and social influence to predict the use of a given technology or product (see Figure 4.3-1). This user study is also based on similar work conducted for electric mobility adoption [5], [15], specifically studies on ultrafast charging [21] and 'mobility as a service' [22], as well as other studies on pro-environmental attitudes [23]–[25].

Table 4.3-1 shows the selected variables for this study after applying the UTAUT framework to solar-powered mobility.

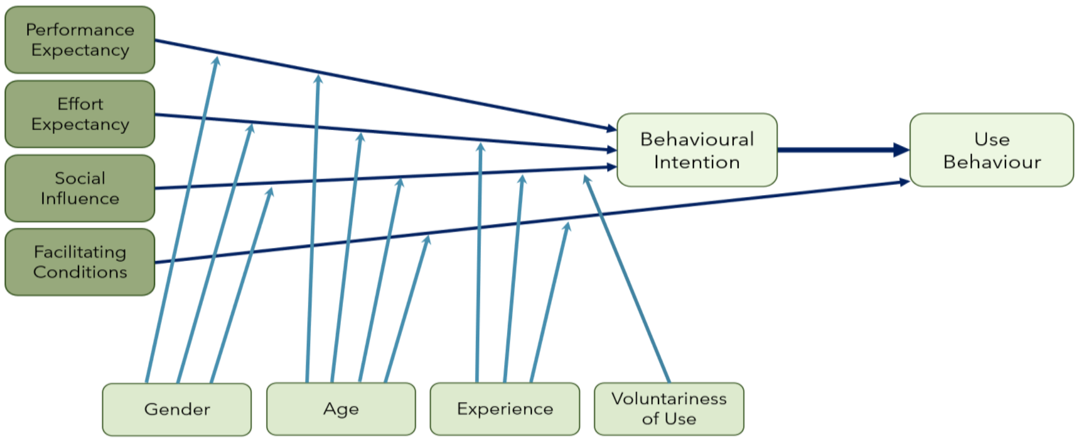


**Figure 4.3-1 UTAUT model framework [16]**

This user study is also based on similar work conducted for electric mobility adoption [5], [15], specifically studies on ultrafast charging [21] and 'mobility as a service' [22], as well as other studies on pro-environmental attitudes [23]–[25].

**Table 4.3-1 Selected user study variables**

| User Variable | UTAUT Component [16] |
|---|---|
| General | |
| Previous experience with PV and EVs | Experience |
| Pro-environmental attitudes | Social Influence<br>Facilitating Conditions |
| Adoption of PV and EVs by peers | Social Influence |
| Future intention to purchase or lease a vehicle | Behavioural Intention |
| Socio-economic and demographic variables | Gender<br>Age<br>Facilitating Conditions |
| PV-powered mobility applications | |
| General perception and willingness to adopt | Voluntariness of Use |
| Evaluation of specific attributes (e.g. sustainability, cost, appearance) | Performance Expectancy<br>Effort Expectancy |

*4.3.1.2 Questionnaire structure and data collection*

The questionnaire created for this user study consisted of 33 questions, both semi-open and closed. A full version of this questionnaire can be found in Appendix D.

The questionnaire is composed of three main parts:

1. Experience with PV and EVs – In this part, respondents are asked about their familiarity with EV use and whether they own a residential PV system. Questions also address respondents' likelihood to buy or lease a vehicle in the near future as well as a list of attitude statements aimed at evaluating respondents' environmentally-friendly or sustainable behaviour.
2. Perception on PV-powered applications – Respondents are introduced to several PV-powered mobility applications, followed by a short series of questions on their general perception of each application, their likelihood to adopt it (i.e. purchase/lease a vehicle or use a charging station in the near future) and their assessment on specific elements such as visual attractiveness and sustainability.
   EV drivers were also asked to respond to an additional question regarding their willingness to pay more for a version of their current vehicle which includes integrated PV cells since these respondents may not

be interested in the specific applications presented in the survey but might still value PV-powered vehicles in general.

3. Socio-economic and demographic questions – This part is used to capture variables such as gender, age, household structure and yearly household income among others.

Table 4.3-2 describes the four different PV-powered applications which were presented to users in the survey, consisting of two vehicles with integrated PV cells and two solar charging stations (see also Figure 4.3-2).

