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Synergies between electric vehicles and solar electricity penetrations in Portugal

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Abstract

The aim of this research is to evaluate the complementarity between the electric vehicle (EV) penetration and large scale grid integration of solar photovoltaic (PV) in Portugal in the following decades. The Portuguese electricity system in 2050 is simulated with and without EV incorporation. Different EV charging scenarios are considered, allowing the determination of the maximum PV penetration feasible for the different EV charging profiles. Results show that EPIA PV scenarios can only be achieved by mid-day EV charging.

Keywords: solar photovoltaic, grid flexibility, RES penetration

1 Introduction

EVs and renewable energy sources (RES) in general have the potential to significantly decrease carbon emissions from both the transportation and power generation sectors of the economy. Particularly, solar electricity has no direct carbon footprint and the EV carbon footprint of driving is directly related to the electricity from which the batteries are charged.

These technologies, more specifically plug-in hybrid EVs (PHEV), pure EVs (PEV) and solar photovoltaic, have expected mass adoption in the following decades across the globe [1], [2], [3], [4]. It is the case of Europe due to European Union (EU) ambitious environmental strategies, such as the Energy 2020 targets [5] and more long term goals [6].

On the other hand, Portugal is a world pioneer in the promotion of the EV, with the governmental plan of Electric Mobility and the deployment of a public recharging infrastructure in the country [7]. Also, Portugal within Europe has the highest levels of solar irradiation [8], and thus it is a very favorable place for PV technology deployment.

Based on the previous considerations, it is therefore of interest to analyze the extent to which transport electrification can further the PV energy integration in Portugal, and vice-versa, getting an overview of the possible impacts of the introduction of PV in articulation with EVs. This study assesses the synergies between these technologies in Portugal, identifying the best options to exploit their interactions and quantifying the technical impacts on the electricity system of various combinations between them in a long-term scenario (2050). The analysis considers, among others, the effect of different recharging profiles on the feasible PV penetration.

2 PV and EV interactions

To illustrate PV and EV deployment in Portugal until 2050 we have constructed the penetration curves shown in Figure 1. The yellow line represents one of the EPIA scenarios for 2030 [3], that was used in a number of analyses for 2050. The total EV fleet in 2050 corresponds to a share of about 40% of the light duty (LD) vehicles fleet at the national level.

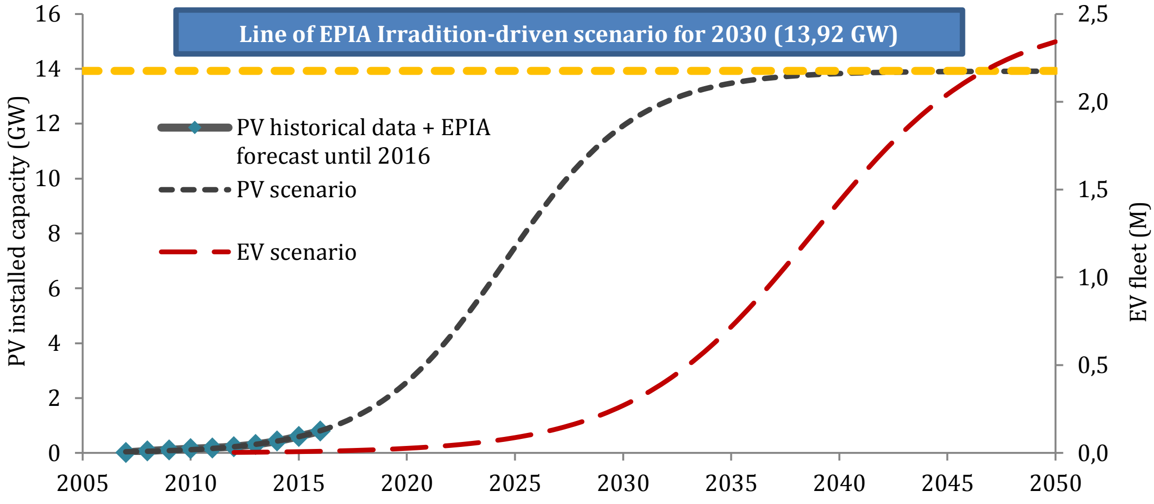

Figure 1 – Scenarios of PV and EV deployment in Portugal until 2050

Technically, mass market penetration of EVs will surely interfere in the integration of renewable energy into existing electric grids, with a number of impacts and benefits [9], [10]. Given the spread of renewable energy sources, EVs can be both a threat and an opportunity.

