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Coupling local renewable energy production with electric vehicle charging: a survey of the French case

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Abstract

The share of renewable energy sources (RES)' production in energy mixes, especially the ones of PV panels and wind farms, has been continuously increasing during the last few years. Similarly, a strong development of battery electric vehicles (EV) is expected within the next years. However, these two new innovations could trigger security issues on electrical grids, in particular local congestions and voltage deviations from the required standards. One way to mitigate these problems could be to combine the charging periods of the EVs with the local RES production. This paper aims at analysing the possibility to implement this kind of smart charging strategy in France by 2020, taking into account the wide diversity of local energy mixes in France and their seasonal dependencies. First, the authors identify four different energy mixes representative of most of the local French mixes, each one related to a region in France. Then, we model the charging load curves of the EVs at the substation level for the same regions. We deduce the "green charging ratio" (GCR) without any charging management strategy. The same ratio is then computed assuming that an Energy Management System (EMS), which goal is to maximize this ratio, controls the EV charging patterns. The results are provided for each region and seasons. They show a wide diversity of green charging ratio achievable: in very windy regions, the GCR without any EMS is already rather high; on the contrary, in sunny regions, the GCR is much improved with the implementation of the EMS. In such regions, the GCR can also be enhanced with the penetration of charging stations at working places.

Keywords: Renewable Energy Sources, Smart charging, Electric Vehicle Management

1 Introduction

European energy-climate objectives for 2030 have just been set by European leaders to a 40% reduction in CO2 emissions, a 27% share of Renewable Energy Sources (RES) in the energy mix, and a 27% increase in energy efficiency. These environmental friendly policies foster the development of RES, mainly through the deployment of PV panels and wind farms.

Similarly, plug-in Electric Vehicles (EV) moved by electric motors and powered by electrochemical batteries represent a promising solution with respect to these goals. With the upcoming decrease in battery costs, and the deployment of charging stations, EV or plug-in hybrids sales are expected to increase within the next few years.

However, the increasing penetration of these two new innovations brings up concerns regarding their impacts on the electrical grid security: on one hand, RES are asynchronous and intermittent by nature, and distributed mostly at the distribution grid level. They could trigger local congestion, frequency and voltage-related problems, as well as system wide balancing issues [1]–[3] ; on the other hand, if these innovation are not managed properly, the massive introduction of plug-in vehicles could jeopardize grid security [4]–[6].

Nevertheless, EVs have a good charging flexibility. In France, a vehicle is used in average 6 hours a week, for a daily commuting trip of 24km [7], what would lead to an approximate daily energy consumption of 4.2kWh. Moreover, when considering a fleet of EVs, the share of EVs being parked never falls below 75% [8].

As a consequence, using EVs as buffer storage units to level the production of RES appears as a promising innovative solution.

The coupling of RES and EVs would require to synchronize EV charging periods with RES production periods and – if Vehicle-to-grid (V2G) capabilities are available – to discharge EVs in case of substantial RES production shortfall. This solution could increase the maximum penetration level of RES, as well as the "green charging" ratio of EVs.

This concept has been intensively studied in the scientific literature since its first introduction in 1997 [9]. We find that most of the literature either considers the balance between RES production and EV charging at the system-wide scale [10]–[12], or in islanded systems watching over frequency deviations [13].

However, although the system-wide balancing mechanism performed by the Transmission System Operator (TSO) is of paramount importance, distribution network congestion and voltage constraints should also be considered. Indeed, most of RES are integrated as Distributed Generation (DG), that is at the distribution network level [14]. Furthermore, the 2015 "energy transition law" is expected to encourage innovative decentralized generation and management of the local electricity grid. More precisely, the French minister of ecology has announced the creation of 200 "Territoires à Energie Positive" (TEPOS). Such TEPOS should have 100% of their demand supplied by local RES [15].

In this context, we propose to study, for the French case in 2020, the possibility to couple RES production with EVs smart charging at the local scale. In order to do so, several local French electricity mixes are studied. Based on these observations, four scenarios representing the main energy mixes are built. For each mix, we propose an unidirectional Energy Management System to optimize the EV charging strategies with RES local production.

The paper is organized as follows. Section 2 deals with the survey of the various local electricity mixes in France. Section 3 presents the EV fleet model as well as the EMS strategy. Results and discussions are provided in section 4. Section 5 is the conclusion.