**Table 4.3-2 User survey – presented mobility applications**

| Application | Description | Cost | Range | Charging Speed |
|---|---|---|---|---|
| Sono Sion | A solar-powered electric car developed by German company Sono Motors with solar panels integrated with the car's roof, bonnet, doors and back. | € 25.500 (est.) | 225 km (est.) [26] | - |
| Lightyear One | A solar-powered electric sports car developed by Dutch start-up Lightyear with solar panels located on the car's bonnet, roof and back. | € 149.000 (est.) | 575 km (est.) [26] | - |
| Fastned | Fastned operates over 100 superfast EV charging stations in the Netherlands, Germany and the UK. The charging stations have integrated solar panels which produce part of the electricity used for charging EVs. | € 0,59 per kWh | - | Up to 150 kW |
| SECAR e-Port | A solar carport developed by Austrian company SECAR with solar panels on its roof which produce electricity for charging EVs as well as shading them from the sun while they are parked. The e-Port has a modular design that can be adapted for charging one or several EVs. | € 0,40 per kWh (est.) | - | Up to 22 kW |


**Figure 4.3-2 PV-powered mobility solutions evaluated during the user survey. Clockwise from top left: Sono Sion, Lightyear One, SECAR e-Port and Fastned charging stations**

The four applications shown in Table 4.3-2 and Figure 4.3-2 were selected because they represent some of the few examples of solar-powered mobility which are at an advanced development stage or already available on the market at the time of writing.

Data collection for this study was carried out using the Qualtrics web-based survey environment, which made it possible to easily distribute the questionnaire to a large number of respondents. An important issue with user studies involves the responsible management of datasets and the adequate protection of personal information. To avoid any potential conflicts on this issue, data protection policies were managed in coordination with the University of Twente's ethics committee, placing special care in complying with the European Union's GDPR regulations.

The survey was initially focused on EV drivers in the Netherlands but was later extended to potential respondents in other locations to increase the respondent sample size; for this reason, the online questionnaire was distributed in both English and Dutch.

A pilot version of the questionnaire was first tested with the participants of a workshop on PV-powered mobility in October 2020 to identify possible improvements or corrections. Additionally, both companies developing solar-powered EVs were contacted to corroborate the descriptions presented in the survey, including driving range and expected market price. The validated survey was then active from November 2020 to January 2021. Respondents were contacted through driving associations, online forums on EVs and social media platforms such as LinkedIn and Twitter.

### *4.3.2 Survey Results*

This part presents the results of the conducted survey starting with descriptive statistics and followed by statistical significance tests and regression modelling, both of which was carried out using the SPSS statistics software.

A total of 108 respondents took part in the online survey. Several answers were excluded from any further analysis due to incomplete or inconsistent data, resulting in a final number of 86 responses. The aim of this study is therefore not to characterise a representative sample of potential adopters for these applications but rather to present exploratory findings on possible user preferences.

#### *4.3.2.1 Descriptive statistics*

Table 4.3-3 presents the demographic composition of the respondent sample. It is possible to see that the majority of respondents are male (84%), highly educated (76%) or with a relatively high income (59%). This is consistent with the results of two recent surveys on EV drivers [27] and people interested in electric mobility in the Netherlands [28], indicating that this is the market segment currently interested in electric mobility.

**Table 4.3-3 User survey – sample composition**

| Gender | | Education | |
|---|---|---|---|
| Male | 84% | High School | 4% |
| Female | 10% | Bachelor's Degree | 20% |
| | | Master's degree or higher | 76% |
| Age Group | | | |
| 0 - 30 | 24% | Household Structure | |
| 31 - 40 | 28% | Single (no children) | 15% |
| 41 - 50 | 23% | Single parent | 0% |
| 51 - 60 | 16% | Couple (no children) | 35% |
| 60+ | 10% | Couple with children | 48% |
| | | Other | 3% |
| Annual Income | | | |
| Less than € 12.500 | 3% | Cars in Household | |
| € 12.500 - € 26.200 | 8% | None | 19% |
| € 26.201 - € 38.800 | 10% | One | 34% |
| € 38.801 - € 65.000 | 21% | Two | 37% |
| € 65.001 - € 75.500 | 20% | More than two | 10% |
| More than € 75.500 | 39% | | |

As a result of the survey distribution process, nearly half (49%) of respondents were from the Netherlands, but there was also significant participation from countries such as Australia (11%), Germany (8%) and Belgium (6%). The remaining responses originated from a diverse group of countries including China, Japan, France, the United Kingdom, Spain, Portugal, Italy, the United States, Canada and Mexico.

**EV Use** – Regarding their experience with driving EVs, 27% of respondents have never driven an EV while 41% have only occasionally used an EV. Among the remaining 33% who do own an EV, most have owned their vehicle for more than four years (10%), followed by 1-2 years (9%) and less than one year (7%).