A threat because intermittent energy sources are difficult to coordinate with existing base load power generation capacities , that possess limited flexibility and ramp rates (i.e. limited ability to balance rapid changes in renewable generation and demand by adjusting their output) and high minimum output levels. This situation can lead to an endogenous electricity production deficit or superavit. A typical example is peak wind generation times, usually overnight, which does not match with peak load periods, hence leading to negative electricity prices in energy markets. Another example is on sunny days, when PV combined with wind pushes down mid-day demand for fossil fuels power, leading as well to negative energy prices in particular at weekends, when demand is lowest, something which has been anticipated [11], [12] and has already happened [13], [14]. On the other hand, sufficient backup generating power has to be available for times with high load and low non dispatchable renewables output, reducing the overall system efficiency and increasing the cost per kWh. If uncontrolled EV charging is added to this already challenging situation, then this can have effects both at the distribution and at the generation level. It is generally considered that small scale EV introduction (up to 5% of the fleet) will not pose a significant threat to advanced distribution grids [15], but beyond that the effects may be significant. On the other hand, the integration of EV on the energy grid is also an opportunity because, in the case of solar, if it is to play a large role in the future energy system, it will require new methods for large scale energy storage at nation sized level, which could be provided from the vehicles batteries [16], [17].

Additionally, mid-day charging has the potential to increase the driving range for commuters' vehicles. For the particular case of PHEVS, this would increase the fraction of miles driven electrically, hence decreasing petroleum use [18].

3 Methodology

3.1 Energy systems modeling

For the analysis of the Portuguese electricity system and integration of renewable electricity sources, different simulation tools were considered. For a comprehensive review see [19]. The EnergyPlan [20] was the tool chosen. EnergyPlan is a validated deterministic computer model designed for energy systems analysis that optimizes the operation of a given energy system on the basis of inputs and outputs defined by the user. The reasons behind the choice are: (1) the objective of this research is to investigate the ability of EVs to facilitate the large-scale solar electricity integration into a country level electricity system, and EnergyPlan is a simulation model at regional and national levels including the major primary sectors of an energy system, namely electricity and transport; (2) we needed an instrument with a temporal fine analysis capability, and EnergyPlan being an hourly

simulation computer tool, instead of an aggregated annual demand and production, satisfies that condition, making it suitable to model the sun power (and power from other renewables) integration, considering its variability; (3) ample previous research about integration of fluctuating renewable energy resources has been carried out by using this tool, such as [21], [22], [23]. These features indicate that Energyplan is pertinent to this study.
Investigations were carried out in sequence and, in order to ensure the model is simulating the Portuguese electricity system correctly, a reference model was created and validated representing the year 2011 (see Section 3.2.1). Since from a techno-economic viewpoint it is desirable that electricity production is consumed locally, export capacity was not considered.

3.2 Portuguese electricity supply

3.2.1 Year 2011 characterization

Electricity consumption in 2011 was 50.5 TWh with a peak power demanded from the grid of 9,192 MW. Minimum load was 4,966 MW. Figure 2 shows the electricity generation shares according to the production sources. It can be seen that electricity production from RES supplied 46% of consumption (18% wind, 22% hydro and 6% other renewables, e.g. biomass and solar). The import balance represented 6% and the thermal generation accounted for 51.8%, with 17.3% from coal and 19.6% from natural gas [24]. Figure 3 shows the normalized duration curves for the entire year, being worthwhile to notice the shape of the PV curve, with a steeper zone (daylight) and an essentially flat zone (which corresponds to the night periods). The overall capacity factor for 2011 was 0.29.

