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A Case Study on Electric Vehicles as Nationwide Battery Storage to Meet Slovenia's Final Energy Consumption with Solar Energy

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Abstract: Despite the global importance of solar energy, its variability requires energy storage to balance production during peak and off-peak periods. Moreover, the transport sector is undergoing a global transition from internal combustion engines to electric vehicles. Since vehicles are idle 95% of the time, electric vehicle batteries, when connected to a grid, can effectively regulate intermittent photovoltaics using vehicle-to-grid technology. This conceptual study investigates the feasibility of a nationwide energy infrastructure that relies solely on solar energy, replacing other electricity sources, such as solid fuels, petroleum products, and natural gas, and utilizes electric vehicles as the sole battery energy storage system. This study aims to demonstrate the significant potential and benefits of such collaboration. The theoretical study combines historical data, assumptions, and conditions to build a simulation model that is modelled similarly as in previous conceptual studies of nationwide energy systems based solely on photovoltaics and electric vehicles, referenced in this article. In Slovenia, the total surface size suitable for the installation of photovoltaic systems is estimated to be 280 km^2. The calculations show that a surface size of 217 km^2 for photovoltaic systems can produce enough energy to cover Slovenia's entire energy demand, Slovenia's final energy consumption. However, simulations comparing photovoltaic production, total energy consumption (electricity, solid fuels, etc.), and the capacity of electric vehicle batteries show that a surface size of more than 500 km^2 with photovoltaic systems and a 200% share of electric vehicles in the Slovenian vehicle fleet in 2022 will provide satisfactory results. Therefore, for a country like Slovenia, in addition to a solar power plant with a surface size of 280 km^2, additional renewable energy sources are needed to cover the total energy demand, as well as additional battery energy storage systems in addition to electric vehicles.

Keywords: electric vehicles; photovoltaics; vehicle-to-everything (V2X); vehicle-to-grid (V2G); final energy consumption; renewable energy sources; electricity demand; quality of life

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1. Introduction

The electrification of mobility is one of the biggest changes in transport. Recently, the number of electric vehicles (EVs) has increased significantly, and this trend is expected to continue [1]. Some reasons for this may lie in new legislation and countries committing to reducing greenhouse gas (GHG) emissions and improving quality of life. The share of transport-related GHG gas emissions in the European Union (EU) was estimated to be approximately 23% in 2020 [1]. Another reason could be that drivers want to reduce their environmental impact and are therefore switching from vehicles with internal combustion engines to EVs.

An important change in the transport sector is that vehicle technologies have developed rapidly in recent years. One of these promising new technologies is vehicle-to-grid (V2G) technology. V2G technology refers to a system in which some types of EVs can feed electricity back into the grid in addition to charging [2]. These new technologies have the potential to transform EVs from an additional burden on the grid into a problem solver if used correctly.

Slovenia is one of the countries committed to reducing GHG emissions. The commitments are based on documents adopted at the EU level. One of the pillars is the European Green Deal [3,4], which was adopted by the European Commission. Under this deal, the EU aims for its economy to achieve net-zero emissions by 2050 and supports a comprehensive environmental protection policy. Within this policy framework, three types of commitments are made:

- phasing out coal, and thus solid fuels as an energy source;
- improving energy efficiency;
- increasing the share of renewable energy sources (RESs) in the energy mix.

As far as energy efficiency is concerned, the obligations arise from two pieces of legislation. First, Directive 2012/27/EU on energy efficiency [4,5] set a target of 20% energy efficiency for 2020. Second, an energy efficiency target of at least 32.5% has been set for 2030 [4,6].

To increase the role of RESs in the energy mix, the European Council has set the target that at least 27% of the final energy consumption (FEC) should come from RESs by 2030 [7,8]. Among the defined RESs, solar energy stands out for its extraordinary theoretical potential to meet the global energy demand [9]. Due to an astonishing annual growth of 30% in photovoltaic (PV) installations between 2011 and 2021 [10], if this trend continues, solar energy will account for 45% of electricity production in 2050 [11]. Because solar energy is simple and promising, this study focuses on it. The inclusion of other RESs in the energy mix could be an extension of this work, a new separate study.