Regarding vehicle ownership, a majority of respondents (67%) indicated that they privately owned their EV followed by business leasing (17%), private car-sharing (13%) and private leasing (3%). Notably, 62% of people who indicated driving an EV have at least two vehicles at home compared to 38% of people who do not own an EV.

Figure 4.3-3 shows the average weekly distance respondents travelled with their personal vehicle. Notably, more than 35% of respondents travelled less than 100 km each week which is well below the average daily distances reported in several countries [29], [30] as well as recent studies on EV drivers in the Netherlands [21]. These comparatively small driving distances could be a result of the COVID-19 global pandemic, where lockdowns forced a large number of respondents to stay at home and change their car usage habits.

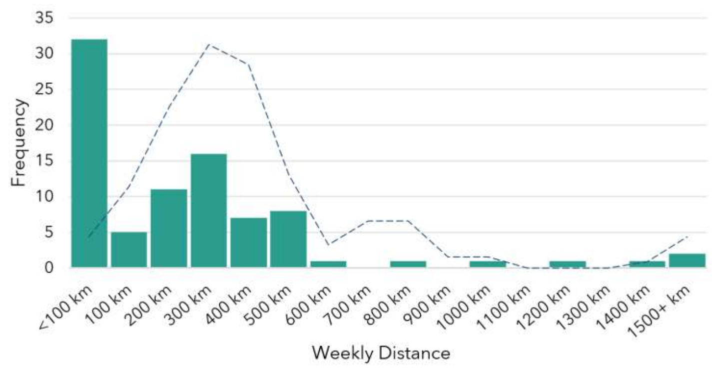


**Figure 4.3-3 Histogram showing weekly distance travelled by the survey respondents; the dotted line shows the distance travelled by Dutch drivers in 2019 [21]**

**PV Ownership and Environmental Attitude –** 42% of respondents reported owning a rooftop PV system at home. This is a relatively high share considering that on average only 26% of Dutch people interested in electric mobility [28] and 5% of Dutch households currently have residential PV [31]. Nearly half (48%) of respondents also indicated having an energy contract that specifically includes 'green' electricity. This partly overlaps with PV owners but also includes a significant number of respondents who do not have PV at home.

Table 4.3-4 below shows the survey response to some of the attitude questions on environmentally-friendly or sustainable behaviour using a 5-point Likert scale. A majority of respondents indicated being mindful of their environmental impact when travelling (62%) and using energy at home (79%), with 70% willing to pay a higher price for more sustainable products.

**Table 4.3-4 Selected environmental attitude statements**

| Statement | Strongly Disagree | Disagree | Neither agree nor disagree | Agree | Strongly Agree |
|---|---|---|---|---|---|
| (1) Being environmentally responsible is very important to me | 0% | 0% | 5% | 38% | 57% |
| (5) I think everyone should behave in an environmentally friendly way | 0% | 2% | 8% | 41% | 49% |
| (7) Environmentally friendly behaviour does not fit my current living situation | 35% | 44% | 10% | 7% | 3% |
| (9) I would buy a more environmentally friendly product even if it is more expensive | 1% | 7% | 22% | 48% | 22% |
| (11) I always try to use energy at home as efficiently as possible | 0% | 6% | 15% | 51% | 28% |
| (12) I always pay attention to environmental friendliness in my travel behaviour | 3% | 9% | 26% | 43% | 19% |

**Evaluation of Mobility Applications –** Figure 4.3-4 and Figure 4.3-5 respectively show respondents' overall impression of each of the four mobility applications as well as their likelihood to adopt them on a 5-point Likert scale. This was defined as the likelihood to purchase or lease one of the vehicles (i.e. the Sono Sion or the Lightyear One) in the next five years or the likelihood to use the charging services (i.e. Fastned and the e-Port) in the next year.