2 Local electricity mixes in France

As RES are mainly integrated at the distribution grid level and as local network management is increasingly considered by policy makers, we are concerned with the coupling of RES production and EV charging at the local scale – namely, at the MV substation level. However, local energy mixes vary a lot from one place to the other and from one season to the other. The aim of this section is to analyse these differences in energy mixes depending on the geographical location and on the season, in France.

2.1 Data

We used publicly available data from Réseau de transport d'Electricité (RTE), the French TSO, in order to identify the different local generation mixes in France. These data are freely available online [16]. They provide the installed RES capacity by energy source and by region, the instantaneous power production by energy source

and by region as well as the instantaneous power consumption by region (with a 30 minute time stamp, over the year 2013).

2.2 Sample characteristics

We studied all the 21 regions of metropolitan France, focusing on the production of wind farms and PV panels, as well as on their installed capacity. Results show a wide diversity of local energy mixes between the regions, both in terms of installed capacity and in terms of instantaneous production. Figure 1 shows the installed capacities of respectively wind farms and PV panels in each region.

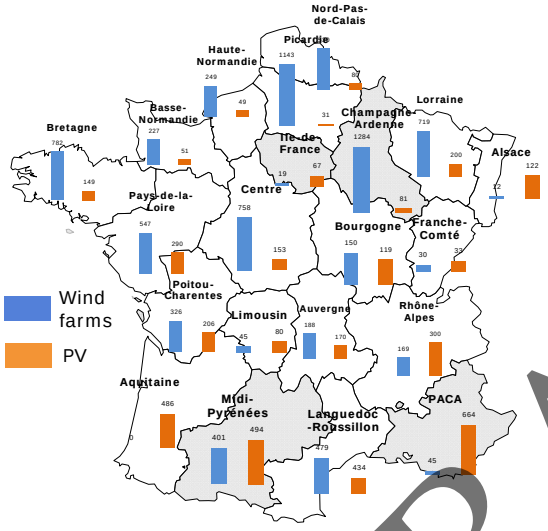


Figure 1: installed wind and PV power capacities by area in France (MW). Extracted from [17]

In France, installed capacities of wind and PV are regionally different and reflect partially the local potential for renewables considering seasonal aspects. As a consequence, France exhibits very different regional profiles for RES and EV possible coupling strategies. In the South of France, the regions typically have a substantial amount of PV installed capacity in comparison with their wind power capacity. Thus, there are major differences in RES production between the seasons; indeed, in sunny summer the production will exceed by far the one in gloomy winter. In the North of France, the wind farm installed capacities are more important than those of PV panels. These regions will undergo less seasonal dependencies. Finally, some other regions perform very bad in terms of installed capacity and have few RES resources to optimize.

Figure 2 shows the production in two typical regions over one year, highlighting regional variations.

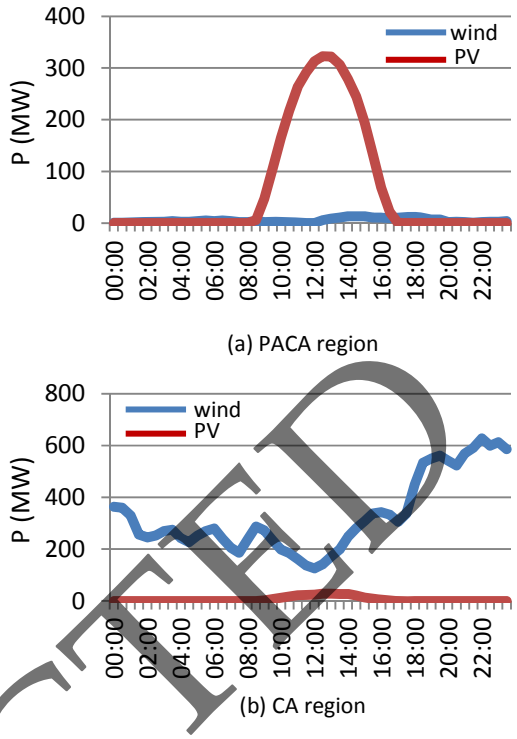


Figure 2: RES production in two regions on December 17th, 2013

2.3 Selection of typical regions

In order to conduct our simulations at the MV substation level, we need first to select some of the aforementioned regions, with various electricity mixes, and then to scale their instantaneous production at the substation level. Our selection should comprise all the different existing energy mixes and various EVs potential development forecasts.

