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The pure PV-EV energy system – A conceptual study of a nationwide energy system based solely on photovoltaics and electric vehicles

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ABSTRACT

The objective of this conceptual study is to reveal the substantial potential and synergy of solar energy and electric vehicles (EVs) working together. This potential is demonstrated by studying the feasibility of a nationwide energy system solely reliant on solar energy and EVs. Photovoltaic (PV) solar energy is already an important energy source globally, but due to its intermittency it requires energy storage to balance between times of high and low production. At the same time, a global drive is underway in the transport sector: the change from internal combustion engines to EVs. Cars are in fact stationary 95% of the time, and when the vehicle is connected to the grid, the EV battery can regulate the intermittent PV source using vehicle-to-grid (V2G) technology. This paper presents a conceptual study of a pure PV-EV based energy system, with Spain as a case study. Provided that Spain's entire fleet of 29.4 million road going vehicles is switched to EVs, the study shows that 3.45 billion m^2 of PV (73 m^2 per capita) could give Spain a completely self-reliant energy system. The theoretical study is based on a combination of measured values, simulations, and assumptions. The conclusion of the analysis is undoubtedly extraordinary, namely that an entire country like Spain can power its complete energy system solely on PV, using EVs as the only energy storage resource.

1. Introduction

1.1. The pure PV-EV energy system

The objective of this conceptual and original research is twofold. Firstly, to reveal the substantial potential and synergy of solar energy and electric vehicles (EVs) working together. Secondly, to demonstrate this potential by studying the feasibility of creating a nationwide energy system solely reliant on solar energy and EVs. This would be a ground-breaking energy system where a country's total energy demand would be covered by photovoltaic (PV) solar energy alone. The energy storage needed to balance the intermittency of PV would come from the batteries of plugged in EVs, using the technology known as Vehicle-to-Grid (V2G). Consequently, there would be no need for conventional centralized power plants. This concept has never previously been taken to this extreme and been studied in literature. The hypothesis is that such a pure PV-EV system is realistic below a certain latitude, with adjustments for local weather conditions.

A global drive to reduce and mitigate climate change have resulted in growing proportions of renewable sources in the energy sector, where PV together with wind energy will be the cornerstones. The renewable energy resource with the largest potential world-wide is by far solar energy, having a potential more than a thousand times greater than the world energy usage [1]. Wind energy comes second with a potential similar to the world energy usage [1]. PV is also by far the fastest growing energy source globally, seeing an annual increase of 30% in power installations between 2012 and 2019 [2]. Having such a high annual increase, PV has in 2020 surpassed wind energy and will in less than five years surpass hydro power, and become the largest installed renewable energy power capacity globally [3,4].

In this paper, we choose to focus exclusively on the vast solar energy resource because of its simplicity and potential. PV is the only energy source that is practical to install on buildings in urban areas, it requires almost no maintenance, will last for at least 25 years (silicon solar cell modules usually come with a 25 year power production warranty), does not require new land areas, and is cost-competitive in most markets in 2020. But how far is it possible to

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stretch an energy system to rely on intermittent solar energy as the sole energy source?

1.2. Literature review

Solutions and strategies to balance the fluctuating demand and supply of energy is needed in an energy system that is based on intermittent energy sources. Relevant technologies are different types of energy storage (including storage of both heat and electricity), demand side management and flexible electricity markets. The role of different types of energy storage solutions is studied in literature by e.g. Refs. [5–7]. In this analysis, the energy load and supply are balanced solely by energy storage capacity of EVs. A large-scale transition to electric transport is necessary in order to create a sustainable transport system, which is key to a sustainable society. As such, EVs represent a solution to the problem of intermittency, as well as a means to reduce emissions from transport. Using EVs as an energy storage medium is very appealing since the round trip efficiency of modern Li-ion batteries is close to 90% [8]. In addition, road going vehicles are predominantly stationary and could be available for V2G services 95% of the time [9].

Authors Zhang, Tezuka [10] have shown that by using 1 million EVs and 1 million heat-pumps (HPs), the excess electricity can be reduced by 2% in Kansai area, Japan. Another more recent study showed that curtailment of variable renewable energy sources could be reduced by 18% when introducing a 16% EV penetration in the private sector [11]. Similarly, Van Der Kam and van Sark [12] performed a case study on a smaller scale in Lombok (a residential neighborhood in Utrecht, Netherlands) and showed that by using EVs, the PV self-consumption can be increased from 13% to 38%. Huber, Trippe [13] studied large-scale effects of PV and EV integration for Singapore, but in this study V2G energy transport was not considered because of lack of data. Studies on increasing the self-consumption by using the V2G technologies have also been performed [14,15]. For a review on interaction between PV generation and EV charging, please refer to Refs. [16,17].

Large scale hybrid renewable energy systems consisting of various combinations of renewable energy end energy storage possibilities have been studied previously in the literature. Rasmussen, Andresen [7] studied the synergies between small short-term storage and seasonal storage in a fully renewable scenario for Europe. Mathiesen, Lund [18] studied how a 100% renewable energy system could be achieved in Denmark by integrating electricity, heating and transport sectors with different forms of energy storage and flexibility, into a so-called Smart Energy System. Child, Kemfert [19] simulated pathways to a fully renewable energy power sector in Europe by 2050 using the LUT Energy System Transition model and two different scenarios for interconnection between areas and regions. The study highlighted the increasingly important role of PV prosumers (i.e. producers and consumers) with batteries to reduce maximum grid loads. Compared to the previous work, this paper is unique in that it simulates a whole country's energy system, powered only on PV and EVs.

1.3. Case study: Spain

The conceptual exercise presented in this paper will show the feasibility of powering a completely electrified energy system of a whole country, in this case Spain, on only PV and EVs. We chose Spain as a case study mainly because of its location in southern Europe with relatively large amounts of solar radiation all year round. The pure PV based energy system will still have some seasonal fluctuations since Spain is on latitude 40°N. At higher latitudes, the sun-hours during winter months drastically decrease, making a pure PV-EV system unrealistic. Above a certain latitude threshold, we must mix in other renewables, such as wind and hydropower. Such as system, also including interconnections to other countries, will be the topic of a future study.

The energy consumption of Spain has increased significantly in recent years. With a population of 47 million inhabitants, the final energy consumption of Spain has on average been 960 TWh between 2014 and 2018 [20]. In the past decade, the production from renewables has increased by 76% while coal and oil-based generation have decreased to nearly half [21]. The primary production of renewable energy in Spain has been increasing and in 2016, the energy produced from hydropower was 36 TWh, solid biofuels contributed with 62 TWh of energy, wind generated 49 TWh and solar 37 TWh of energy. The share of renewable energy was 17% in the total energy mix. Only looking at electricity, the renewable share in Spain was 37% in 2016 [21]. However, Spain is heavily dependent on energy imports. In 2016 Spain had an energy dependency rate (defined as the extent to which a country relies upon imports in order to meet its energy requirements) of more than 70%.