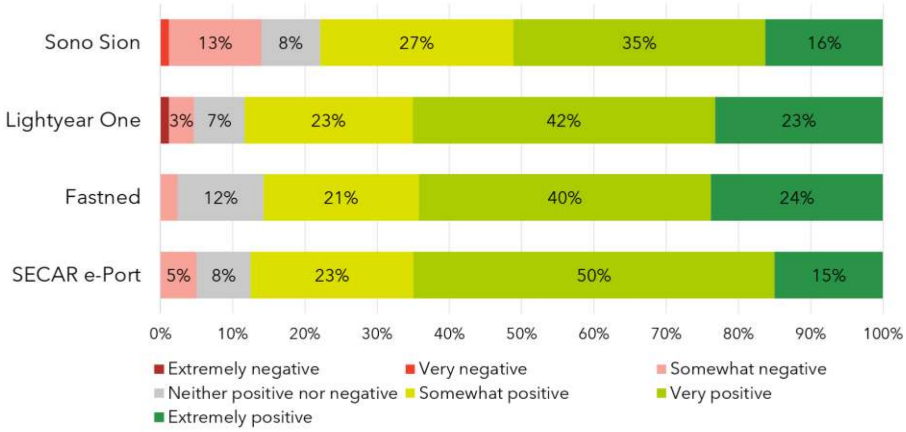


**Figure 4.3-4 Histogram Respondents' overall impression of the presented mobility applications**

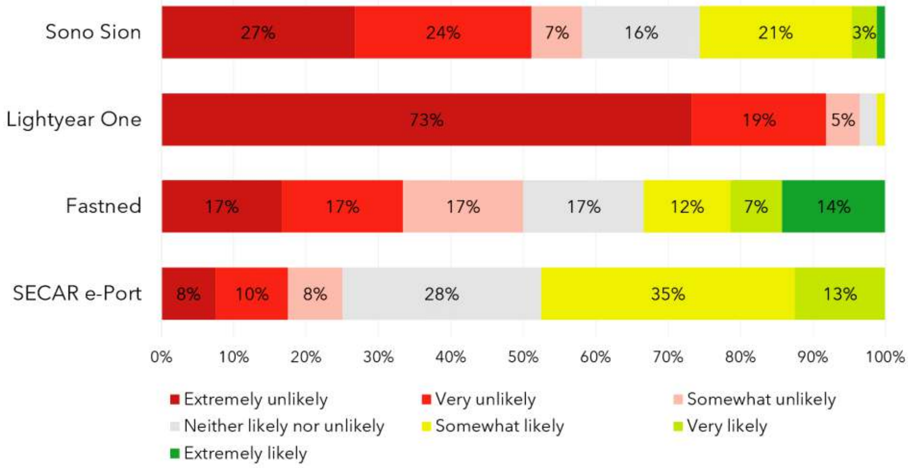


**Figure 4.3-5 Respondents' likelihood to adopt (purchase/lease/use) each of the presented mobility applications**

As expected, while the impression of all applications is mostly positive, the likelihood of adopting them is comparatively lower. This is more evident for the Lightyear One which at an expected market price of €149.000 is well beyond the financial reach of most respondents. Results for the Sono Sion, however, are remarkably close to the likelihood to buy an EV (26%) reported on a recent Dutch survey [32].

Responses towards both solar charging stations, on the other hand, were found to be significantly more positive with 48% of respondents being likely to use the e-Port and 33% being likely to use Fastned stations. While this difference could be attributed to the former's lower cost (€0,40 per kWh compared to Fastned's €0,59 per kWh), it is important to consider that there is a trade-off between cost and charging speed between both applications since Fastned can charge at over 100 kW while the e-Port has a maximum charging power of 22 kW. From the survey results, however, it is difficult to determine whether the respondents took this trade-off into account.

Table 4.3-5 shows the respondents' evaluation of specific attributes for each application. There is a general agreement among respondents that all applications will reduce their environmental impact, as well as on the applications' visual attractiveness. An exception to the latter assessment was observed for the Sono Sion, although most respondents indicated the vehicle will save them money in the long run; this could indicate that this application will be valued on sustainability and cost-effectiveness rather than appearance. Interestingly, with the exception of the Lightyear One, there was not a clear consensus among respondents on whether the cost of these applications is too high.

**Table 4.3-5 Select Solar mobility solutions – specific attribute evaluation**

| Application | Strongly Disagree | Disagree | Neither agree nor disagree | Agree | Strongly Agree |
|---|---|---|---|---|---|
| Sono Sion | | | | | |
| Environmental impact reduction | 3% | 9% | 7% | 49% | 31% |
| Long-term money savings | 2% | 9% | 21% | 41% | 27% |
| High purchasing cost | 9% | 26% | 43% | 17% | 5% |
| Attractive appearance | 13% | 37% | 26% | 22% | 2% |
| Independence from plug-in charging | 5% | 16% | 21% | 49% | 9% |
| Lightyear One | | | | | |
| Environmental impact reduction | 5% | 8% | 10% | 55% | 22% |
| Long-term money savings | 21% | 36% | 22% | 13% | 8% |
| High purchasing cost | 7% | 8% | 13% | 23% | 49% |
| Attractive appearance | 2% | 7% | 21% | 40% | 30% |
| Independence from plug-in charging | 1% | 6% | 20% | 51% | 22% |
| Fastned | | | | | |
| Environmental impact reduction | 3% | 18% | 25% | 45% | 10% |
| High charging cost | 3% | 13% | 40% | 35% | 10% |
| Attractive appearance | 0% | 8% | 18% | 55% | 20% |
| Reduced convenience compared to other charging stations | 20% | 18% | 48% | 15% | 0% |
| SECAR e-Port | | | | | |
| Environmental impact reduction | 5% | 0% | 18% | 53% | 25% |
| High charging cost | 3% | 15% | 43% | 40% | 0% |
| Attractive appearance | 5% | 3% | 23% | 58% | 13% |
| Reduced convenience compared to other charging stations | 2% | 25% | 53% | 18% | 3% |

