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Photovoltaics at the electric mobility's service: French case study

Khaled Hajar, Reza Razi, Majid Mehrasa, Antoine Labonne, Ahmad Hably, Seddik Bacha

Abstract The use of renewable energy sources like solar photovoltaic (PV) to charge electric vehicles (EVs) is an intriguing possibility with various technological and economic benefits. The challenges associated with greenhouse emissions caused by internal combustion engines can be alleviated by combining emission-free EVs with low-carbon PV power generation. For this purpose, this paper provides a case study of a French residential house to maximize the PV power use to charge the EV.

1 Introduction

The European Commission has defined a policy framework for 2030 which implies a 40% reduction of CO₂ emissions compared to 1990 [1]. This entails reducing energy consumption, improving energy efficiency, and increasing the proportion of energy demand met by renewable sources.

PV and EVs are promising technologies for enhancing energy efficiency and using of renewable energy sources in power and transportation networks. Spatial-temporal modeling of PV power generation and EV charging is important for numerous objectives, including urban planning, power grid design and management, when it comes to the deployment, usage, and system integration of these technologies.

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However, some challenges remain in the way of EV battery charging, including charging time, charging station (CS) infrastructure, and the impact of these stations on the current electrical power grid. Using rapid charging techniques, the charge period may be decreased to minutes [2]. Large electricity demands are imposed on the utility system by these procedures, which have negative impacts in different way. For example, many issues arise when a large number of CSs are linked to the utility grid at the same time, such as overload, voltage instability, and voltage volatility [3]. The upgrading of electrical system is one answer to these problems, but it needs a significant expense. A PV system that may operate as a buffer between the EV charging station (EVCS) and the grid is another preferable approach [4].

Fortunately, France has appropriate level of sunshine duration. Most areas have an average sunshine of more than 2000 hour per year and have an average solar-irradiation levels between 2 and 6 kWh/m² per day [5]. However, EVs are usually charged at home at night. A better way to use of solar energy; without the need for expensive battery storage, is to charge vehicles during the day; using a PV arrays at the workplace.

In France, even with the progress of public transportation, approximately 70% of the employees use their own car to go to the workplace each day [6]. In this regard these vehicles are parked the most of the time during working hours. Besides, the number of EVs is increasing massively in France, such that more than 7 hundred thousand EVs are used until those days, and with more than 35% of vehicle market in 2020, while the objective is to reach one million EV at the end of 2022.

On the other hand, in the first quarter of 2021, the manager of 95% of the public electricity distribution network in France, i.e. ENEDIS had more than 100,000 customers connected for individual self-consumption. In fact, private or professional customers, which are equipped with PV panels, have the capability to produce their own electricity demand and consume it for all or part of their

uses. For customers living in individual accommodation, the self-consumption share is around 20% [28]. Thus, the customer can benefit in part from the energy produced with its own PV panels and resell the surplus to the network managed by ENEDIS.

Several previous studies have investigated the architecture of an EVCS based on PV [7-14]. The advantage of charging EVs with solar energy has been noted in [15-17], where this structure enables the growth of both technologies. According to [18], the negative consequences of surplus solar energy can be addressed by using it to charge EVs.

Given the highlighted issues, this paper intends to develop a simple and smart technique for EV smart charging in the presence of PV power production. In this context, a conventional method for smart charging of EVs [19-20] is the state flow approach based on PV power forecasting with the aim to:

- Reduce peak load on the main grid
- Reduce charging costs
- Increase PV self-consumption

The rest of the paper is organized as follows: Section II describes a typical configuration of EV charging station briefly. Section III introduces the proposed smart charging algorithm. Section IV and V present the simulation results and conclusion of this paper.

2 Charging station model

First and foremost, the standard layout of a EVCS and the roles of various components in it must be introduced. The desired structure is depicted in Fig. 1, which includes the Distribution Operator System (DSO), home or workplace loads, solar arrays, and EVs.