The public-services sector and the residential sector are the largest electricity consumers in Spain. Each of these sectors consume around one third of the generated electricity, while only 2% is consumed by transport [22]. On the other hand, the part of the transport network that is not based on electricity accounts for around 56% of the oil consumption. In comparison, the industry and energy sector consume 15% and 11% of the oil, respectively [22]. Because of the transport sector's large dependence on oil, it remains the largest GHG emitter and therefore it is a natural focus area of the Roadmap 2020 [22].

The format of this paper is as follows. Section 2 provides an overview of the method and the pure PV-EV energy system model. Section 3 presents the results, which is followed by discussions in Section 4 and conclusions in Section 5.

2. Method

In order to simulate the pure PV-EV nationwide energy system, a MATLAB model was constructed. The core of the code can be found in Section 2.5 and a flowchart describing the model is shown in Fig. 5. The hourly generated PV power is taken as input to the model, see Section 2.4. The energy load, besides road going transport, of Spain is discussed and calculated in Section 2.1. The hourly energy load, besides road going transport, is calculated and used as input to the simulation model according to the profiles shown in Section 2.3. Lastly, the hourly energy load of the road going transport is calculated according to Section 2.2 and subsequently given as an input to the simulation model. The simulation models calculates the state of the charge (SOC) for the aggregated EV fleet with an hourly temporal resolution. Moving vehicles and stationary vehicles are treated separately in the calculation.

A brief explanation of the simulation is as follows (for more information, see Section 2.5 and Fig. 5); if the PV generation is larger than the load then the excess energy is stored in the EV batteries. If the aggregated EV batteries have reached a SOC of 100% and there is still excess energy, then this energy is wasted. If the PV generation is less than the load, then the missing energy is taken from the EV batteries as long as the limit on a minimum of 10% SOC is not reached. If neither PV nor the EV batteries can supply the load, then the model generates a failure hour.

2.1. Data and assumptions

Some of the required input energy load parameters for Spain were not available and some parameters had too low temporal resolution. Consequently, some assumptions had to be made. The following section lists the used data and the required assumptions.

Data on electricity generation and energy load for the whole country is retrieved from the Eurostat database [23]. The total energy demand is approximated by the annual final energy consumption (FEC) used by Eurostat, which is defined as "[…] all energy supplied to industry, transport, households, services and agriculture (it excludes deliveries to the energy transformation sector and the energy industries themselves). This quantity is relevant for measuring the energy consumption at final place of energy use […]" [20]. With small-scale, distributed energy sources, such as PV systems on buildings as well as free-standing installations, much of the losses related to energy production and transmission can be avoided. In addition, the simulated scenario assumes that all energy consuming processes are electrified. Consequently, using FEC as the definition of the total energy load of the country is an appropriate assumption. During the period 2014–2018, Spain had a FEC varying between 920 TWh and 1010 TWh and the average value of 960 TWh is used here [20].

The FEC values were only available as total annual sums. Consequently, the monthly distribution of FEC had to be generated by mimicking the monthly variation pattern of another energy parameter, found with better time resolution. A national energy parameter that Eurostat provides monthly values for, is the net electricity generation. Hence, the monthly distribution pattern of the net electricity generation values was used to create a monthly distribution of the FEC values from the annual FEC value of 960 TWh. The distribution (Fig. 1) shows that the monthly variation over the year is relatively small.

2.2. Electric vehicles

In the simulation model, all road traffic has been electrified. The total amount of road going vehicles in Spain was 29.4 million in 2018, out of which 82% were personal vehicles, 16% light commercial vehicles and 2% medium and heavy commercial vehicles [24].

The average daily distance driven by personal vehicles Spain in 2018 was 36 km [25]. Data from the daily driving distance of commercial vehicles was not possible to obtain for Spain, and the results from a large-scale study on European transport data [26] was used to approximate this. This large-scale study included ten different provinces around Europe, with in total more than 120 000 commercial vehicles. Paffumi et al. defined commercial vehicles as light vans, medium duty vehicles and heavy-duty vehicles, and the average daily driven distance for these commercial vehicles was 110 km. Consequently, an average daily distance for all road-going vehicles in Spain can be calculated, using a weight of 82% for the personal and 18% for the commercial vehicles. The average distance driven for all road-going vehicles is then 49 km.

Next, the energy consumption of this fleet of vehicles must be found. According to Smith, Graves [27], the average consumption of electrified cars and light duty commercial vehicles is 325 Wh/mile or 202 Wh/km. The average consumption of electrified heavy duty commercial vehicles is 2000 Wh/mile or 1240 Wh/km. Accordingly, the average consumption of electrified road-going vehicle fleet in Spain is calculated to 224 Wh/km, using a weight of 98% for all personal and light commercial vehicles and 2% for the medium to heavy duty commercial vehicles.

To exemplify driving patterns on a national scale, synthetic driving patterns were generated, using log-normal distributions [28]. The distribution, as shown in Fig. 2, was generated using the probability distribution function 'makedist' in MATLAB (keeping mean of log at 12 and standard deviation of logarithmic values at 0.3). Hence, Fig. 2 represents the percentage of moving EVs for each hour during a 24-h day. As can be seen, a maximum of 12%, around noon, of the EVs are moving at the same time. By adding up the percentages of moving EVs during a 24-h period we end up with 100%. That is, all EVs have been driven sometime during this 24-h period. The average daily driving distance per vehicle in Spain is 49 km, as described above. The 24-h distribution was then multiplied by 49 km to obtain the daily driving distribution for Spain. It was assumed that the driving pattern remains the same for all days of the year. This distribution was used mainly for two reasons. First, there is a lack of available data on driving patterns for Spain, and second, log-normal distributions are observed to be a good representation of the travelling patterns of large number of vehicles [28].

One of the assumptions made in this study is that all the EVs are connected to the electricity grid when parked. As the daily rush hours approach, there is a lower number of vehicles connected to the grid, see Fig. 2, which in turn reduces the amount of available