3.2.2 Future assumptions

Scenarios are essential to describe possible development paths, to give decision-makers a broad overview and show how far they can shape the future electricity system.
For our research, we have created a reference scenario built upon long term EU objectives for the climate-energy area and upon several scenarios that are presented in the literature (e.g. [25], [26], [27], [28]), most of these derived from partial equilibrium technical-economic models of the evolution of the energy systems over a defined time horizon, such as MARKAL/TIMES [29]. Data temporal extrapolation was applied for the scenarios with a time horizon less than 2050. The criteria for choosing the considered scenarios were: (1) EU or, preferably, Portugal scope; (2) scenarios built 2009 onwards, in order to reflect the effects of the financial crisis that started in 2008 and lead the EU to an economic downturn; (3) scenarios or objectives that met the above criteria but comprise future conditions that have already been achieved in Portugal were discarded.

3.2.3 Coal

EU has very ambitious long-term policy plans in areas such as transport, energy and climate change that foreseen until 2050 a marked decline in coal electricity generation [30]. In Portugal, it is seen as plausible the deactivation (until 2022) of a significant part of the existent coal generation capacity [31] and it is conceivable that this tendency is maintained until 2050. For this reasons, we did not consider any electricity generation from coal in the energy portfolio in our 2050 scenario.

3.2.4 Natural Gas and Biomass

Conversely to coal, biomass and more significantly natural gas sees an addition of about to 70% in the installed capacities.

3.2.5 Hydro

We have considered that all the new large hydro capacity predicted in the *Programa nacional de barragens com elevado potencial hidroeléctrico* [25] is installed in 2050, pumping included.

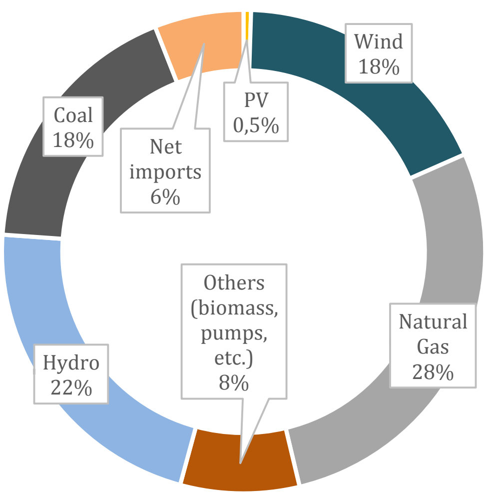

Figure 2 – 2011 electricity shares in Portugal

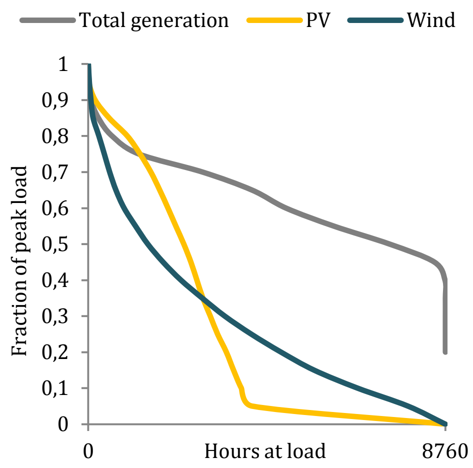

Figure 3 - 2011 normalized load duration curve

3.2.6 Solar PV

Historically, and in contrast to wind projections, photovoltaic installed capacity forecasts have been too conservative. For example, EPIA's Solar Generation 5, published in 2008, underestimated PV market growth even in its advanced scenario in 56% for 2010; on the other hand, IEA WEO 2000 estimations for 2010 were reached 6 years before. This happens mainly because solar PV costs have dropped significantly faster than any projections. For some OECD countries, solar PV has already reached grid parity with fossil fuels in 2012. Nonetheless, long term projections for solar photovoltaic do not just depend on cost improvements, but also on available storage technologies. For this reason, grid integration can actually be a bottleneck to PV penetration much earlier than anticipated [32].