After having analyzed carefully all the 21 French regions, we retain the four next ones (please refer to Figure 1 for their precise location):

- **Ile-de-France (IDF) region**: this region typically has low RES production, either from PV panels or from windmills. Moreover, in this very dense and rather rich area, we expect to have a high number of EVs.
- **Champagne-Ardenne (CA) region**: this region typically has a significant wind power production, but a low PV production. As CA region is not very economically dynamic (in terms of share of the national GDP) and not densely populated, we expect to have a low number of EVs.
- **PACA region**: on the contrary, this sunny region has an important PV production

capacity in comparison with its wind farm capacity. In this very dense and rather rich area, we expect to have a high number of EVs

- **Midi-Pyrénées (MP) region**: this region has a more diversified energy mix, with almost as much wind capacity as PV capacity. As MP region is not very economically dynamic too, we expect to have a low number of EVs.

The Table 1 sums up the particularity of each selected region with respect to their expected RES production and EV development forecasts:

Table 1: The rationale for region selection

RES available / EV take rate	Two RES sources	One RES source
Low	MP	CA
High	IDF	PACA

In France, there are N_t = 2240 substations [18]. In order to scale the region production to the substation level, we have to define the number of substation in each region; however, this data is not publicly available, so we deduce it by scaling the number of substations in a region *r*, N_r, proportionally to its yearly consumption share over one year (using data from [16]), according to equation (1).

$$N_r = N_t * \frac{C_r}{C_t} \quad (1)$$

with C_r and C_t the total yearly consumption of the region in question and of all the regions, respectively. As a result, the number of substations per region is provided in Table 2.

Table 2: Calculated number of substations per region

Region	Number of substations
Ile-de-France	345
Champagne-Ardenne	50
PACA	194
Midi-Pyrénées	94

There are many substations in IDF region because it is the densest region of all. PACA also concentrates many inhabitants. On the contrary, CA and MP regions are less densely populated.
In order to assess the PV and windmills productions in 2020, we consider that the yearly regional penetration ratio during the coming years is equal to the last non-null yearly penetration ratio of PV/wind capacity in the considered region. With this rather simple solution to forecast the 2020 period, we have similar results than the one projected by the French TSO [19].

3 EV fleet modelling

3.1 EV characteristics

Based on RTE forecasts [19], we assume that there will be N_{EV} = 500 000 EVs on the French roads by 2020. We deduce the number of EVs in each region r, N_{EVr}, in proportion to the regional Gross National Product (GNP) share (extracted from [20]), according to equation (2):

$$N_{EVr} = N_{EV} * \frac{GNP_r}{GNP_t} \quad (2)$$

with GNP_r and GNP_t the regional and national GNP, respectively. Finally, the number of EVs per region and per substation is provided in Table 3:

Table 3: Number of EVs per region and per substation

Region	Number of EVs per substation
Ile-de-France	445
Champagne-Ardenne	185
PACA	183
Midi-Pyrénées	214

We assume that all the vehicles are full-electric vehicles, with a battery capacity of 22kWh (which corresponds to 65% of the EV battery capacities in France in 2013). We add the constraint $0.2<SOC/SOC_{max}<0.9$ with SOC and SOC_{max} respectively the current and maximum State Of Charge (SOC) of the battery; these limits are commonly accepted as those within which batteries should operate in order not to undergo too significant battery wear.
The EV trip characteristics are based on several references: internal PSA Peugeot Citroen data, ministerial surveys [7] and demonstration project results [21]. The EV fleet model is stochastic and dynamic. EV average distance trips (D), departure time (T_d), daily number of trips (N) and seasonal energy consumption (E) are provided in Table 4. D and T_d are distributed according to Gaussian distributions with mean μ and standard deviations σ. It is noticeable that our model only covers people commuting back and forth to work.