**Solar EV 'Version'** – As shown in Figure 4.3-6, 88% of respondents indicated they would be willing to pay more for a version of their vehicle with integrated solar cells, equivalent in most cases to up to an additional 10% of the original vehicle's purchasing cost.

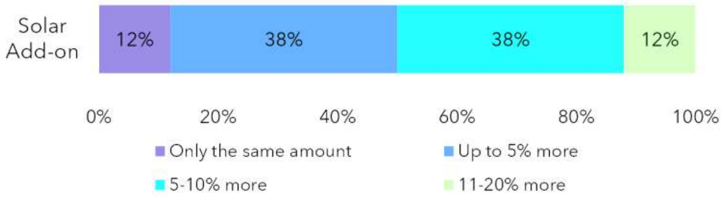


**Figure 4.3-6 EV drivers' willingness to pay an additional cost for a 'solar' version of their vehicle**

Comparing the market price [26] of each respondent's EV model with their indicated response, it is possible to estimate that this additional cost amounts to an average of € 2.150, with values ranging between €850 and €4.480. While these values are only indicative due to the small sample size (N = 38), they can provide an initial estimate of the perceived added value of integrated PV cells on EVs.

#### *4.3.2.2 Influence of residential PV ownership*

In addition to the descriptive statistics results presented in the previous subsection, the specific impact of PV ownership on respondents' EV experience and their likelihood to adopt (purchase/lease/use) the solar mobility applications was statistically analysed.

Figure 4.3-7 shows respondents' experience with EVs comparing those who own a residential PV system and those who do not. It can be seen that both groups have different levels of experience with EVs, with a majority of PV owners having driven an EV at least occasionally (33%) or owning an EV outright (64%), as opposed to other respondents who have mostly never driven an EV (44%) or only driven one occasionally (46%). This difference among both groups was found to be statistically significant using a statistical t-test ($t = 6.54$, $df = 84$, $p<0.001$).

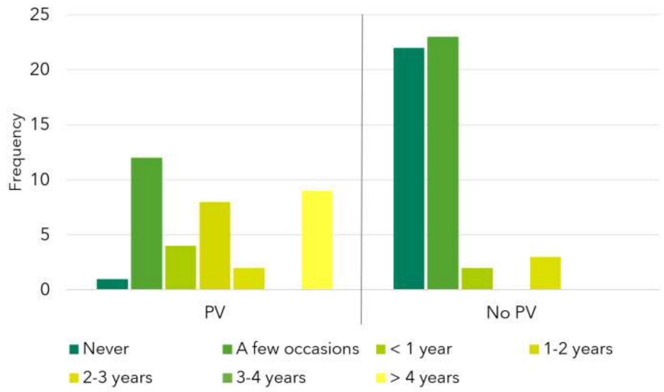


**Figure 4.3-7 Experience with EV use among respondents with and without a residential PV system**

The results of a statistical analysis of other variables of interest can be seen in Table 4.3-6. Perhaps unsurprisingly, significant differences between both groups were found in several environmental attitude statements including (1) the importance of being 'environmentally responsible', (8) paying attention to sustainability when purchasing appliances and (11) efficient energy use at home.

Demographic indicators such as age and income were also found to be significantly different among both responder subsets; regarding respondents' likelihood to adopt the presented mobility solutions, the only significant difference was observed for the Lightyear One.

**Table 4.3-6 Residential PV ownership – T-test results**

| Variable | Test Statistic | p-value (2-tailed) |
|---|---|---|
| Age ** | t = 5.114 (df = 78) | <0.001 |
| Annual Income * | t = 2.018 (df = 78) | 0.048 |
| Household Structure | t = 1.583 (df = 78) | 0.147 |
| Experience with EV use ** | t = 6.542 (df = 84) | <0.001 |
| Env. Attitude (8) - Attention to sustainability when purchasing appliances * | t = 2.376 (df = 84) | 0.020 |
| Env. Attitude (13) - Peers' opinion on using public transport as much as possible* | t = -2.199 (df = 66) | 0.031 |
| Likelihood to Adopt | | |
| Sono Sion | t = 1.795 (df = 84) | 0.076 |
| Lightyear One * | t = -2.048 (df = 84) | 0.044 |
| Fastned Stations | t = -0.420 (df = 40) | 0.968 |
| SECAR e-Port | t = 1.037 (df = 38) | 0.307 |

* Significant at 95% level. ** Significant at 99% level.