Nonetheless, for our 2050 scenario we have considered as reference/objective an installed capacity of 13,900 MW, which corresponds to the capacity in the EPIA's Irradiation-driven Scenario for Portugal for 2030 [3], representing a PV share in the electricity mix of 29%.

3.2.7 Wind

Portugal had in 2012 the second highest wind power penetration in the EU, with 17% of share of total electricity consumption [33]. This means that scenarios of future wind penetrations in the EU with no country specific details have no direct transposition to Portugal, since wind technology in this country has less space to grow than in the majority of other EU countries (EU electricity wind share is on average 7% [33]). Furthermore, few studies with national level projections are available. For these reasons and because (1) there are studies that found that maximum feasible wind power penetration in the electrical grid from both a technical and economic point of view is under 30% [21] and (2) optimum mix of electricity from wind and power sources are achieved when there is an equilibrium of both [34], we considered for wind a penetration level of 26%.

3.2.8 Demand

Assuming strong growth in electricity demand, we have considered for the 2050 scenario an increase by 30% with regard to 2011, already including EV demand.

3.2.9 EV modelling

The maximum system power drained from the grid by the EV fleet is calculated multiplying the power drain of a single car by the maximum number of cars plugged in at any given time. The entire set of batteries was modeled as country sized energy storage, charged according to the set of schedules in Figure 4, and discharged during driving.

4 Results

Figure 5 illustrates the electricity production from the different power sources for a period of a week in April in 2050, without EV introduction. Residual power injection from thermal power plants and large hydro even in periods of excess of energy supply is needed for two reasons: (1) assure frequency regulation of the grid and (2) due to techno-economic reasons (since cold start-ups from thermal power plants are expensive).

One should note the substantial amount of excess solar electricity during daytime hours which must

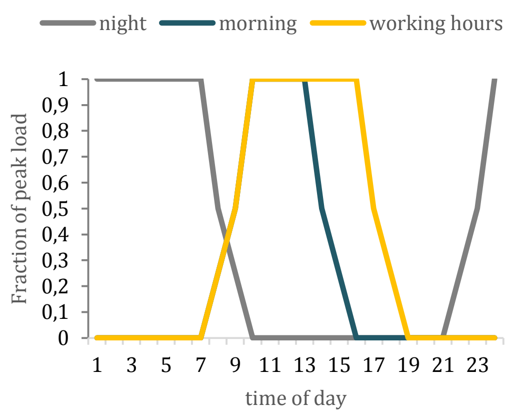

Figure 4 – EV charging profiles

be exported or curtailed. Since neighboring countries that can import this energy will have, with great probability, at the very same time a peak generation from their own PV production, eventually this energy is exported at low or null prices, with costs and losses involved. This already happens currently in Portugal with wind energy during the night. For the whole year, this amount is close to one fifth, 18.2%, of all the electricity production. It is worthwhile to note also that the total LD EV fleet consumption in a year would represent about half of this excess of electricity.

Figure 6 shows a new load diagram for the same week, but now considering the effects of EV on the electrical grid. This scenario reflects the EV penetration, distributed between PEV and PHEV, depicted in Figure 1. It is interesting to note the substantial decrease in the mid-day generation surplus due to the good match between EV charging and PV production. For the whole year, the surplus is about 12%, which means that, even with a significant share of EV, there is still the need to export or curtail electricity.

These results show, in order to warrant grid stability and optimizing electricity costs, the expected large scale dissemination of PV in Portugal can only be achieved if there is a significant penetration of EVs, and vice versa. This conclusion thus leads to the requirement of a matching penetration of these technologies in the local energy system without incurring in technical and economic challenges. Figure 7 illustrates the allowed PV installable capacity as function of different EV charging profiles. *Feasible* is defined here as the value above which the excess annual energy production is larger than 15%. These results show that only with daytime EV charging can the EPIA Irradiation-driven scenario for 2030 be achieved.