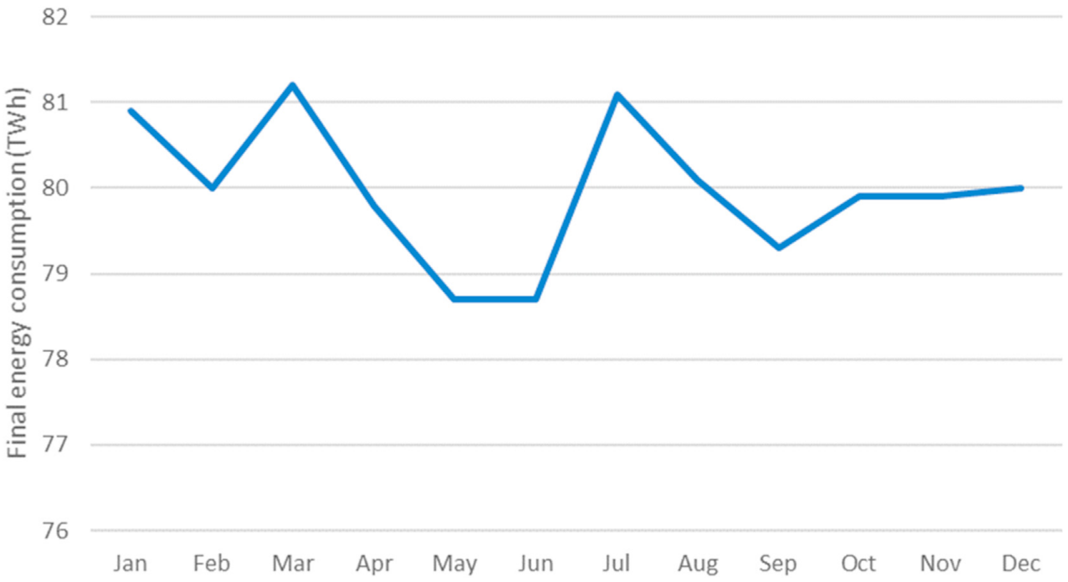

Fig. 1. The monthly distribution of the final energy consumption (FEC) was created based on the monthly distribution of the values for net electricity generation from Eurostat.

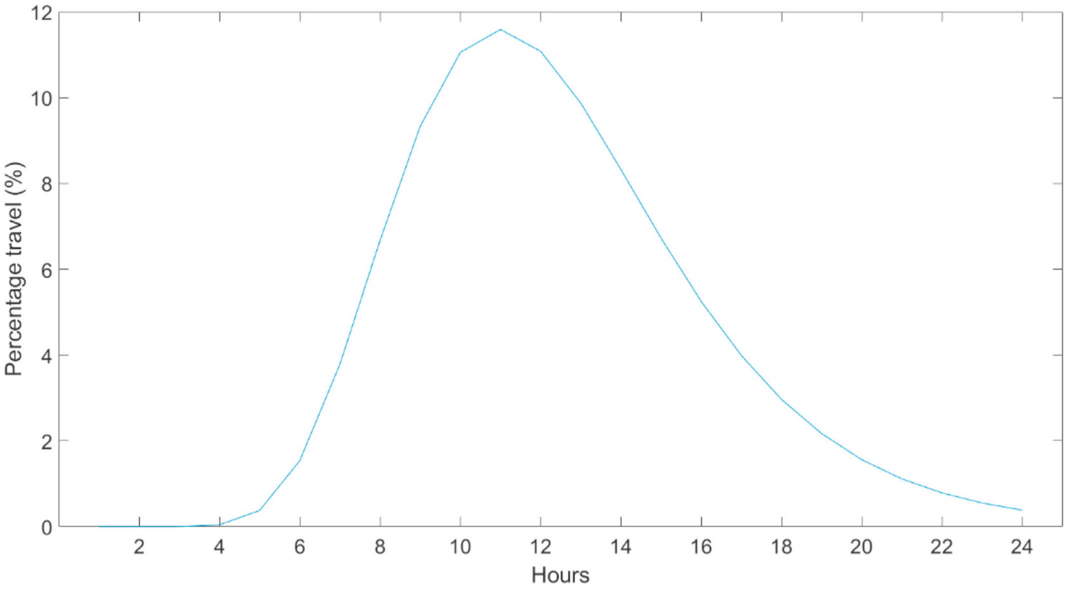

Fig. 2. Log-normal waveform representing the general driving pattern in Spain during a 24-h period. The y-axis shows the percentage of EVs that are moving at any given time.

storage. On the contrary, at night a very large percentage of EVs are parked and thereby connected to the grid. Consequently, at night when PV is not producing energy, Spain's energy system solely relies on the energy stored in the EV batteries. The percentage of parked EVs is modelled by inverting the driving pattern shown in Fig. 2, and is shown in Fig. 3. In this scenario, the parked EVs represent the available battery capacity in the grid. Consequently, at night when the sun is down and auxiliary energy is needed the most, the access to EV batteries is also the highest.

2.3. Household and industry load profiles

The authors have not been able to find scientifically validated load profiles for Spain. Hence, the household and industrial load profiles used in this study were generated using a MATLAB model proposed by Sandels, Widén [29]. According to the authors, the model proved to be very accurate during the summer when validated with measured data from Swedish households. Swedish summer temperature conditions are close to average temperature conditions in Spain.

The Sandels model generates load profiles with an hourly temporal resolution for household and industrial sectors. The load profiles used in this study are shown in Fig. 4. The daily load for households was obtained by dividing the annual household load value (which was 18% of FEC, see section 2.5) by 365 and then distributing the load according to the percentage distribution shown in Fig. 4a. A daily household profile was used since the difference in household loads between weekdays and weekends is relatively small. Hence, a weekly profile is not necessary for the household load.

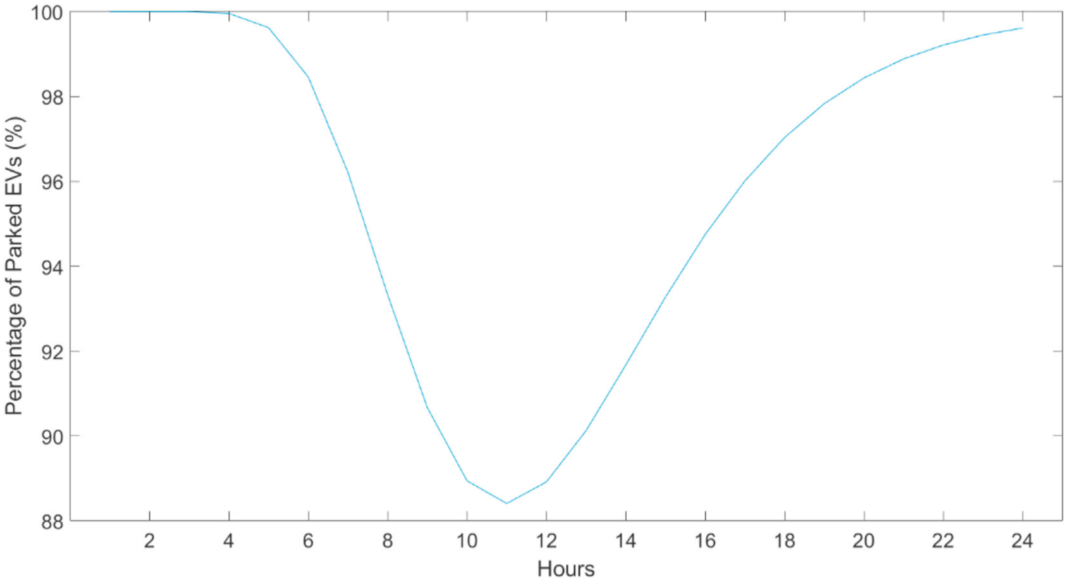

Fig. 3. Variation in the percentage of parked EVs during a 24-h period. In this scenario, the percentage parked EVs, shown on the y-axis, represent the available battery capacity in the grid.