Table 4: EV trip characteristics

Parameters	μ	σ
D (km)	22	4.5
T_d (h)	8 am	2
	18 pm	
N	2	
E (kWh/km)	in winter $c_w = 0.18$ in summer $c_s = 0.13$	

3.2 EVSE characteristics

Under our assumptions, EV owners commute back and forth to work every day – apart from weekend periods. Thus, they can charge either at home, on their *primary EVSE*, or at work on their *secondary EVSE*. Electric Vehicle Supply Equipment (EVSE) characteristics are based on French ministerial forecasts [22]. The repartition of the EVSE powers depending on their location is provided in Table 5: We consider usual power levels corresponding to existing charging stations in France – that is, 3kW, 7kW, 22kW and 43kW. Home charging is mainly done at low power, while working charging stations are more equally distributed (although fast charging is still marginal).

Table 5: EVSE repartitions in 2020

EVSE Power plug (kW)	Primary EVSE	Secondary EVSE
Slow A – 3kW	93%	35%
Slow B – 7kW	7%	34%
Intermediate charging – 22kW	0%	29%
Fast charging – 43kW	0%	2%

For *primary EVSEs*, we assume that all EV owners have an EVSE at home. Regarding the penetration of EVSEs at work (*secondary EVSEs*), we consider two extreme scenarios:

- **Scenario A**: the penetration of *secondary EVSE* is 0% (no EV owner is able to charge at work)
- **Scenario B**: the penetration of *secondary EVSE* is 100% (all EV owners are able to charge at work)

3.3 Energy Management System modelling

The aim of the Energy Management System (EMS) is to maximize the "green charging ratio" of the EVs.

In order to define our "Green Charging Ratio", we only consider the investments done and forecasted in wind and PV technologies and set aside the previous installed green energies like hydro or biomass. The main reason we focus on "new renewable" main investment sources is that they are commonly considered as a threat toward the network safety and management in their actual dynamics.

In this paper we want to investigate the positive outcomes of coupling RES and PV at the local network level and see how the decentralized solution management system we propose can be a positive resource for local networks.

At each time stamp, the EV fleet can be divided into two groups: the EVs that need to charge at full power for transportation needs, which are not flexible, and the other EVs, which are flexible. The latter are available for the EMS. Each EV *i* from this category provides the EMS with its available charging power P^i_{charg} for the next time stamp:

$$P^i_{charg}(t) = -\min\left(P^i_{EVSE}, \frac{SOC^i_{max} - SOC^i(t)}{\Delta t}\right) \quad (3)$$

with P^i_{EVSE} the EVSE power, Δt the simulation time stamp (30 minutes), SOC^i_{max} and $SOC^i(t)$ respectively the maximum and current SOC of the battery (negative power values stand for EV charging mode).

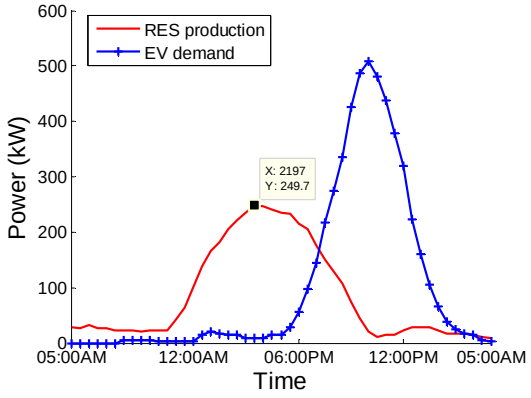
Then, depending on the current RES production $P_{RES}(t)$, the EMS computes the required charging power from the available EVs $P_{EV\_EMS}(t)$:

$$P_{EV\_EMS}(t) = \max\left(\sum_i P^i_{charg}(t), -P_{RES}(t)\right) \quad (4)$$

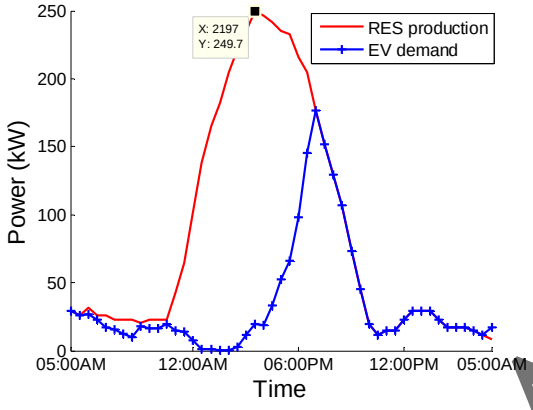
We assume that the EMS has a very precise forecast of the RES production over the next time frame (15 minute), what seems plausible considering today forecast accuracies of roughly one hour for wind and solar electricity generation.