Nevertheless, PV production is not without its problems. These include periods without production at night and possible overproduction during some periods of the day. To control unpredictable production, one possible approach is to integrate energy storage systems (ESSs) into the power grid. The implementation of an ESS depends on its technical characteristics, implementation location, electrical energy source (conventional or renewable energy type), and associated costs. An overview of the latest developments in the field of ESSs can be found in [12]. One subgroup, battery energy storage systems (BESSs), has emerged as one of the main players in this field. The latest techniques for the sizing, placement, and management of individual and shared BESSs in residential areas are presented in [13].

If we narrow down the type of storage even further, EVs present a promising solution, as they can be considered batteries on wheels. The idea of using EVs as BESSs to balance supply and demand is interesting and continues to be explored. This approach is very interesting due to the efficiency of modern lithium ion batteries, which reaches approximately 90% [14]. Additionally, a significant share of vehicles are idling; on average, a vehicle is stationary approximately 95% of the time [15]. During this time, EVs could be used as BESSs.

There are significant research efforts toward the use of EVs for the storage of solar energy. The concepts, advantages, capacity allocation methods and algorithms, and control strategies of integrating EV charging stations with PVs are investigated in [16], and the integration of PVs into EVs is considered in [17], where the development, benefits, and challenges associated with solar-powered vehicles, and vehicles with integrated PV systems, are addressed.

In this study, a Python, version 3.11., program model is used to simulate a system in which EVs using V2G technology are used as the only BESS to store excess PV production. The simulations are performed using different shares of EVs and different PV surface sizes. At each step, i.e., every hour, the PV production and the total FEC are compared. In cases where the production of the PV system exceeds the demand, the overproduced energy is stored in the batteries of the EVs. If energy is left over, then this is considered a system failure and is referred to as energy loss. Conversely, if PV production is not sufficient to meet demand, then the energy produced by PVs and stored in the EVs' batteries is used as an additional source. If demand still cannot be met, then this is categorized as a system failure and referred to as a failure to supply the demanded load. In this model, EVs are only charged when there is an overproduction of energy and solar energy is the only energy source in the system. The stored energy is fed back into the system in times of under- or non-production to cover the entire energy demand at the national level, i.e., in Slovenia. When a system produces all the required energy to meet the system's demand solely from PV and uses the batteries of the EVs as the only storage system, it is also referred to as a pure PV-EV system [18] (Figure 1).

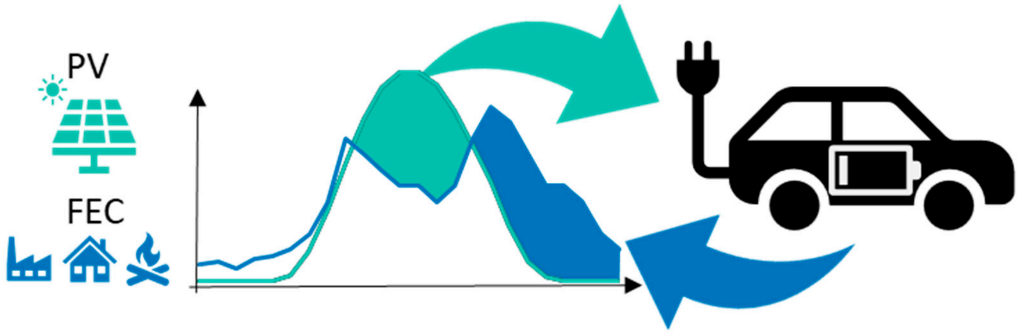

Figure 1. Using electric vehicles as battery storage system to store photovoltaic overproduction and to cover needs for energy in times of underproduction.

2. Related Work and Motivation

Pure PV-EV systems have not yet been used in practice. To the best of our knowledge, there are only a few theoretical studies [18,19]. The study in [18] outlines a hypothetical scenario in which the entire energy demand of Spain is covered exclusively by PV production and EVs serve as a storage solution. The conclusion of [18] is that a country such as Spain could meet its energy needs through solar energy and EVs as the only ESS.

In comparison, this case study for Slovenia is focused more on the worst-case scenario. It is restricted to personal vehicles and thus reduces the size of the BESS capacity (Table 1). In addition, the losses of energy transmission, from production facilities to end users, and conversion between different types of energy are considered.

Another narrower limitation is the application of the case study to Slovenia, a small country in central Europe. It has diverse landscapes, including the Julian Alps, the Pannonian Plain, and the Mediterranean coast. The country has a latitude between 45.1 and 46.8 degrees north. Temperatures and solar radiation vary from region to region or from city to city [20]. Slovenia has an average annual PV yield lower than that of Spain, which pushes this case study further towards the worst-case scenario (Table 1).