Finally, Figure 8 shows the evolution of the surplus of energy in the system as function of the size of the EV fleet. To improve readability of the graph, morning charge line it is not shown since it is very close to the working hours charge line. It can be seen that daytime recharging options, at the commuters' worksite or daytime parking locations, for example, is the best option because it allows for less excess in the electricity generation, and this effect is more prominent with the increase in the size of the EV fleet.

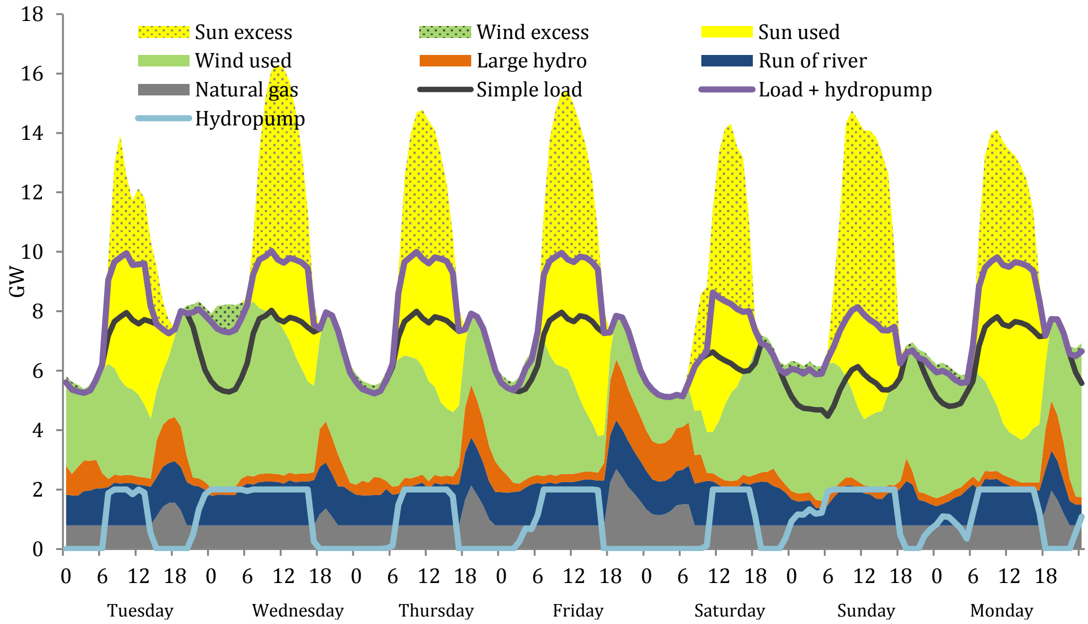

Figure 5 - 2050 electricity grid load diagram for a late April week without introduction of EV