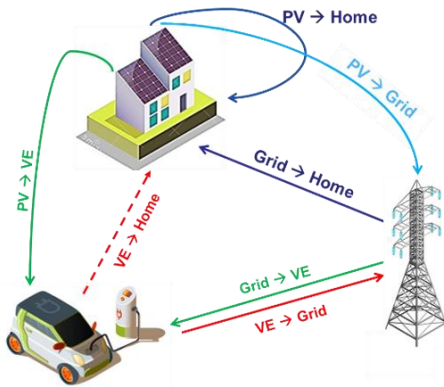


Fig. 1 Desired configuration of charging station

The production of solar energy per time slot $E_p(t)$ is estimated using HelioClim irradiation database [29]. It is assumed that there is a setup with N solar panels. For this purpose, it is obvious that the output power of PV $P_p(t)$ is the total power P_{PV} generated by each single PV module

[21]. Second, based on the PV panel's efficiency \mathcal{E} , the power of a single panel is linked to the sun irradiance according to the following equation:

$$P_{PV} = \mathcal{E} \times I_r \times A \quad (1)$$

Where A is solar panel's area. As a result, if the sun intensity by square meter be $I_r(t)$ at time slot t , the solar power generation can be assumed to be:

$$P_p(t) = N \times P_{PV} \quad (2)$$

At moment t , we assume that the CS utilizes the produced energy $P_p(t)$ to charge EVs. However, if such trading is possible, the CS can also purchase $P_{p.out}(t)$ from the grid or sell $P_{p.in}(t)$ to the grid.

On other side under consideration, there are different time-varying loads with varying and time-varying power needs, depending on the location of CS in residential buildings, workplace, private or public parking lots [15]. When the CS is located in a residential situation, as it was illustrated in Fig. 1, the load demand is near zero during the day and reaches its peak during the night. It should be highlighted that, like power generation in solar arrays, load demand contains uncertainties. The load demand is usually predicted using proper algorithm and must be fully met by the other components in the standard structure.

EV plays a significant role in smart charging algorithms due to its nature [12-13]. It is evident that the EV's constraints like output power P_{EV} constraint, EV energy E_{EV} constraint and its SOC must be considered as Equations (3)-(5). Flexible managing of EV's charge/discharge due to the parking time equal to approximately 90% of their life time, can provide some economical and technical benefits [15].

$$P_{EV}^{\min} \leq P_{EV} \leq P_{EV}^{\max} \quad (3)$$

$$E_{EV}^{\min} \leq E_{EV} \leq E_{EV}^{\max} \quad (4)$$

$$SOC(t) = \begin{cases} SOC_{init}; & t = t_{arrival} \\ SOC(t - \Delta t) + \frac{P_{EV}(t)}{E_{PV}^{nom}} \Delta t; & t_{arrival} < t < t_{departure} \\ SOC_{final}; & t = t_{departure} \end{cases} \quad (5)$$

The EV's user, the CS's owner, and the grid operator are all actors. In this regard, the driver must give some information regarding the parking time, battery specification, initial and desired state of charge (SOC).

At the end, the grid, as the dominating player, is directly responsible for power balancing among different components in this system. In fact, the grid power P_G has to compensate for the shortage or exceed generated power, while satisfying the load demand P_L as shown in the following equation:

$$P_G(t) + P_p(t) = P_L(t) - P_{EV}(t) \quad (6)$$

This equation is known as the power balancing equation. In other words, if total power generation is less than total

power consumption, the grid injects the difference into the system. In general, the main goal should be reducing the cost of energy exchanged with the grid.