#### *4.3.2.3 Logistic Regression Modelling*

In addition to the previous results, a regression analysis using a binary logit model was carried out. This type of model can estimate the probability of a binary response variable (in this case whether a respondent is likely to adopt (purchase/lease/use) one of the mobility applications) based on several predictor variables. Although an ordinary logit model would in principle be more suitable for this type of question, due to the small sample size a binary logit model was selected instead.

For this purpose, survey responses involving the likelihood to adopt the applications were classified into two groups ('likely' and 'neutral or unlikely'), and based on the analysis shown in the previous parts the following variables were selected as predictors:

- Annual Household Income
- Experience with EV use
- Type of Electricity Contract
- Residential PV Ownership
- Environmental attitude statements:
  - (1) - Importance of being 'environmentally responsible'
  - (5) - Sustainable behaviour expected from everyone
  - (8) - Attention to sustainability when purchasing appliances
  - (9) - Paying more for a sustainable product
  - (12) - Sustainability in travel behaviour
- Likelihood to purchase or lease a vehicle in the near future

Avoiding multicollinearity (i.e. a strong association between two predictor variables) is an important condition in regression modelling to ensure that all predictor variables are independent of each other. Therefore, the correlation between these variables was investigated as a preliminary step. Overall, while some variables were found to be significantly correlated with each other (particularly between some of the attitude statements), none of these were strong correlations (i.e. Pearson coefficient > 0.65) meaning that the non-multicollinearity condition is satisfied. A full correlation matrix including all variables can be found in Appendix E.

Table 4.3-7 presents the parameters from the resulting regression model for the Sono Sion which had a log-likelihood of 60.07 and a Nagelkerke R Square of 0.45, indicating a moderately good fit to the input data. Four parameters were found to be significant; these are in order of impact:

- Environmental Attitude (9) – Paying more for a more sustainable product ( $\beta = 1.86$ );
- Likelihood to purchase a vehicle ( $\beta = 0.68$ );
- PV Ownership ( $\beta = -2.41$ );
- Electricity – 'Green Contract' ( $\beta = -3.41$ ).

**Table 4.3-7 Residential Binary logit model parameters – Sono Sion**

| Variable | Estimate ($\beta$) | Standard Error | Wald | df | p-value |
|---|---|---|---|---|---|
| Income (High) | | | 1.79 | 2 | 0.409 |
| Income (Low) | 0.66 | 1.09 | 0.37 | 1 | 0.545 |
| Income (Mid) | -0.96 | 1.01 | 0.90 | 1 | 0.342 |
| EV experience (None) | | | 1.79 | 2 | 0.408 |
| EV experience (Occasional) | 0.19 | 1.02 | 0.04 | 1 | 0.851 |
| EV experience (Own) | -1.23 | 1.27 | 0.94 | 1 | 0.332 |
| Electricity (Don't know) | | | 6.09 | 3 | 0.108 |
| Electricity (Energy co-op) | -1.10 | 2.11 | 0.27 | 1 | 0.604 |

| | | | | | |
|---|---|---|---|---|---|
| Electricity ('Green' contract) | **-3.41** | 1.72 | 3.96 | 1 | **0.047** |
| Electricity ('Grey' contract) | -1.30 | 1.38 | 0.89 | 1 | 0.346 |
| PV | **-2.41** | 1.18 | 4.17 | 1 | **0.041** |
| Env. Attitude (1) | -0.14 | 0.85 | 0.03 | 1 | 0.867 |
| Env. Attitude (5) | -0.40 | 0.72 | 0.32 | 1 | 0.579 |
| Env. Attitude (8) | -0.30 | 0.53 | 0.33 | 1 | 0.563 |
| Env. Attitude (9) | **1.86** | 0.81 | 5.32 | 1 | **0.021** |
| Env. Attitude (12) | -0.72 | 0.47 | 2.33 | 1 | 0.127 |
| Likelihood to Purchase | **0.68** | 0.26 | 6.68 | 1 | **0.010** |
| Likelihood to Lease | 0.30 | 0.20 | 2.27 | 1 | 0.132 |
| Constant | -0.13 | 4.62 | 0.00 | 1 | 0.977 |

Similar model results for the Fastned charging stations and the SECAR e-Port can be found in Appendix E. It is important to mention that since these applications were only shown to respondents who indicated owning an EV, the sample size used for estimating these two models is comparatively smaller and results should be interpreted with caution. Finally, a statistically significant regression model for the Lightyear One could not be estimated given the small number of respondents who indicated a positive likelihood to adopt this application in the near future.