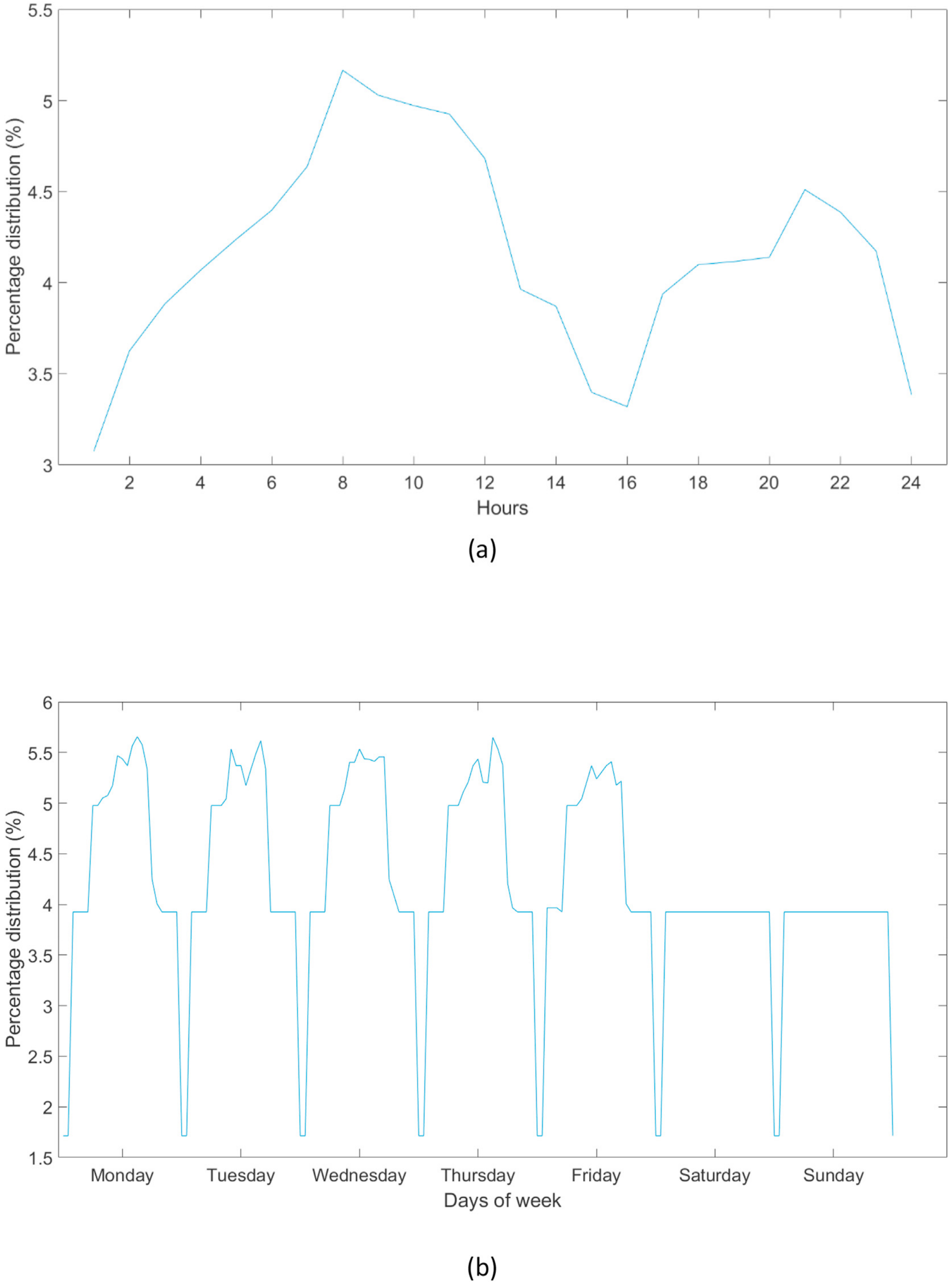

Fig. 4. (a) a daily bimodal distribution for the household load and (b) a weekly load waveform for the industrial load.

For the industrial load, a weekly load profile was obtained by averaging the industrial annual load (which was 40% of FEC, see section 2.5) over a week. A weekly industrial load profile was created in order to take into account the relatively lower loads on weekends, as can be seen in Fig. 4b.

2.4. Photovoltaics

The production data for PV energy generation in Spain was acquired from the PVGIS (Photovoltaic Geographical Information System) database [30]. The data was obtained for electricity generation from optimally inclined PV modules, which in Spain is around 35°. The spatial and temporal averaging of the data was performed by randomly selecting and averaging PV generation from 35 data locations in Spain between 2007 and 2016. Since this conceptual study explores a future concept it makes sense to utilize state-of-the-art efficiencies on the PV modules. In this case the highest efficiency crystalline silicon modules from SunPower was