Once the required charging power has been computed, it has to be dispatched among the available EVs. The strategy implemented consists in charging successively the EVs in ascending order of SOC.

The Figure 3 shows the EV charging patterns over one day (March 1st, 2013) both in the uncontrolled and controlled scenarios. The EMS strategy is clear on this figure: EV charging periods are synchronized with RES production periods:



(a) Uncontrolled charging



(b) Controlled charging

Figure 3: EV load curve and RES production curve in March 1st, 2013 for controlled and uncontrolled strategies under scenario A

4 Results and discussions

We perform simulations over one year with a 15 minute time stamp, for the four regions identified in 2.3. For each simulation, we evaluate the green charging ratio of our modelled EV fleet, defined by the overall energy percentage that was charged using local RES production. We consider two different charging strategies: the uncontrolled charging which only allows EVs to "charge as plugged"; and a second strategy in which the EMS maximizes the Green Charging Ratio for EVs.

4.1 Uncontrolled charging

In this scenario, the EVs implement a "charge-as-plugged" strategy, meaning that all EV owners will plug their EVs as soon as they can, and EVs will charge as soon as they are plugged in. Under this uncoordinated scenario, some wastes of RES production are expected to happen and we anticipate them to be worse in the case of regions having a single RES available.

Results are provided in Table 6, for each region and per season. A distinction is made between *scenario A* (0% EVSE at working places) and *scenario B* (100% EVSE at working places).

Table 6: Green charging ratio, uncontrolled strategy

Region	Scenario	Green charging ratio (%) Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
IDF	A	7.7	23.0	24.5	13.0
	B	14.4	36.2	35.2	16.8
CA	A	98.8	99.8	99.9	98.8
	B	99.5	99.9	99.9	99.3
PACA	A	56.4	82.5	77.4	53.3
	B	80.1	91.3	87.8	74.6
MP	A	93.9	99.1	98.5	95.6
	B	97.8	99.7	99.2	98.0

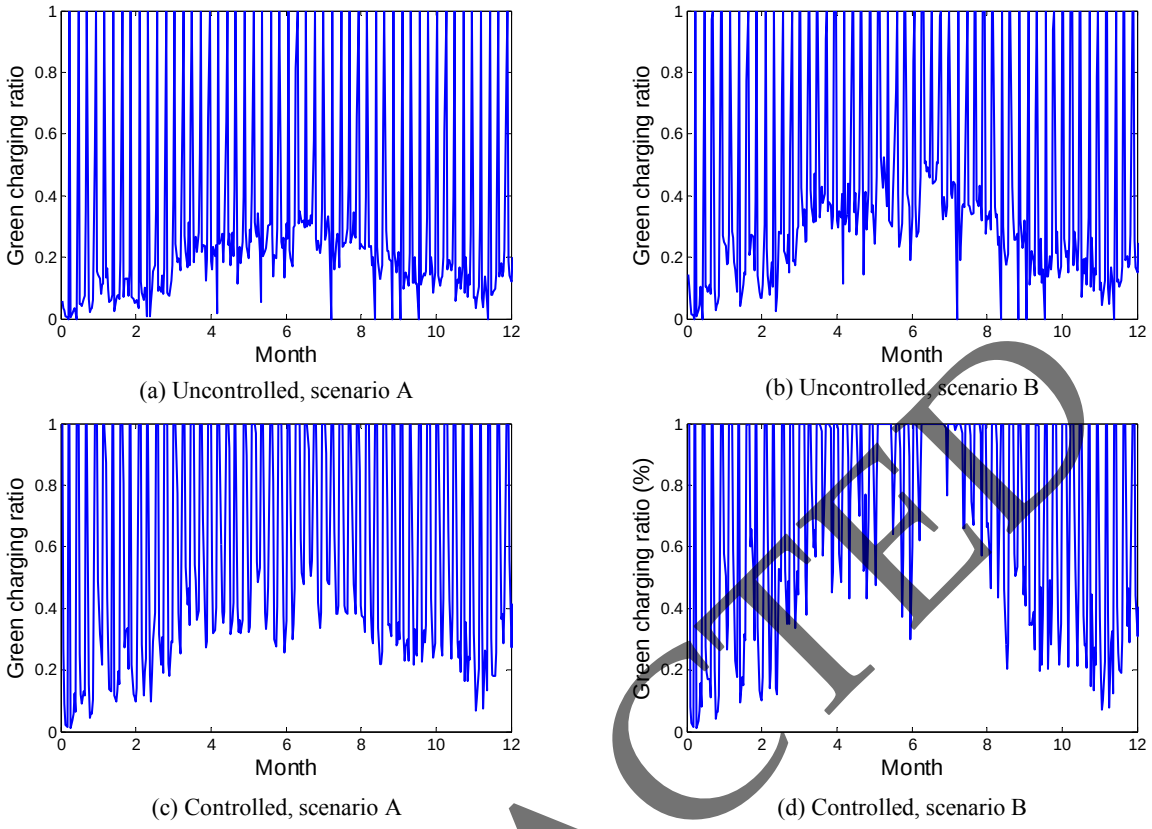
The first result from our simulations is that there is not any scenario, with the solution "charge as plugged" by 2020, in which RES production and EVs charging are perfectly coupled. The worst GCR is 7.7% (IDF, January to March, scenario A) and the best is 99.9%.