There are also advantages to studying a pure PV-EV system in Slovenia. One of them is the availability of statistical data on various aspects of public life. These data include data on transport, total energy production and consumption, the frequency of sunny days, and hours of sunshine for specific regions, among other factors relevant to this study.

The input data, data sources, and modeling of inputs for this study and [18] are listed in Table 1. The similarities between them are mainly in PV production modeling. Both studies use the same source and similar methods to determine PV production per hour of the year. The other two important inputs, FEC and EVs, are modeled differently and are based on different input data. An important difference in the case of EVs is that working and non-working days are being distinguished when modeling driver profiles, and only personal vehicles are considered, whereas in the case study for Spain, personal and commercial vehicles are considered, and all days are treated equally.

In the case of the FEC, losses due to transmission and energy conversion are also considered. The demand for the FEC was modeled separately for different energy sources, electricity, solid fuels, petroleum products, and natural gas, in hourly intervals and then added together. In the case study for Spain, the FEC is split by month and then tailored to different usage profiles, industries, and households.

Table 1. How the input data are obtained, modeled, or calculated in [18] and in this study. Extensions, tighter limitations, and inputs that are modeled on real historical data are presented in bold.

	T. Boström et al. [18]	**This Study**
PV production		
Source	PVGIS [21]	PVGIS [21]
Points	35 locations across Spain.	5 locations across Slovenia.
Input data	22.5% efficiency on PV panels, standard system loss factor of 14%, panels angle of 35 degrees.	22.5% efficiency on PV panels, standard system loss factor of 14%, panels angle of 32 degrees.
Annual yield	Calculated, 365 kWh/m^2.	**Calculated, 237 kWh/m^2.**
EVs		
Vehicles used for model	Personal and commercial vehicles.	**Only personal vehicles.**
Number of parked EVs	Is modeled by inverting the driving pattern.	Modeled by inverting the driving pattern.
Kilometers driven per trip, per day	Not possible to obtain for Spain, and the results from a large-scale study on European transport data were used to approximate.	**Data** on the length, number, and duration of trips for Slovenia **are available.**
Consumption of EVs	Using a weight of 98% for all personal and light commercial vehicles and 2% for medium to heavy-duty commercial vehicles.	Obtained **from database** [22].
Driving patterns	Synthetic driving patterns were generated, using log-normal distributions.	**Data on** the length, number, and duration of trips for Slovenia **are available**. In the model, **work and non-workdays are considered.**
FEC		
Total energy demand	Approximated by average annual FEC for years between 2014 and 2018.	Value of FEC in 2022 **plus losses** due to transmission and conversions, and without RESs.
Modeling of FEC	A monthly distribution pattern of net electricity production was used to create a monthly distribution of FEC.	**Each of the different energy sources** is **modeled separately**, for example, hourly electricity demand is based on the distribution of consumption of energy consumption in industry, while consumption of households is modeled depending on temperature.
Load	Industrial load presenting 40% and households presenting 18% of FEC were modeled according to the model proposed by Sandels, Widén.	Household load is modeled separately for different energy sources and was based on assumptions that the majority is used for heating, so modeling was based on temperature. Industry load is modeled according to electricity consumption.

If we take everything into account, the aim of verifying the feasibility of a pure PV-EV system for Slovenia is to use a model similar to that presented in [18], extended based on historical data, lower storage capacity, lower PV production, and demand including losses. If the pure PV-EV system proves to be feasible for Slovenia, then the threshold can be moved even further in the next study; if not, then the threshold can be sought between the Slovenian and Spanish cases.

Another motivation for conducting this study is to suggest and investigate one of the possible ways in which Slovenia can fulfil its commitments to reduce GHG emissions. The results of this study could serve as a signal for the directing future plans for Slovenia's transition to reduce GHG.

This section concludes with a description of the structure of the paper. The introduction presents the key concept of the paper, namely a pure PV-EV system (Figure 1), a literature review, and an indication of the rationale for this study and how it differs from similar studies. Section 3 provides an overview of the simulation methods and modeling of the inputs, followed by the results in Section 4. The results are discussed in Section 5 and the conclusions are drawn in Section 6.

3. Materials and Methods

When creating the model, the data for PV production rely on the data from PVGIS [21]. The data from the report of the Slovenian Ministry of Infrastructure [23] and the Statistical Office of the Republic of Slovenia (SiStat) [24] are used for modeling energy consumption. SiStat is also the source of data on vehicles, their mileage, usage times, etc.