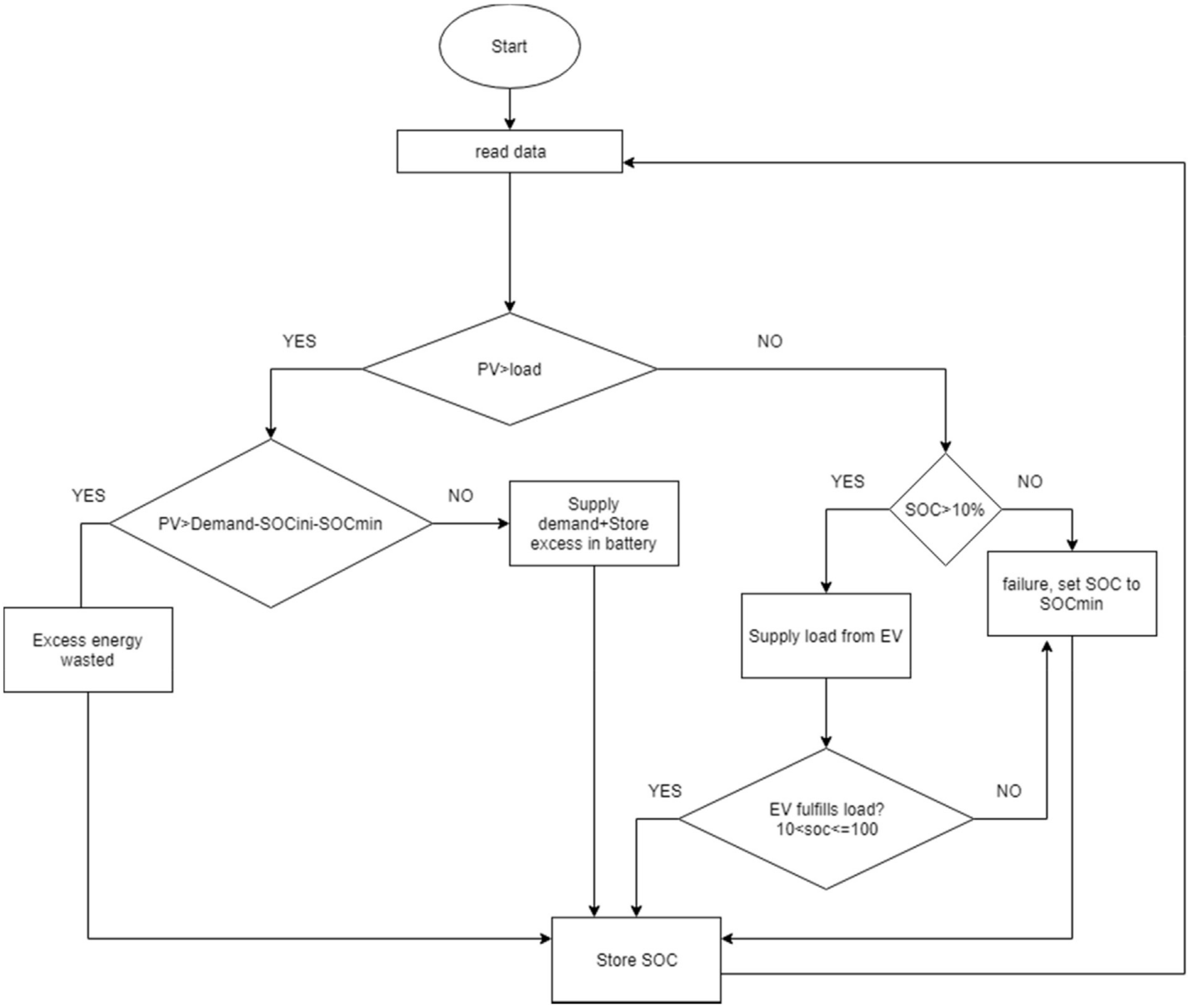

Fig. 5. A flowchart of the EV-PV simulation.

utilized [31]. These commercially available modules have an efficiency of up to 22.8%. In this work, PV modules with 22.5% in efficiency were used in the simulations. The amount of energy available from the PV panels was reduced using the standard system loss factor of 14% in PVGIS. There is some degradation of PV modules with time but recent work on degradation of modern silicon modules have shown that the amount of degradation is small in high quality modules. The degradation is typically less than 0.5 relative percent per year [32,33]. Hence, degradation of the PV module efficiency has been disregarded in this study. Given this input to PVGIS, the calculated averaged annual yield for Spain is 365 kWh per m^2. For more in-depth analyses, the data points for calculating solar irradiance could be selected by giving more weight to regions where the population density is larger. In addition, an optimal azimuth and slope angle is used in the analysis. For a more realistic scenario, varying angles should be used to simulate for example PV on buildings.

2.5. Modelling a 100% PV-EV scenario

The 100% PV-EV scenario was modelled using MATLAB. The total final consumption (as explained in the previous sections), the energy production from the PV systems, state of charge (SOC) and the excess energy stored in the batteries of EV were used as input to the model.

The final energy consumption was divided into percentages for each sector, corresponding to the Spanish case. In 2016 the transport sector accounted for 42%, residential (household) 18%, and industry and commerce 40% [34]. The resulting energy demand for each sector was fitted to the industry and residential load profiles described in section 2.3. Since all road traffic is assumed to be conducted by EVs, and therefore simulated separately in this study, the energy consumption from road transport had to be deducted from the total energy demand of the transport sector. Road transport amounted to 79% of the total transport load. The remaining 21% of the transport load derives from rail, maritime and air transport, and was also added to the industry load pattern.

In the model there are two fundamental conditions: A) All ground-based vehicles are electric. B) Whenever these vehicles, referred to as EVs for the rest of the paper, are not moving, they are connected to the grid so that their internal battery can be used to either feed or take energy from the grid. There will be some losses when charging and discharging the EV battery. There are very few empirical studies on the roundtrip efficiency of V2G but there is one recent study that have shown roundtrip efficiencies between 83% and 87% [8]. Since this is a conceptual study looking into the future, it makes sense to use the state-of-the art efficiency of 87%. Hence a loss of 6.5% when charging a vehicle and an additional loss of 6.5% when the EV is supplying power to the grid has been implemented into the simulation model.

Equation (1) shows the core of the model,

$$SOC_{tot}(t) = SOC(t-1) + PV(t) - FEC(t) - EV_{batteries}(t), \tag{1}$$

where SOC_{tot} is the total state of charge, t is the time-step, PV is the electricity produced by grid connected PV, FEC is the final energy consumption and $EV_{batteries}$ is the energy used by the EV for daily transport. As seen from Equation (1), the model is based on the SOC of the whole system. The EVs batteries can receive and deliver power with the limitation of EVs in motion (driven by owners). Consequently, moving cars and the stationary (parked) cars are treated separately in the simulation. The following equations explain how these fractions are handled in the simulation. In Equation (2) the SOC values for parked, SOC_p and moving, SOC_m cars are added from the previous iteration, t-1.

$$SOC_{tot}(t) = SOC_p(t-1) + SOC_m(t-1) \tag{2}$$

Equation (3) is calculating a new temporary $SOC_{p,temp}$ and $SOC_{m,temp}$ according to the fractions, r_p and r_m of parked and moving cars at time t.

$$SOC_{p,temp}(t) = r_p(t) \cdot SOC_{tot}(t), \quad SOC_{m,temp}(t) = r_m(t) \cdot SOC_{tot}(t) \tag{3}$$

Now updated values for SOC_p and SOC_m can be calculated according to Equation (4) and (5).

$$SOC_p(t) = SOC_{p,temp}(t) + PV(t) - FEC(t) \tag{4}$$

$$SOC_m(t) = SOC_{m,temp}(t) - EV_{batteries}(t) \tag{5}$$

Before starting the simulation, the SOC was set to 50% of the total available capacity. The simulation starts first with analyzing the energy generation from PV, the final energy consumption and the SOC. If the load cannot be supplied by available energy from PV, then energy is withdrawn from the SOC (from the EV batteries) to fulfil the energy requirements. In cases where PV produces more energy than the FEC load, the excess energy is stored in the EV batteries, resulting in an increase in SOC. This type of model gives rise to two main extreme points, i.e. when the SOC drops below the pre-set minimum level (see Table 1) and when there is excess energy that cannot be stored in the available SOC capacity. In this first case, there is a lack of energy in the overall system and it is shown by a failure, while in the second case the extra energy is wasted, as this energy cannot be utilized nor stored. A flowchart of the simulation is shown in Fig. 5 and Table 1 shows the parameters used in simulating the model shown in Equation (1).

3. Results

A first simple calculation can be performed in order to find out how many m^2 of PV are needed to cover the FEC of Spain. Using the calculated annual average PV yield of 365 kWh per m^2 from PVGIS and importantly, disregarding PV's inherent intermittency and the hourly load variation, it was found that in total, 2.63 billion m^2, or 56 m^2 per capita, of PV is needed to cover Spain's annual FEC.