Table 1 Feed in tariff for PV in France at the end of 2021

PV power capacity	Price/kWh for the total sale	Price/kWh for the sale of surplus energy
Less than 3 kW _p	0,1756 €	0,10 €
Less than 9 kW _p	0,1493 €	
Less than 36 kW _p	0,1064 €	0,06 €
Less than 100 kW _p	0,0925 €	

In reality, in France the energy price for residential users typically has two different levels. For example, the electricity price for most of applications is 13.46 and 17.99 cents per kilowatt-hour, during normal and peak hours respectively. The feed-in tariff for PV power generation is reassessed every quarter; Table 1 sums it all up according to the last evaluation at the end of 2021.

3 Proposed rule-based smart charging

It is a fact that proper planning of electrical energy is vital due to the energy crisis and high energy costs [22]. It improves the system efficiency, resulting in considerable energy savings and cost reductions [23].

In general, there are two types of smart charging algorithms for EVs: optimization methods [7] - [24] and rule-based techniques [14] - [16]. Optimization algorithms look for available optimum solutions while taking into account objective functions and system limitations.

On the other hand, the rule-based algorithm follows various rules but may not always result in the best answer. This methodology is typically used as a supplementary approach and real-time solution to correct immediate faults because of its minimal computational volume and relatively high response. The suggested energy management strategy is made up of some various rules, mostly in the form of 'if - then' statements. The 'if' statements are associated with various circumstances, and the 'then' expressions execute the operating modes [25]. These modes carry out the energy transfer among components of the system [26].

Mode 1: Grid to load

In this well-known mode, the energy is purchased from the grid when the provided energy from PV is null or not enough to cover the load's demand.

Mode 2: PV to EV

The energy is transferred from PV to EV in this mode. PV power usage is the first priority to reduce the energy received by the grid [27]. The energy is sent in a power scale

higher than P_{EV}^{min} to respect the safety and the health of battery. The quantity of energy transferred from PV to EV fluctuates depending on the scenario. If the PV output power is adequate to meet the EV demand, the EV is charged autonomously and the system is electrically isolated from the grid. As a result, the produced energy by the PV equals the entire energy consumed by the EV.

Mode 3: PV to load

The PV power feed the load local directly to cover its part or full demand. This mode is activated for different cases as follows:

- The EV's demand is null and the load demand can be covered by PV power.

- The EV's demand can be covered by the PV power and it still have an excess of energy to cover a part or full load's demand.

Mode 4: PV to grid

PV to grid energy flow occurs only if PV output power is greater than the total demand of EV's and load. As a result, the quantity of energy transferred is determined by the EV's SOC.

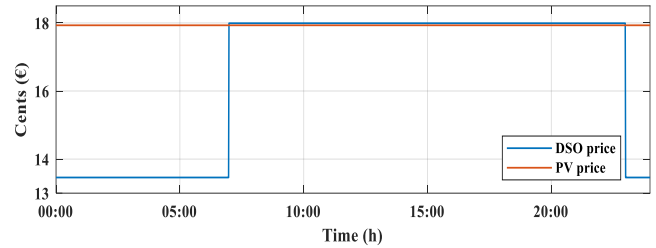


Fig. 2 PV and DSO kWh prices

As mentioned, PV output power is purchased by the main grid as shown in Tab. 1. However, it is sold to the grid at 0.043 cents euro lower less than the current grid power price during peak (Fig. 2). This mode is operated in two steps: the DC-DC converter and the bi-directional inverter [24]. This function is critical in compensating for the economic losses caused by continuous daylight charging at a fixed price.

Mode 5: Grid to EV

In this mode, energy is obtained from the grid to charge the EV at grid price. In this situation, when the PV is unable to meet the EV's demand under the grid overload situation, the grid meets deficit. The quantity of grid energy used to charge an electric vehicle equals the difference between EV demand and PV energy.

Mode 6: Grid at energy user subscription

This mode will be activated when the PV couldn't meet the EV demand at first and the load demand at second. At this time the maximum power subscription of the user will be used as the following equation.

$$P_G = P_{max} - P_{PV} + P_L \quad (7)$$

The suggested algorithm (Fig. 3) divides the functioning of a PV-EV-grid system into four major cases. They are classified based on the EV demand and PV power:

- Overload: PV power is lower than the EV demand.
- Underload: EV demand is available but equal or less than PV power.
- Load: EV demand is 0 and PV power is available.
- Inert: PV power and EV demand are 0.