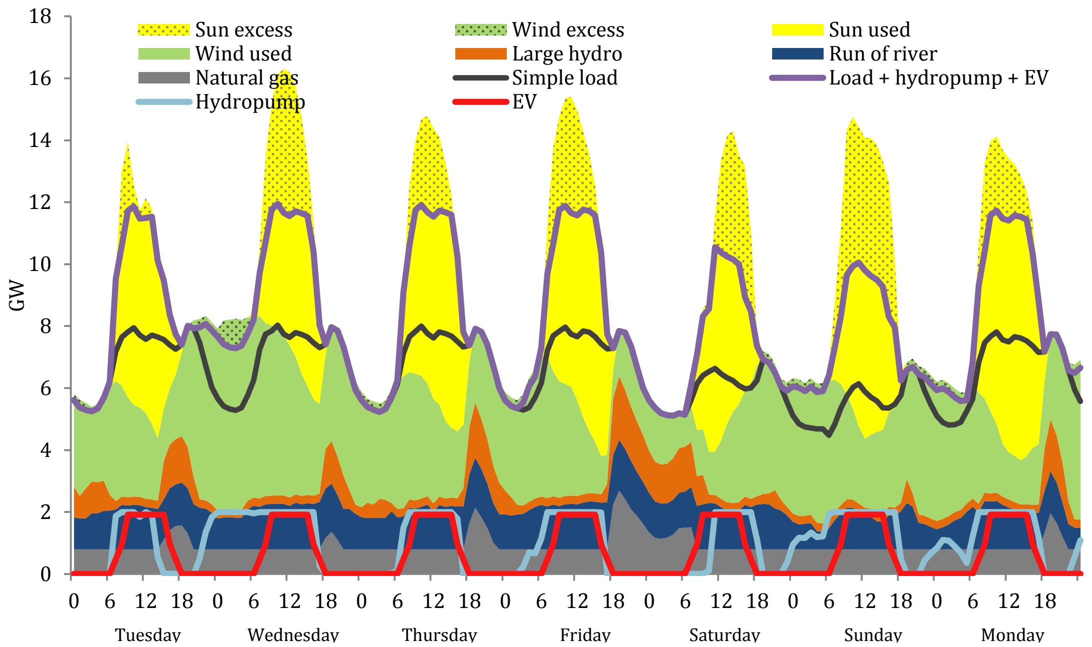

Figure 6 - 2050 electricity grid load diagram for a late April week with EV (working hours charging profile)

5 Conclusions

In this study we have evaluated the EV as a solar PV enabling technology.

The fundamental imbalance of supply and demand likely represents the ultimate limit on system penetration of variable renewables in electric power systems. The concentration of solar PV output in a relatively short daily window can produce unusable electricity and, thus, unusable PV capacity, which will increase costs, preventing the ability to achieve very high PV quotas.

We have developed a model of the Portuguese electricity grid to test the effect of different recharging profiles on the feasible PV penetration. As expected, daytime charging profiles can the best solution in order to better exploit the synergies between both technologies.

Even in a scenario of high share of EV in the national LD vehicles fleet (40%), it was clear that not all the electricity generation can be absorbed internally. It can then be concluded that avoiding excessive curtailment and exportation will likely require not only EV as the solution but also

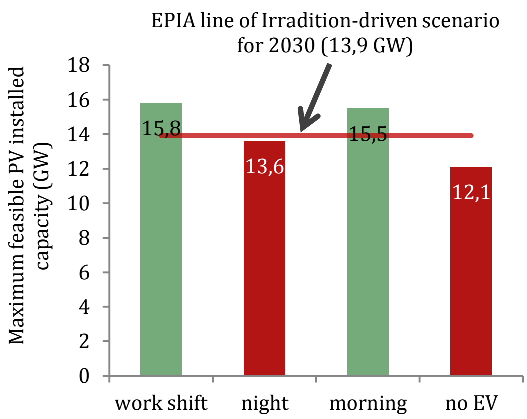

Figure 7 - PV maximum feasible installable capacity as function of different EV charging time-profiles

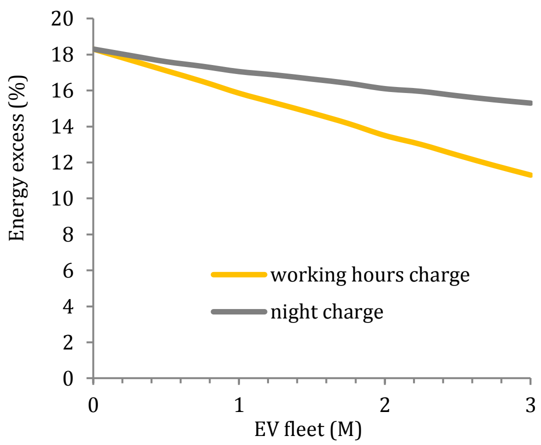

Figure 8 - Excess of energy in the grid as function of the size of the EV fleet

probably a variety of technologies, like load shifting.
In order to fulfill the EU ambitious objectives in the climate-energy area, given the long deployment time and lifetimes of many electricity generation technologies, it may be useful to think imaginatively about possible ways to begin moving towards a fossil free electricity system.

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