Table 1
Model parameters for load balancing.

Parameter	Value
Population	47 million
Vehicle energy consumption	224 Wh/km
Average daily travel	49 km
Vehicle battery capacity	100 kWh
Number of vehicles	29.4 million
$SOC_{initial}$	50% of the total SOC
SOC_{max}	100% of the total SOC
SOC_{min}	10% of the total SOC

In order to see the actual effect of PV's intermittent nature, Spain's energy system was simulated, using an hourly time resolution and no energy storage in EVs. Consequently, the electricity produced by 2.63 billion m^2 PV was either instantaneously consumed or wasted. Fig. 6 shows the results of such a configuration, and it can be seen that the system has a very large number of failure points and an hourly self-reliance of only 37%. The definition of self-reliance refers to the time fraction that the hourly PV system output can cover the hourly load. Consequently, over a year the system can experience both lack of energy, mainly during the nights, and excess of PV energy during the days. Fig. 6 also shows the industrial and household loads in the system. The excess energy in the system presented in Fig. 6 is massive and amounts to 513 TWh and the lack of energy amounts to 360 TWh. Without any form of storage, this type of system becomes unfeasible.

Fig. 6 highlights the drawbacks of an intermittent source of energy. One of the feasible options to overcome this intermittency is by using a storage unit. In this study, the batteries of EVs are proposed as the sole energy storage units in addition to being used as the energy source for the EVs. Whenever any EV is parked, it is assumed to be connected to the network so that energy can either be stored in the EV battery or fed from the battery to the grid. The batteries were discharged to a minimum set limit of 10% SOC to feed the load when PV is not available. If neither PV nor the EV batteries can cover the energy requirement, a failure in the system is indicated. It should be noted that charging control strategies were not analyzed in this conceptual study. The charging and discharging of EVs were assumed to be instantaneous.

In the second case, the batteries of the EVs are used as energy storage units of the system. Fig. 7 shows the results of the simulation by using the base case with 2.63 billion m^2 of PV. With EV batteries as energy storage, the hourly self-reliance of the system significantly increased, to 93%. Still, during the summer, large amounts of PV energy is produced which cannot be stored in the batteries and results in wasted excess energy, in this case 144 TWh. It can be seen that already from February and all the way until October, the batteries of the EVs are fully charged and the self-reliance is 100%. Still, the system lacked 45 TWh and there were 649 h of system failure during winter-time in this simulation. In order to go beyond 93% in self-reliance, the PV area needs to be increased in order to provide enough energy during the winter months.

Using a larger amount of PV area than the base case will increase the self-reliance but at the cost of excess energy. This is shown in Fig. 8, where the black vertical line marks the PV area (2.63 billion m^2) needed to achieve self-reliance on an annual basis. In order to achieve 100% self-reliance, the PV area is increase and marked by a green vertical line. Here 3.45 billion m^2 of PV or 73 m^2 per capita is employed but with a large amount, 365 TWh, of excess energy. Fig. 8 shows that the cumulative yearly excess energy has a weak exponential trend with the PV area while the self-reliance increases steeply for smaller PV areas before plateauing at around 3.25 billion m^2. A simulation with 3.45 billion m^2 PV but without any storage in EV batteries was also performed and showed that the hourly self-reliance was only 39%, i.e. not much more than for the base case simulation (37%), which is not surprising since there is no energy storage availability in both these cases.

A final analysis was performed considering the optimal PV area case of 3.45 billion m^2 and by varying the battery storage of the EVs. In the default model, all EVs have 100 kWh of battery capacity, see Table 1. It was found that increasing the battery capacity of EVs

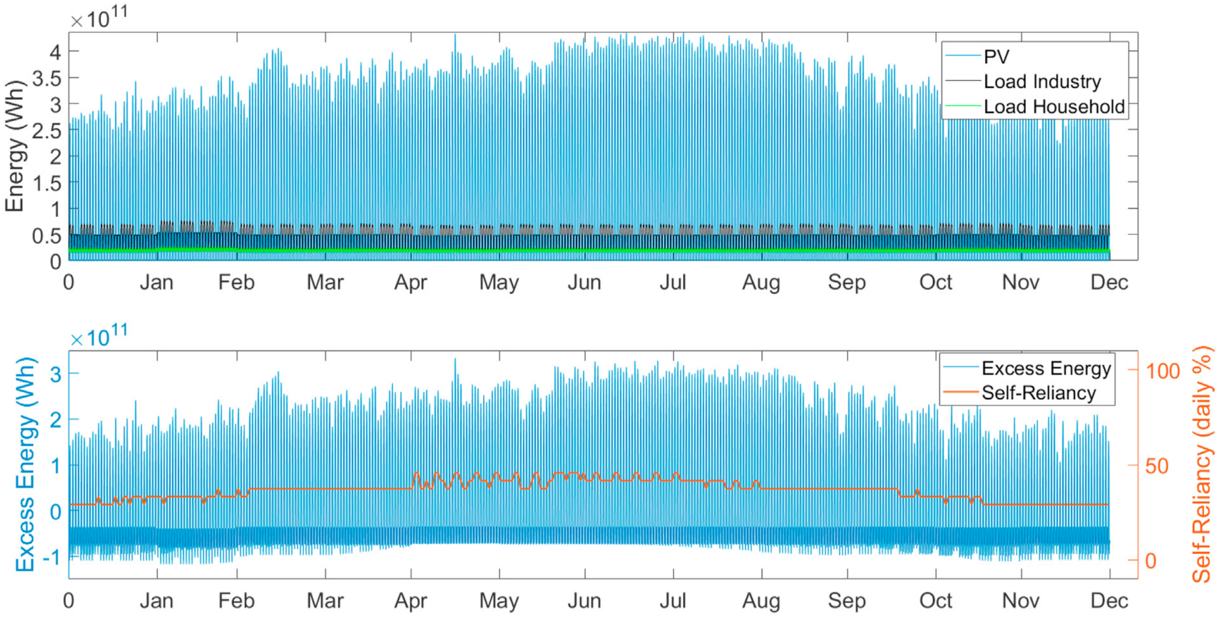

Fig. 6. Base case analysis of the FEC load coverage with 56 m^2 PV per capita but without energy storage. The upper figure shows the hourly PV generation and loads. The lower figure shows the hourly self-reliance and the excess or the lack of energy.