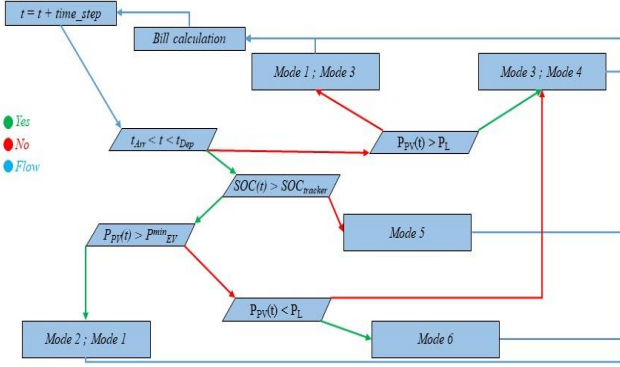


Fig. 3 Proposed algorithm chart

The overload and underload actions are intended to provide continuous charging at a fixed price. However, in order to compensate for system economic losses, the operation under no load and stagnant is started when specific predefined circumstances are satisfied.

To reach the SOC at departure time as user demand, a reversible calculation technique is elaborated. This technique consists, before executing the algorithm, to draw a line of EV's SOC while full power charging, going backward from departure time until reaching its 0 value. While executing the algorithm if the SOC(t) reaches this line the full power charging is applied to respect the user demand. Fig. 4 shows an example of the Renault ZOE R110 where the driver wants to leave at 5 p.m. with full charge which takes almost 3 hours

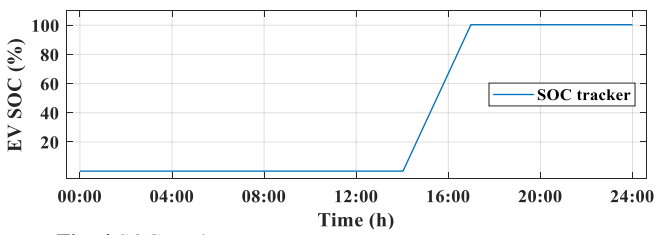


Fig. 4 SOC tracker

The next section will discuss different scenarios' results of EV charging during different weather conditions.

4 Simulation results

In this work, the Renault Zoe R110 is used in our simulation with the specifications shown in Table 2, as the most popular EV in France.

Table 2 Renault ZOE R110 specifications

Symbol	Description	Value
$P_{EV}^{min/max}$	Minimum/Maximum EV power	-22/22 kW
E_{EV}^{nom}	Nominal capacity of EV battery	41 kWh
$SOC_{EV}^{min/max}$	Minimum/Maximum EV State of charge (SOC)	20%/90%
$P_{ch}^{min/max}$	Minimum/Maximum charger power	1,6/15 kW

As for PV in France, three installation possibilities exist:

- Partial self-consumption with resale of surplus;
- Total sale of electricity to an energy supplier;
- Total self-consumption.

Today, installing self-consumption solar panels with surplus resale is the most interesting for a main residence. This makes it possible to consume one's own production throughout the life of the solar panels and to inject and resell the surplus kWh produced on the network for a fixed tariff over 20 years. Indeed, in a situation where a house of approximately 100m², if the used energy is entirely electric and if it uses standard electrical equipment (washing machine, dishwasher, dryer, oven, television...) it will need to install 3 kW_p of solar panels. This amount of power represents approximately 20 m² of roofing and 10 solar panels in all (the number of modules depends however on the nominal power of the chosen photovoltaic panel). In addition, to charge Renault ZOE R110, it needs to use 9 solar panels on average, which represents a power of approximately 3 kW_p. During a day of full sunshine, such an installation produces on average the equivalent of 155 km. According to the information above an installation of 6 kW_p will be taken in account for simulation. The irradiation data used in simulations to calculate the PV systems performance are getting from HelioClim forecast archives for Lyon city.