This model is based on the following main assumptions:

- The first is that all electricity, and consequently all energy, is produced by PVs.
- All EVs are V2G-capable, and their batteries are used to store overproduction and meet energy demand. The share of EVs in the Slovenian fleet of personal vehicles is a variable and simulations with different shares of EVs in the personal vehicle fleet are performed.
- Another important assumption is that all EVs are always connected to charging stations (CSs) and consequently to the grid when they are not used for driving. This assumption is not realistic, as the ratio of EVs to CSs needs to be one to one, but serves as a best case.

3.1. Modeling PV Production

As mentioned, the data on PV production in Slovenia are taken from the PVGIS database [21], the 'PVGIS-SARAH2'. The PV technology used is crystalline silicon cells with an inclination of 32 degrees and an azimuth of −5 degrees, which are optimal values for Slovenia [25].

Slovenia is geographically and climatically very diverse. Therefore, the input for PV production is calculated as an average of five points across Slovenia, each representing a specific terrain and climate. These include Murska Sobota with lowlands and a continental climate, Brežice with hills and a continental climate, Ljubljana at the border of all three climate zones, Jesenice, a city in the Alps with an alpine climate, and the coastal city of Koper with a Mediterranean climate (Figure 2).

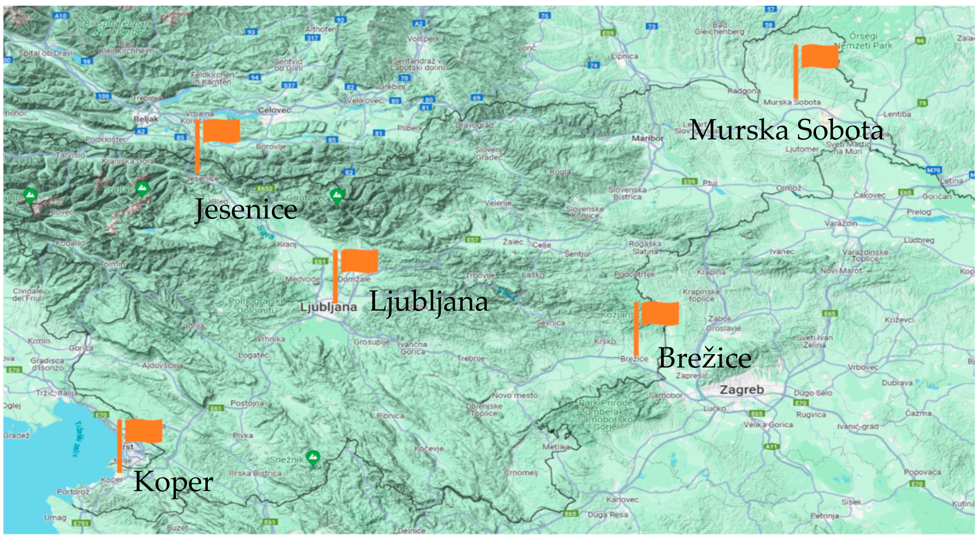

Figure 2. Relief map of Slovenia with marked locations for calculating the average irradiance.

The PVGIS database provides different types of data. For our model, the average monthly irradiance per hour is used. These data show the irradiance for each hour of the day as an average for a given month, as presented in Figure 3.