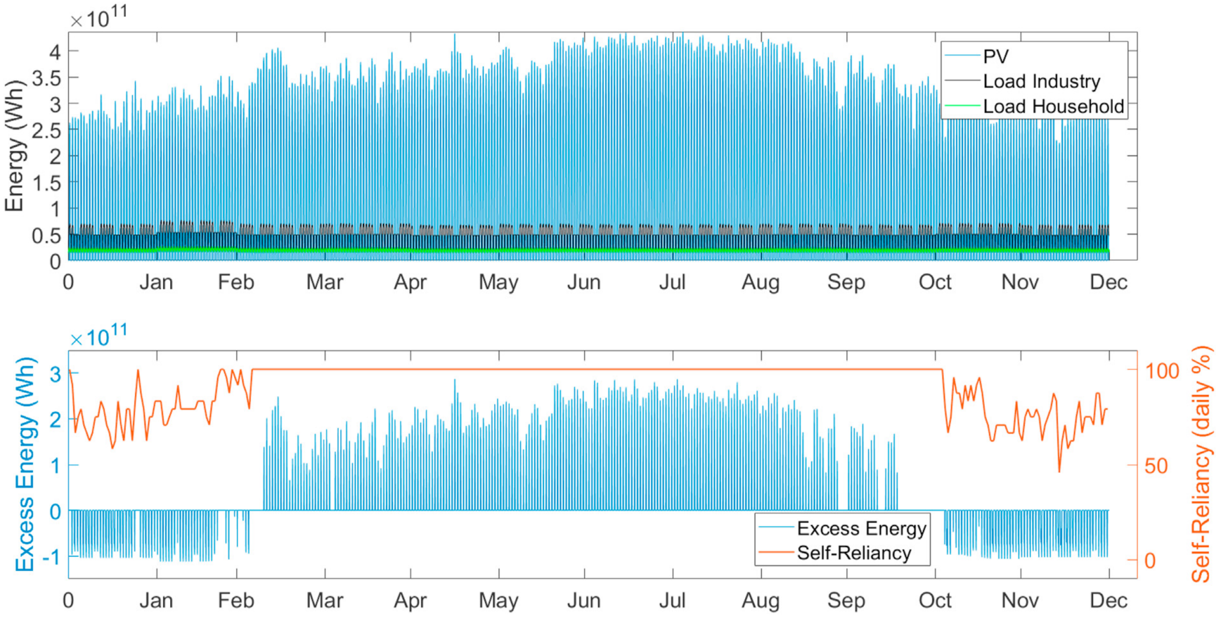

Fig. 7. Base case analysis of the FEC load coverage with 56 m^2 PV per capita and using EV batteries as energy storage. The upper figure shows the hourly PV generation and loads. The lower figure shows the hourly self-reliance and the excess or the lack of energy.

initially sharply increased the self-reliance of the system before plateauing at around 50 kWh, see Fig. 9. The cumulative excess energy behaves inversely to the self-reliance. The self-reliance is actually 99.5% for the case with 50 kWh batteries, i.e. PV and batteries only fail to fulfil the load during 45 h per year. Increase the battery size to 75 kWh and the corresponding numbers are 99.9% self-reliance and 13 h of system failure. Nevertheless, the battery size needs to be 100 kWh to achieve no failed hours and a self-reliance of 100%.

The simulations above were also tested with different initial SOC values (default = 50%). It was found that a varying initial SOC value had no noteworthy impact on the self-reliance of the system. In addition, the influence of the household and the industrial load profiles, see Fig. 4 were also tested by comparing to completely flat loads. Also in this case, it was found that changing the load profiles to a flat form had a minute impact on the self-reliance, less than 1%.

4. Discussion

The authors would like to highlight that this is a conceptual study and that several assumptions had to be made. Nevertheless, the groundbreaking results of the study remains valid as discussed in this section. The assumptions can be divided into three categories; 1) technically unrealistic, 2) technically feasible but not

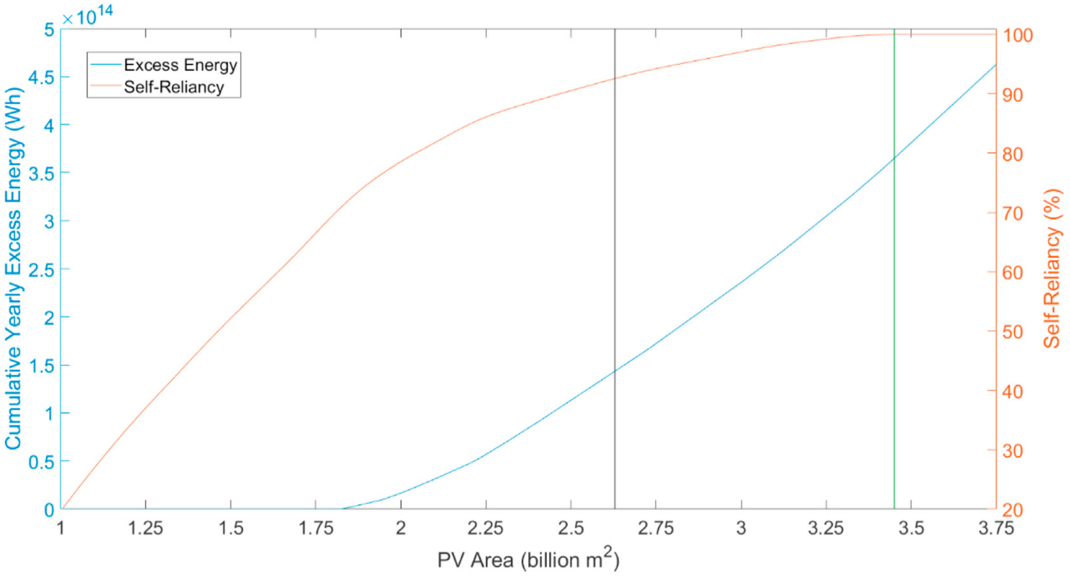

Fig. 8. Installed PV area and the sequential variation in self-reliance and cumulative excess energy. The green vertical line marks the optimal PV area of 3.45 billion m^2 or 73 m^2 per capita and the black line marks the base case with 2.63 billion m^2 or 56 m^2 per capita.

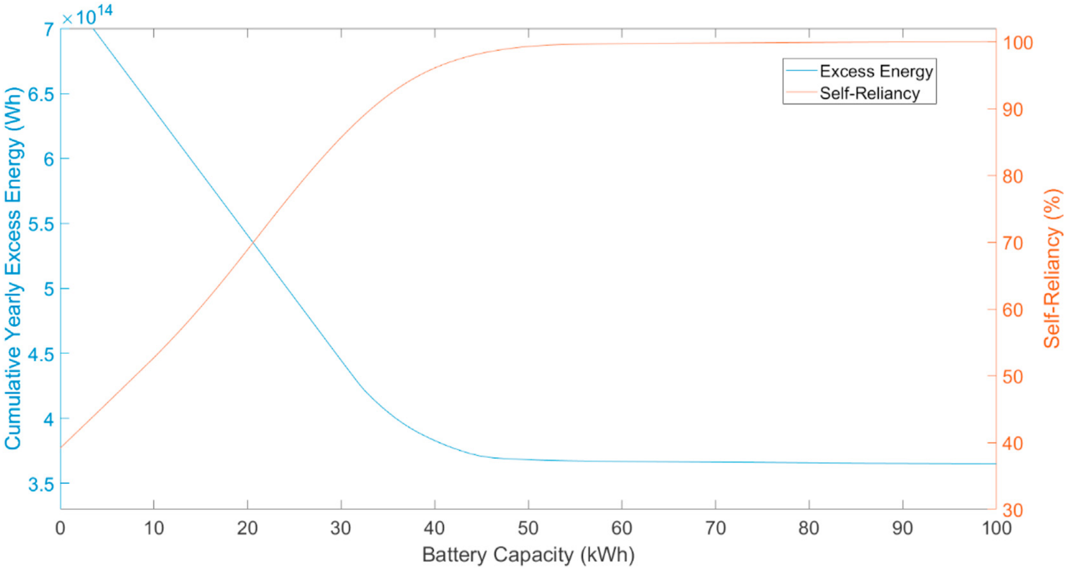

Fig. 9. Effect on the self-reliance and cumulative excess energy when varying the battery capacity of the EVs.

likely to occur and 3) technically feasible and likely to occur.