Furthermore, the data concerning the residential load are collected from ENEDIS open data center (Fig.5) while the user power subscription is 9 kVA.

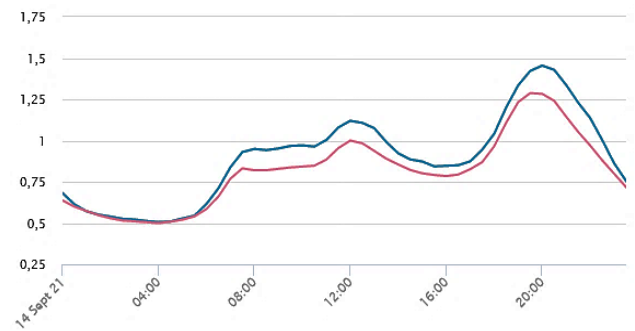


Fig. 5 Residential electricity profile coefficient: (Red: static, Blue: dynamic) (Resource: ENEDIS)

Three main simulations, using MATLAB, will be presented for different date. The chosen dates are selected according the PV production intermittence, according to longest and shortest day of the year as for 21st June and 21st December respectively. The third simulation deals with

uncertainties of the PV power production during cloudy day on the 6th of April.

In simulations the user plans his departure at 5p.m. as he arrived at 8a.m. to recharge his EV from its initial SOC of 20% to 90%. Charging the concerned EV with 70% of its capacity means that its range increase about 350km. The average distance made by a car in France is about 31km daily. That means that the scenario taking into account can at least let the user drive his EV about 10 days, since this scenario will not be repeated daily.

In the first simulation, dated on 21st of December, the maximum PV power production reaches 3kW since the sun irradiation is low at this date (fig.6).

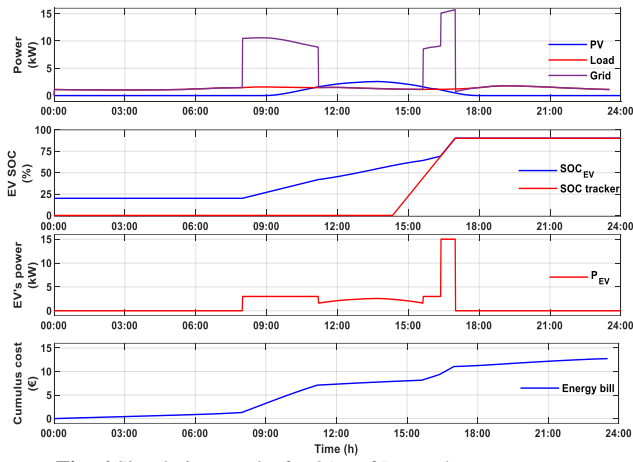


Fig. 6 Simulation results for 21st of December

The simulation shows that, PV power is not enough to charge the EV, then different modes are applied to satisfy the user demand. Mode 1 and Mode 5 are applied from 8am to 9:30am to feed the load and charge the EV, the same application between 3:30pm and 4:30pm. When the P_{PV} rises and still lower than P_{EV}^{min} , the PV feed the load and the grid feed the load with the deficit power in addition of the power to charge the EV using Mode 6 between 9:30am and 11am. As the $P_{PV} > P_{EV}^{min}$ between 11am and 3:30pm, all the P_{PV} is used for charging the EV (Mode 2), and the load purchased the power from the grid at this time (Mode 1). At 4:30, the SOC reaches the SOC tracker line, which in this situation the full power EV charging is applied, purchased from grid to arrive to the desired SOC at departure time (Mode 5). According to cumulus cost calculation the user will be charged about 13€, when there is no excess power to sell it to the grid.