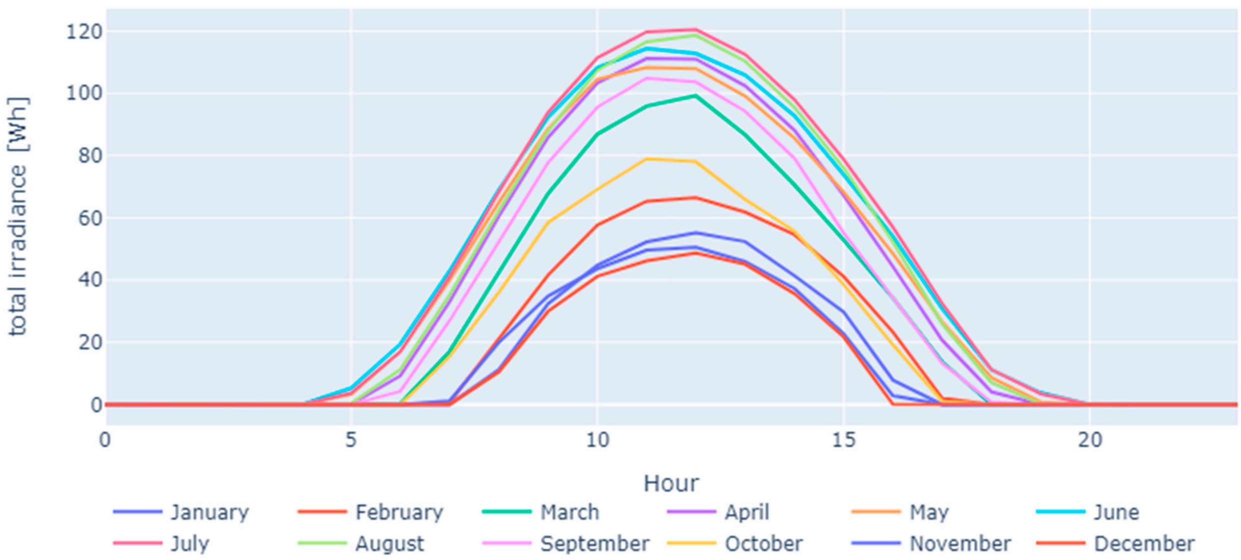

Figure 3. Average irradiance on a surface of 1 m^2.

The total annual yield for the irradiance on a surface size of 1 m^2 is 237 kWh, which is approximately 19% of the given average value for Slovenia of 1242 kWh/m^2 [26]. This also agrees with the input data. The data from PVGIS are for PV panels with 20.5% efficiency.

To compare the results obtained from the simulations, the total surface size of PV installations in Slovenia and the estimation of the maximum possible surface size are needed, in addition to the data mentioned above. The data on the current PV surface size are not available for Slovenia. Information on PV systems is given as peak power. The total Slovenian peak power of installed PVs in 2022 was 631.9 MWp. To estimate the surface size, an example panel on the market with a peak power of 400 Wp and a surface size of 1.95 m^2 [27] was used. The estimated result is a surface size of 3.08 km^2 of installed PVs in 2022. Another view on the matter is the estimation that in Slovenia, 280 km^2 of surfaces, such as rooftops, parking lots, etc., are suitable for the installation of PVs [25].

3.2. Modeling EVs

The number of EVs connected to the grid at certain times of the day and the consumption of EVs per hour are needed for simulation. This information is necessary to calculate the possible storage capacity for each hour of the simulation and to include the energy consumed by the EVs in the energy demand.

The input data for EVs are based on data available for personal vehicles, i.e., cars of all engine types [24]. Since the input data for PVs are provided with a granularity of 1 h, the input data for EVs are also structured hourly.

Initially, the focus is on determining the number or share of personal vehicles on the road at a given time of day. These numbers are used to calculate the consumption of EVs at a given hour. A distinction is made between working days and non-working days. The numbers of EVs on the road are determined from the values for trips that started at a specific time of day. These data are displayed cumulatively for all mobility types, including personal vehicles, buses, trains, etc. [24]. The total number of trips per day for each mobility type is available in [24]. It is assumed that all trips end at the same hour at which they begin. The values obtained in this way indicate the number of personal vehicles on the road at a given hour.

To obtain the figures for the parked personal vehicles shown in Figure 4, the figures for the EVs on the road are subtracted from the total number of EVs. In Slovenia, in 2022 there were 1,207,755 personal vehicles. The total number of EVs is not fixed in our simulations but represents the share of the Slovenian personal vehicle fleet in the year 2022.