Our second result is more contrasted. We expected regions with only one RES type available to be less efficient than the regions with balanced energy mix. This trend is not confirmed in our results due to the relative abundance of RES production levels compared to EVs demand forecasts.

Our third result measures the actual diversity from one region to another and from one season to another. The seasonal dependency is substantial in the IDF region, with a GCR during sunny periods twice to three times as high as the GCR computed in winter periods. This is due to the importance of the PV production in the GCR values, what can be also understood from the GCR improvement from scenario A to scenario B. On the contrary, the CA region, due to its very high wind production, has a very high GCR for all the scenarios and all the seasons. This trend can also be observed in the MP region, although the GCR falls down to 93% from January to March under scenario A. Finally, the GCR of the PACA region is extremely sensitive to the solar radiation: there are significant differences in GCR between the seasons, and between scenarios A and B.

4.2 Controlled charging

In this scenario, the EV charging decisions are controlled by the EMS described in 3.3. Results are provided in Table 7.



(a) Uncontrolled, scenario A

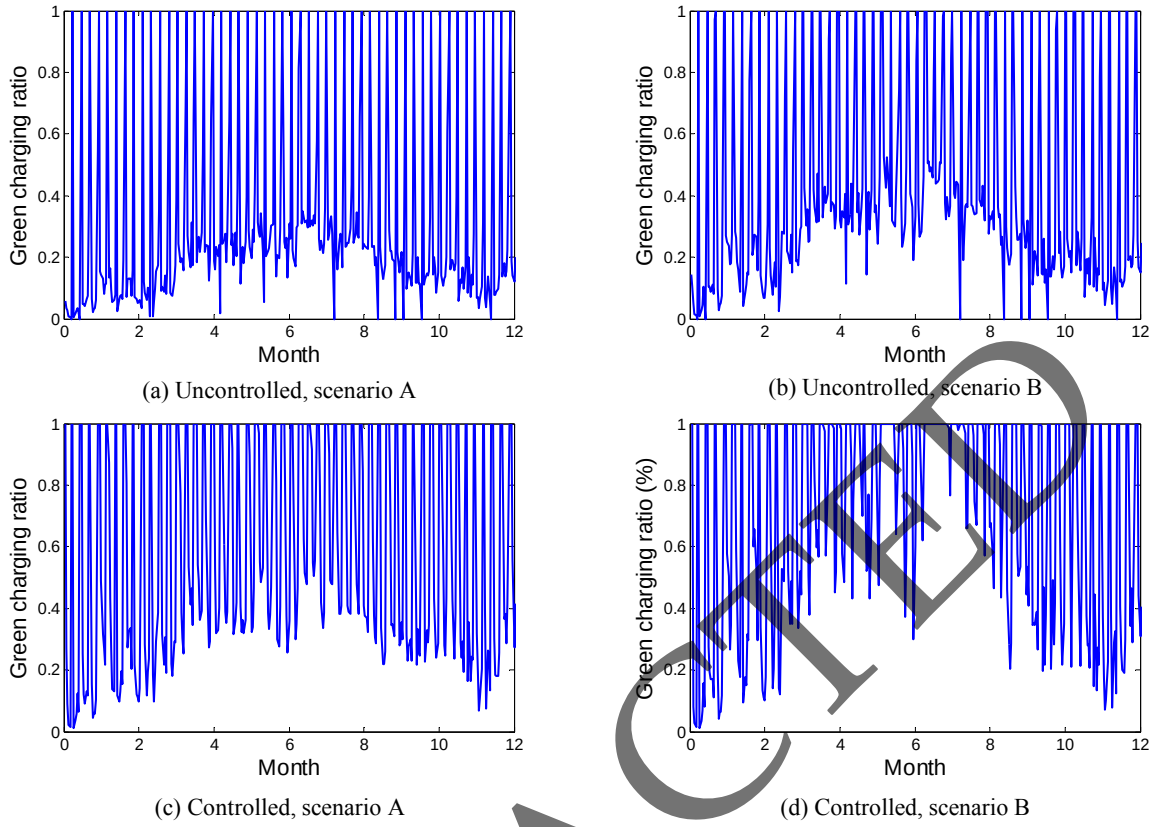
(b) Uncontrolled, scenario B

(c) Controlled, scenario A

(d) Controlled, scenario B