### *4.3.3 Discussion*

As with any statistically-based study, the robustness of the presented results depends on how accurately the obtained sample represents the target population. Although the number of responses (N = 86) is comparatively lower than the approximately 400 responses required for an accurate representation of the EV driving population, it is worth considering that given the novelty of these applications there is still a low level of awareness among the general public and gathering a large volume of responses is difficult. These results therefore offer an initial exploration into the needs and motivations behind the user adoption of solar-powered mobility applications.

Beyond the specific results for the four presented applications, the survey shows that a majority of respondents do see an added value in solar-powered vehicles, with 88% indicating they would be willing to pay more for a version of their current vehicle which had integrated solar cells on it. Further validation of these results in surveys with larger sample sizes could involve comparing solar-powered mobility applications with electric mobility in general through stated choice experiments, following a similar approach to existing studies which have compared EVs themselves to ICE vehicles [6], [33].

Another key factor that needs to be considered when interpreting the presented results is the complexity of decision-making processes involved in transport use and car ownership. One respondent, for instance, mentioned not owning a car and only using car-sharing with different EV models while another indicated being a 'transit-oriented' person with no intention to ever own a personal vehicle. Future studies on this topic should therefore analyse the behaviour of car owners and non-car owners separately as the decision-making process of these two groups is likely to be different.

Finally, it is worth mentioning that obtaining a larger sample can make it possible to use other tools such as principal component analysis and cluster analysis which are commonly applied in transport research [22]. Additional qualitative results can be also obtained through semi-structured interviews or focus groups where respondents can be introduced in further detail to solar-powered mobility applications in order to obtain a more comprehensive impression of each solution. The key issues covered in these interviews can then be identified using grounded theory analysis, following a similar approach as previous studies on electric mobility [9].

### *4.3.4 Conclusions*

The results of this user study show that in general, while respondents tend to have a positive perception of the presented PV-powered mobility applications, their likelihood to adopt them in the near future appears to be relatively low. This is especially the case for the two vehicles, which is not surprising given that purchasing or leasing a new vehicle requires a stronger commitment than using a charging station, making comparisons between both types of applications difficult. Despite this low likelihood to adopt, a majority of respondents indicated they would be willing to pay slightly more for a version of their vehicle with integrated solar cells.

A binary regression analysis of the survey responses for one of these applications, namely the Sono Sion, found that factors such as owning a residential PV system, the type of household electricity contract (e.g. 'green' or 'grey' energy) and some pro-environmental attitudes can have a significant impact on the willingness to adopt this application. Notably, a significant difference in EV ownership in general was found between respondents with residential PV and respondents without it, indicating a positive relationship between the use of solar energy at home and an interest in electric transport.

Overall, the presented results offer an initial indication of user needs and motivations regarding solar-powered mobility applications in an international context. In order to yield more robust results specifically for the Dutch market, this survey should be conducted with a sample of at least 400 Dutch respondents with various backgrounds and different incomes, or larger samples if user segmentation is to be done. A larger sample size can also enable the use of other analytical tools used in transport research such as principal component analysis, cluster analysis and stated choice experiments.

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# 5 CONCLUSIONS AND FUTURE WORK

Rapid growth in the number of EVs has been increasing the demand for power, which places an extra burden on the public grid, causing greater fluctuations in load. This is an impediment to further market penetration by EVs. New technologies associated with new economic models are needed to improve the operation of the public grid and EV user experience. Innovative systems and infrastructures based on PV energy for charging EVs can potentially reduce the impact on the power grid. The present report focuses on the generation of PV energy at charging stations equipped with PV panels (on car parking shades or buildings equipped with a PV system) that can then be used to charge EVs.

PVCS may offer significant benefits to drivers and an important contribution to the energy transition. Their massive implementation will require technical and sizing optimization of the system, including stationary storage and grid connection, but also change of the vehicle use and driver behavior. Long parking time for EVs, short driving distance (around 45 km), and slow charging mode are the most realistic requirements and feasibility conditions for increasing PV benefits for PVCS. In addition, the EV charge controlling allowing intelligent communication between the operators and the end-users, based on powerful algorithms, remains necessary to increase PV benefits for EVs charging.