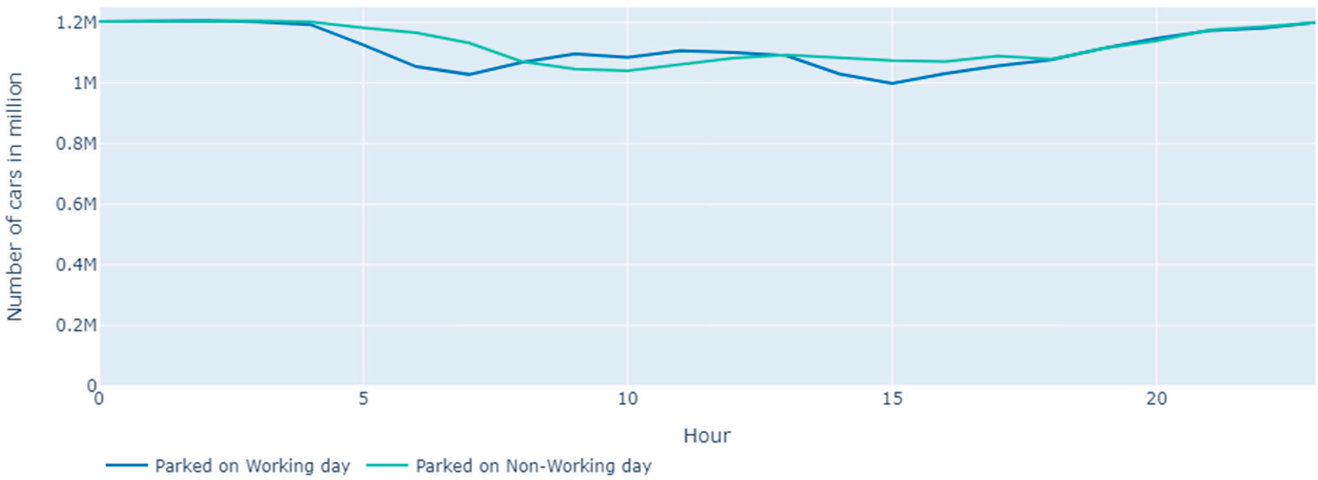

Figure 4. Number of parked EVs at a given hour of the day, shown for weekdays and non-working days.

Figure 4 shows that, as expected, the number of parked personal vehicles is highest at night. On working days, two drops can be observed, the first at 7 a.m. and the second at 3 p.m. On non-working days, the drop can be observed at 10 a.m. The number of EVs on the road is not shown, as it is merely an inverted representation of Figure 4.

The main purpose of EVs is to get around; they are primarily used for driving and not as batteries for the storage of excess PV production. The average value for the energy consumption of EVs is 195 Wh/km [22] at the time of the simulation. Considering the average length of a trip [24] and public holidays and weekends in Slovenia in 2022, an EV consumes 3076 kWh in one year. The yearly energy consumption of EVs, if the Slovenian personal vehicle fleet were 100% electric, would be 3715 GWh.

3.3. Modeling Energy Consumption

The primary interest of this study is whether a pure PV-EV system can cover the entire energy demand of Slovenia. To determine this, PV production and total FEC are compared. For this article, the term total FEC is used to describe the FEC as defined by Eurostat [28] adding the losses in energy transmission, from production facilities to end users, and energy conversion processes and excluding the consumption of energy from RESs.

The FEC, according to Eurostat's definition, in Slovenia in 2022 was 55,936 GWh, and the total FEC, also accounting for losses, was 58,463 GWh. In addition, RESs accounted for 6746 GWh [24]. For simulations, the consumption of energy for each hour of the year needs to be modeled. The consumption of each of the main types of energy, electricity, solid fuels, petroleum products, and natural gas is modeled separately. The consumptions of different energy types for each hour of the year are then added together, as presented in Figure 5.

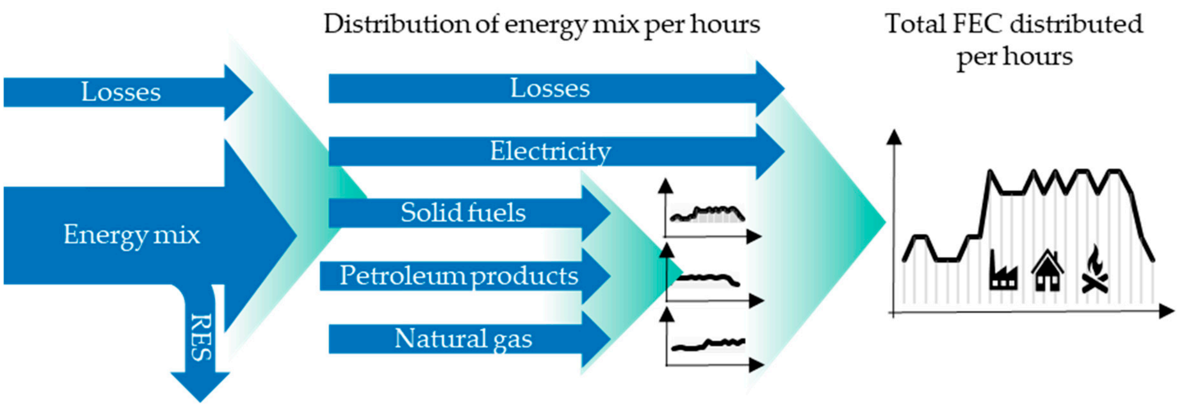

Figure 5. Modeling total FEC in Slovenian case study of the pure PV-EV system.