Figure 4: Green charging ratio for the IDF region over one year

Table 7



(a) Uncontrolled, scenario A

(b) Uncontrolled, scenario B

(c) Controlled, scenario A

(d) Controlled, scenario B

Figure 4: Green charging ratio for the IDF region over one year

Table 7: Green charging ratio, EMS implemented

Region	Scenario	Green charging ratio (%) Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
IDF	A	30.4	58.3	59.5	41.3
	B	39.3	82.0	83.6	45.3
CA	A	100	100	100	100
	B	100	100	100	100
PACA	A	98.9	99.2	98.4	95.5
	B	100	100	100	100
MP	A	100	100	100	100
	B	100	100	100	100

The first noticeable result is the great improvement in GCR values: in 20 out of 32 scenarios, we achieve to have a perfect coupling of RES production and EVs charging. In all these cases, our EMS helps to better manage locally the coupling of RES and EVs.

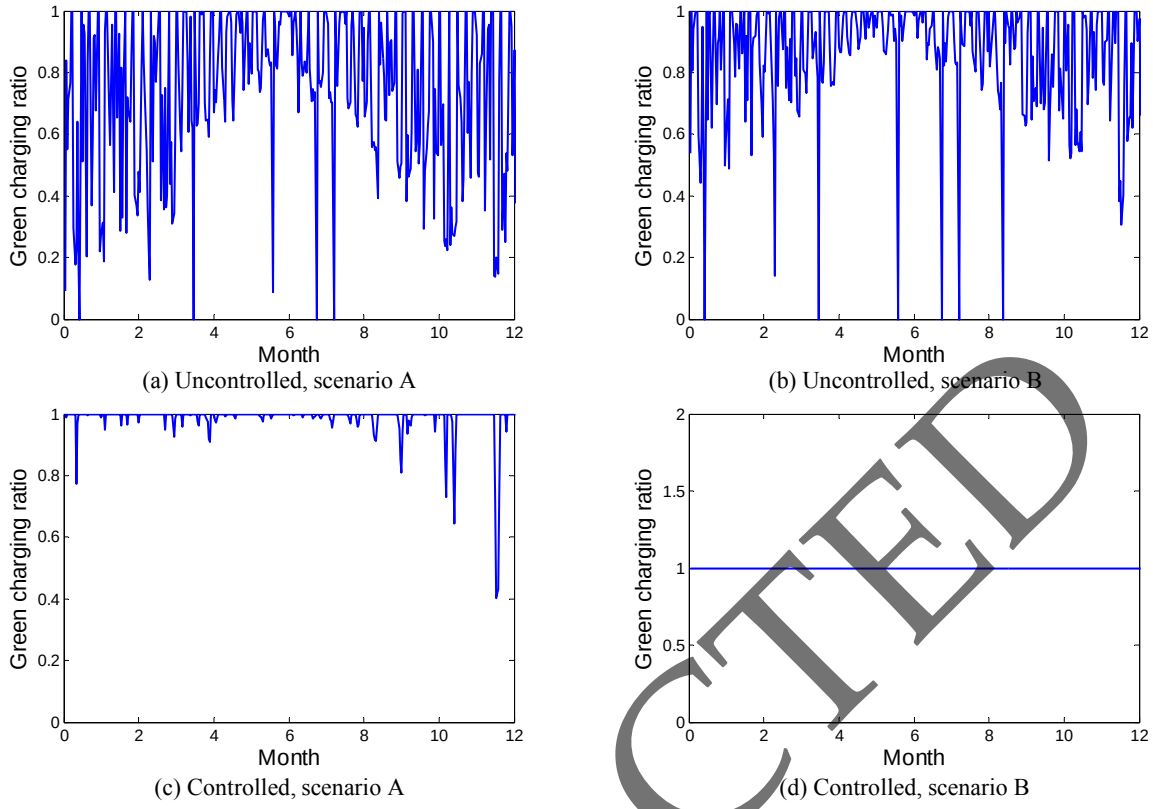
The diversity of 12 incomplete GCR needs a further analysis: our results show significant differences between the regions. In regions CA and MP, the green charging ratio (GCR) achieved is 100% in all seasons and both scenarios. However, the GCR of these regions was already very high without controlling the charging patterns of the EVs. Similarly, in the PACA region, the GCR attained is 100% (or close) for all seasons and all scenarios. Thus, the GCR has been much improved in PACA, especially under the hypothesis of scenario A, compared to its value in the uncontrolled case study.