On 21st of July, the PV power reaches its maximum as sun path is clear (fig.7). It shows clearly that after the full charge of the EV before departure time by P_{PV} using Mode 2, precisely at 2:15, the PV power is used to feed the load (Mode 3). At the same time, the excess of energy is sold to the grid at the specific price (Mode 4). Hence, the bill shows an interesting profit as the cumulative cost for such scenario is about 0,7€.

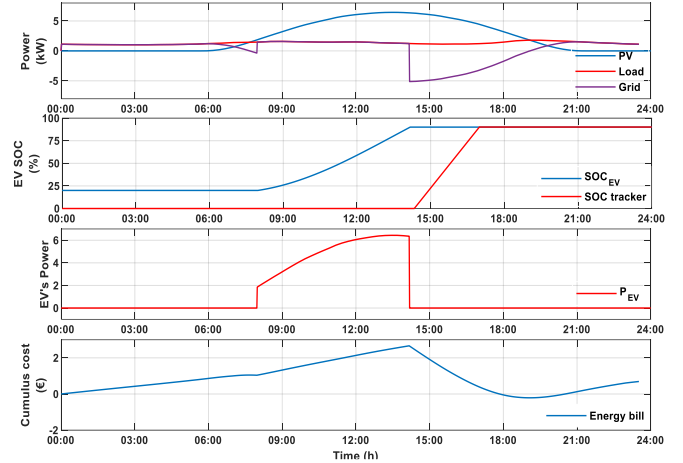


Fig. 7 Simulation results for 21st of July

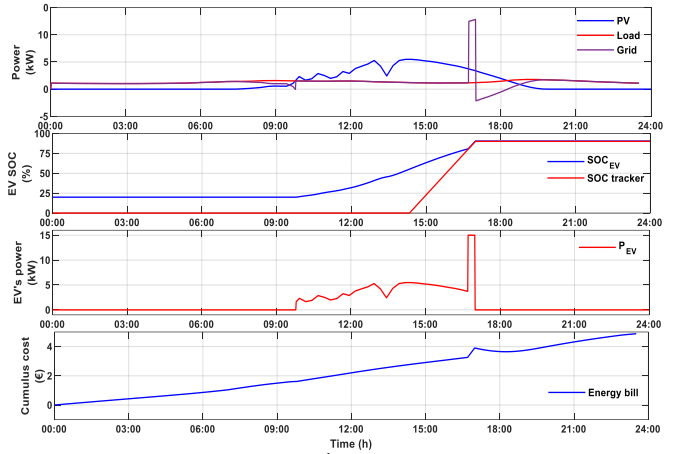


Fig. 8 Simulation results for 6th of April

A cloudy Day, 21st of April, is shown in Fig.8 where the intermittence of irradiation has an effect on the PV power. The Load during this day is fed from the grid (Mode 1) after EV's departure time and its arrival time where the system applies Mode 3 to cover the load demand by PV power. Mode 2 gives the opportunity to charge the car from PV power during parking time, unless when the SOCEV reaches the SOC tracker line where the full charge is applied to satisfy the SOC user demand on departure time.

As it was illustrated in the simulation, the proposed algorithm shows how the maximizing PV power use help to reach the final desired SOC at departure time specified by the user.

5 Conclusion

In this paper, a flow chart technique was developed, using rule-based to control EV charging in residential case in a way of synchronizing the PV power use with. For this importance, the user contributes to the EV charging by pointing out the arrival and departure time and the corresponding SOC.

The charging algorithm combined with the suggested approach selects the most appropriate charging duration, power amount, and power flow direction in this regard. It should be noted that it was possible to simulate another scenario, but taking into account the irradiance intermittence, the shortest and longest days give a global idea of the algorithm technique that can be implemented in real time without any cost calculation. In other words, the constraints used in this case study show the importance of PV's integration to be used in a synchronous way with EV charging. Then, the effectiveness of the proposed technique was proved by bill calculation and the profit that the user can benefit.

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