There is only one assumption that is technically unrealistic, category 1, namely instant charging and discharging of EV batteries This assumption was made to simplify the simulation. However, state-of-the-art EVs can handle power rates of more than 200 kW of charging and discharging. Accumulating 200 kW over the 29.4 million EVs used in this study provides a power rate of 5.9 TW. The maximum energy load for Spain (industry plus household) is around 1×10^{11} Wh per hour, see Figs. 6 and 7, which equals 0.1 TW. Consequently, the cumulative capacity of EV batteries can easily supply the maximum power needed to operate Spain, even if the V2G connection had a power output of only 10 kW per vehicle. Furthermore, with 200 kW charging power, a 100 kWh EV battery can be fully charged in 27 min (a minimum SOC of 10% is assumed in this study). With 90 kWh net battery capacity and an energy demand of 0.224 kWh per km, the EV would then have a range of 402 km. Very rarely is this long range required, and the charging durations will normally be much shorter than 27 min. Most cars that are parked during daytime when PV power is available are stationary for more than half an hour (for example at work or when shopping), and should therefore be able to acquire the charge needed. Parked cars at home can easily both feed power to the grid or be charged from the grid when needed. Accordingly, the instant charging and discharging assumption is reasonable to make but more importantly, does not alter the conclusions of the paper.

Category 2 assumptions are: a) every EV is connected to a V2G point whenever parked and b) having no other energy source besides PV. Assumption a) is undeniably unpractical but not impossible to achieve. A future study should look into what percentage of parked cars actually need to be connected, and what power rate on the V2G connection actually would be required. Another solution would be to use wireless power transfer (WPT) technologies to charge moving cars. WPT is expected to play a significant role in the electrification of the transport sector [35]. Assumption b) is clearly feasible, but it will be challenging to install 3.45 billion m^2 or 73 m^2 of PV area per person in Spain. According to OECD statistics, the built-up area of Spain in 2014 was 8.4 billion m^2 or 179.2 m^2 per capita, corresponding to 1.6% of the country's land area [36]. The suitable area for PV installations on buildings can be estimated using the method developed by IEA PVPS Task 7, where the so-called solar-architectural suitable area is determined from the ground floor area and rule-of-thumb utilization factors [37]. Based on a number of case studies performed in the IEA member countries rule-of-thumb values for the solar-architectural utilization factors were determined to $u_r = 0.4$ (roofs) and $u_f = 0.15$ (facades) [37]. Using this methodology, the total solar-architectural area in Spain is 3.35 billion m^2 on roofs and 1.26 billion m^2 on facades. Though, it should be noted that the definition of the built-up area according to OECD is not identical with IEA PVPS Task 7 use of ground floor area. But the conclusion is that, it would be theoretically possible to fit the required PV area solely on the built-up area in Spain. However, it is more realistic is to also include free-standing grid-connected PV systems, which already today are common in Spain. Spain had by the end of 2019 installed 8.7 GW_p of cumulative grid-connected PV [38]. These 8.7 GW_p of PV will on average have a much lower efficiency than what is used in this study. Assuming an average efficiency of 17%, then the 8.7 GW_p will be equivalent to about 0.5 billion m^2.

Category 3 assumptions are: a) all road going transport is electrified and b) all road going EVs have the same battery capacity in kWh. Assumption a) is not attainable in the short term but should, and actually have to be, realized in the long run in order to combat global climate change. Already today, EVs are so mature that they can substitute most means of transportation except long-distance boat and air traffic. For the latter two, the most realistic solution would be a mix between using hydrogen fuel cells and batteries. Assumption b) is not realistic when studying vehicles on an individual level, but since the simulation looks at an entire country it makes more sense to look at an average EV battery capacity. In reality, heavy-duty EV vehicles will have much larger battery capacities and many personal vehicles will have smaller battery capacities. However, for the purpose of the study this discrepancy is negligible, especially since the percentage of medium to heavy-duty vehicles is only 2% of the entire fleet. In addition, various battery sizes have been studied in this paper and Fig. 9 shows clearly that a very high self-reliance can be achieved even though the average EV battery size is substantially less than 100 kWh. Modern Li-ion EV batteries are expected to last longer than the expected lifetime of the car itself. In addition, second hand EV batteries can be and are presently used for stationary energy storage purposes. However, it is clear that the lifetime of the EV batteries will be reduced if they are used to a large extent for grid support. How large or small effect the V2G usage will have on the EV battery lifetime and cycle expectancy is unknown. There is no empirical research done on this topic yet. However, the degradation could be simulated, but that is also a matter for a future paper.

Lastly, it should be emphasized that the proposed energy system is resilient and democratic. Having an electric power system consisting of millions of separate units that can both deliver and store energy provides redundancy and makes the system resilient to disturbances in the grid [39,40]. This energy system also becomes democratic since most of us will take part in it [41]. PV systems and EVs will literally be household names in the near future.

5. Conclusion

The visionary conceptual study presented here shows that it is indeed theoretically possible to power a complete country like Spain solely by the use of photovoltaics (PV), and to balance the intermittency solely by using the battery capacity of a fully electric transport system and V2G technology. Surplus energy from PV generation is stored in electric vehicle (EV) batteries. The same batteries power Spain's energy demand during times with low availability of solar energy, e.g. during the night. The study shows that 100% self-reliance can be achieved for Spain when having 3.45 billion m^2 of PV (73 m^2 per capita), and in combination with 29.4 million electric vehicles. The system can also provide a very high self-reliance even at much lower installed PV capacities. For example, if the installed PV capacity is reduced to 2 billion m^2 (43 m^2 per capita), the self-reliance is still 79%. Combine this amount of PV with additions of wind and hydro power and Spain could have a very attractive energy system. However, this remains a study for a future paper. The authors hope that the presented research will encourage stakeholders to look in new directions when designing the future energy systems.

CRediT authorship contribution statement

Tobias Boström: Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision, Funding acquisition. **Bilal Babar:** Writing – original draft, Data curation, Software. **Jonas Berg Hansen:** Software, Visualization, Formal analysis, Investigation. **Clara Good:** Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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