Hourly electricity consumption is modeled based on the hourly electricity volumes accepted by the Slovenian Transmission System Operator (TSO) [29]. These consumptions are scaled so that the final annual total corresponds to the FEC plus losses, which was 15,061 GWh in 2022 [24].

In 2022, most solid fuels in Slovenia were converted to other energy types. A total of 6246 GWh were used for pure electricity production and 2075 GWh were used in plants to produce electricity and heat. Only 394 GWh were consumed by end consumers, mainly in industry; the share of household consumption is negligible [24]. The energy consumed for manufacturing is divided into the same parts as electricity, as described in the previous paragraph.

The quantities for electricity production are omitted from the modeling because they are already included in the modeling of electricity consumption. In electricity and heat production, approximately 3/4 of the energy generated was heat [30]. Further, 3/4 of 2075 GWh was distributed according to the temperatures measured in Ljubljana in 2022 at 7 a.m., 2 p.m., and 9 p.m., with the lower temperature accounting for a larger share [31].

The final consumption of petroleum products totaled 26,291 GWh, of which 21,722 GWh or 83% was used for transport. Industry and households each consumed approximately 5% of the total [24]. The energy consumed by personal vehicles needs to be subtracted from the total consumption for transport, as these are modeled separately. The share of petrol for personal vehicles was 17.4%, with the assumption that the share of volume equals the share of energy consumed. No data on how energy consumption in the transport sector is broken down further are found; for this reason, it is spread evenly across all hours of the day. Petroleum products consumed by households and industry are modeled in the same way as solid fuels.

In 2022, 6523 GWh of energy was consumed from natural gas. Approximately 60%, i.e., 4673 GWh, is accounted for by industry. The second largest consumers were households with 14% or 1165 GWh [24]. The natural gas consumption of households and industry is modeled in the same way as that of solid fuels.

Figure 6 shows the total FEC per hour of the day. The average value for each hour is marked, and the average electricity consumption per hour and its upscaled values are added for comparison. We see that the average values for total FEC and scaled electricity consumption show similar trends, with the lowest values occurring at night and two peaks occurring during the day.

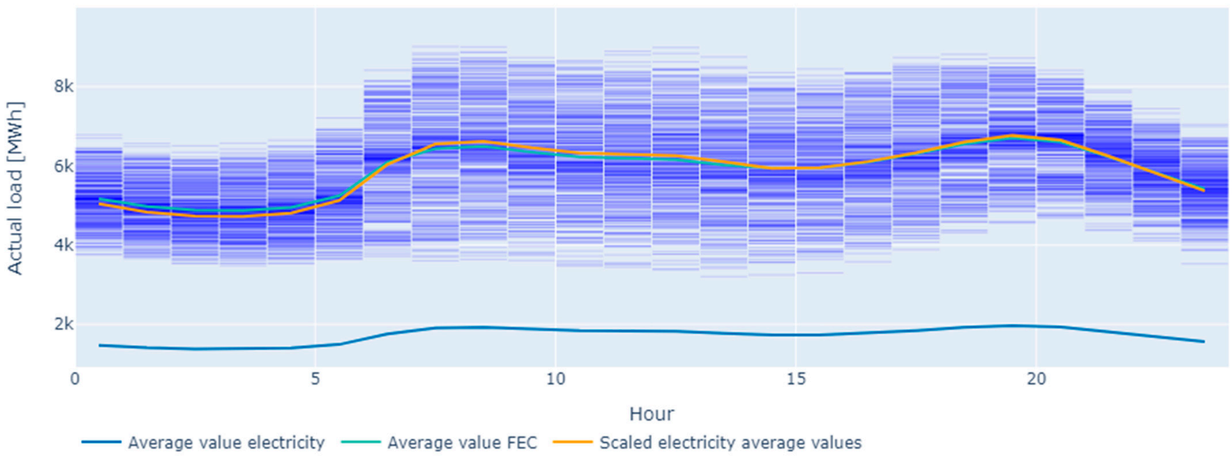

Figure 6. Distribution of total FEC per hour of the year.