Finally, the IDF region GCR has also been significantly increased by means of the EMS strategy. Nevertheless, its value is still quite low in winter seasons, and under scenario A hypothesis. Table 8 provides the conclusion of the interest of using our EMS to improve the coupling of RES with EVs.

Table 8: The interest in implementing an EMS

RES available / EV take rate	Two RES sources	One RES source
Low	MP: low	CA: low
High	IDF: high	PACA: high

Our simulations clearly show that our approach is more useful in regions where the number of EVs is forecasted to be significant and where RES are mainly consisted of solar sources.



(a) Uncontrolled, scenario A

(b) Uncontrolled, scenario B

(c) Controlled, scenario A

(d) Controlled, scenario B

Figure 5: Green Charging Ratio for the PACA region over one year

4.3 Discussions

From the previous results, we can identify different trends in the regions ability to provide the EVs with a good GCR. First, there are the regions that do not need any EMS; the RES production is important compared to the EV consumption and occurs at EV charging periods. These regions correspond to the CA and MP case studies. Then, there are the regions – such as the PACA one – which have a sufficient level of RES production, but in which the latter is not synchronized with the EV charging periods. In this case, the implementation of an EMS to couple EV charging periods and RES production can have a substantial impact on the achieved GCR. Finally, there are the regions in which the EV energy consumption exceeds the RES production capability – namely, the IDF region. In this kind of region, implementing an EMS can improve the GCR, but the latter will not be able to reach 100%. Figure 4 and Figure 5 show the GCR evolutions over one year for PACA and IDF regions, for scenarios A and B.

5 Conclusion

Managing EV charging periods in order to maximize the green charging ratio of the EV fleet could be a way to mitigate local grid issues (voltage control, congestions) and to improve local consumption. However, local energy mixes can be very different from each other, and this diversity should be considered when mentioning this solution.

In this paper, the authors tackle the French case in 2020. We demonstrate first that there is indeed a great diversification of local energy mixes in France. This leads to very different green charging ratio when not considering any smart charging strategy: we have results ranging from 7.7% for the IDF region, in winter with scenario A to almost 100% for the CA region, for all seasons and both scenarios.

The Energy Management System is able to increase the GCR of regions that had a rather low one without EMS. This is in particular true for the PACA and IDF regions, where the EV charging periods were poorly synchronized with the RES production.

Future work could be to conduct this analysis for all the 22 regions in France. We also plan to look

into the maximum number of EVs that could be integrated in each region in 2020 with a minimum level of GCR. At last, we could also include more uncertainty in the RES production forecast.

Acknowledgments

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