PVCS have the potential to further decrease the $CO_2$ emissions impact of electrified transport and accelerate the adoption of EV overall due to decreased dependence on the public grid. In order to effectively implement the PVCS, techno-economic and environmental approaches including a life cycle analyze will be important for assessing the role and benefits of PV electricity for EV charging infrastructures.

As a concept of bridge technology to V2G / V2H services, it will be possible to consider that PVCS, including a well-designed power management strategy, would provide an environmental benefit in these services, although V2G / V2H systems are not yet ready for industrial-scale use.

The questions of how to directly use and manage PV electricity for different types of PVCS, driving profiles and locations with different solar irradiance, and how to integrate PVCS components with keeping mechanical and physical reliability and safety including standardization will be important for all kinds of PVCS.

Regarding the social acceptance of PVCS and V2G / V2H services, it will be important to identify factors that potential users of PVCS perceive as benefits or barriers, as well as their impact, and to explore a wide variety of possible designs, knowing that in this early phase of innovation the range of designs has not yet fully crystalized.

These promising results point to a number of key recommendations as well as a number of main issues for effectively implementation and use PV-powered charging stations:

**Key recommendations**

- PV-powered infrastructures for EV charging require stationary storage in both configurations grid-connected and off-grid;
- Charge / discharge controlling, optimization, PV production forecasting, and intelligent communication between the operators and the end-users remain necessary to increase PV benefits;
- Main requirements and feasibility conditions for increasing PV benefits are:
    - Daily charge instead weekly charge;
    - Charging power of up to 7 kW;
    - Based on PV and stationary storage energy;
    - Stationary storage charged only by PV;
    - Stationary storage of optimized size;
    - Stationary storage power limited at 7 kW (for both fast and slow charging mode);
    - EV battery filling up to 6 kWh on average, especially during the less sunny periods;
    - User acceptance for long and slow charging;

- Technical and economic optimization of PVCS under local meta-conditions (site, weather conditions, user profile, etc.) and over the lifespan is strongly recommended to make full direct use of the PV energy;
- Assessment of PV benefits over the lifespan prior to setting up PVCS allows a faster massification of infrastructures;
- Power management well-conceived strategies with integrated V2G reduces the peak pressure on the public grid while meeting the needs of users, and provide an environmental benefit in the operation of V2G / V2H services;
- Societal impact and social acceptance, as well as aesthetic design aspects, of PVCS and new services associated have to be considered and undertaken as preliminary studies;
- Complexity of decision-making processes must lead to design methodologies and tools allowing stakeholders to act quickly and increase the PVCS market.

**Main issues for effectively implementation and use of PV-powered charging stations**

- Lack of understanding on the advantages and disadvantages of slow charging versus fast charging from the stakeholders' perspectives;
- Charging points have been deployed without the necessary planning due to insufficient insights on user behavioral, driving patterns, and solar potential, thus not fully optimized;
- Charging energy distribution unknown leading to hide the PV benefits;
- Underdeveloped user experience for different PVCS solutions and multiple use-case scenarios leading to a lack of standardization in user interfaces;
- Lack of proven models for the user experience to make optimal decisions in selecting charging points and improving their overall trip planning;
- Lack of necessary data for optimal planning infrastructure due to uncertainty over fast charging as an alternative for mass low power charging;
- No clear evidence on influence of bidirectional charging (V2G / V2H) on the life of EV battery and power electronics;
- Lack of strategies that take battery aging into account;
- Lack of tools, services and strategies to reach total V2G / V2H flexibility and fully optimized wider PVCS infrastructure (value chain);
- Lack of business models and business process implementation and optimization tools to increase PV benefits;
- Non-optimal use of the current slow/medium power charging solutions;
- Lack of recognized optimal charging strategies in various scenarios, e.g. public (including on-road and covered parking), private (residential and office buildings), in cities, for light and heavy-duty vehicles.

To effectively implement and use PVCS, expected benefits should be further validated and evaluated from viewpoints of not only energy, the environment, and from the perspective of users, but also the related industries, and shared with stakeholders and relevant policy organizations.

The next steps for the subtask 2 will focus on:

- Case studies on: e-bus fleet charged from PVCS in Australia, PVCS in Lisbon, requirements for PVCS in the Australian outback;
- Global cost and carbon impact assessment methodology;
- Human-system interfaces;
- Charging control and power management with demand response;
- Real time power management including optimization algorithm;
- Experimental validation and analyze of experimental results;
- PV benefits assessment for V2G / V2H;
- New survey on the social acceptance of PVCS and new services and the analysis compared to the first survey.

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