3.4. Modeling Pure PV-EV System

The simulation is based on the algorithm for the pure PV-EV system (Figure 7). In this section, the algorithm is presented and the corresponding equations are described. In the presented algorithm and equations, new acronyms are introduced. For easier presentation, acronyms for quantities and their names and descriptions are presented in Table 2.

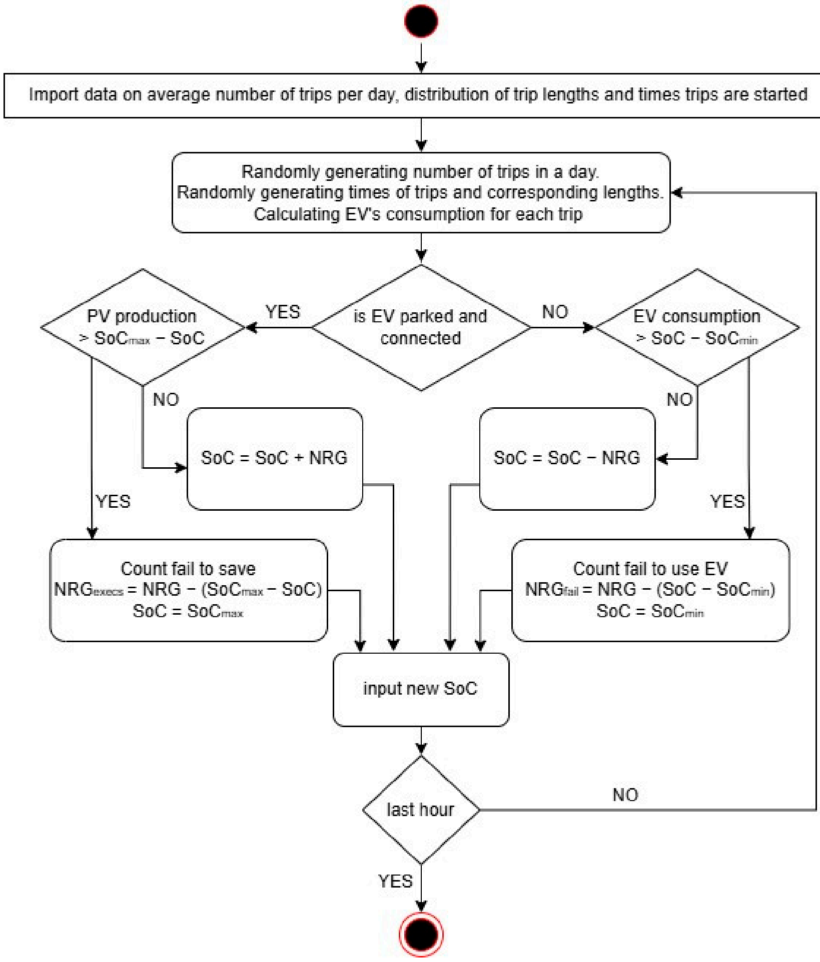

Figure 7. Algorithm to simulate pure PV-EV system.

Table 2. Acronyms for quantities occurring in the algorithm and equations.

Acronym	Name	Description
SoC	State of Charge	Quantity is presented as a percentage. When *SoC* is presented without a subscript, it represents the initial *SoC*, that is, the *SoC* of the current step in the iteration. *SoC* with the subscript max represents an upper limit set for *SoC*, and *SoC* with the subscript min represents a lower limit set for *SoC*.
NRG	Energy	When *NRG* is presented without a subscript, it represents overproduction, that is, a difference between production and consumption. *NRG* with the subscript total represents energy stored in batteries in the current step in the iteration. *NRG* with the subscript charg represents energy EVs received with charging, and the subscript cons represents energy used by EVs for driving.
DMND	Demand	*DMND* represents additional demand for energy, that is, a difference between consumption and production.
N	Number	When written with the subscript EVP, it represents the number of parked and connected EVs, and when written with the subscript EVR, it represents the number of EVs on the road.
PV	Photovoltaic	Represents PV production, either written without a subscript, as in the algorithm, or with the subscript prod, as in the equation.
Load	Total FEC	Represents the total FEC of the current step in the iteration.
l	Length	Represents length of the trip.
t	Time	Represents time or the current step in the iteration.

The simulation of the pure PV-EV system runs different shares of EVs and different PV surface sizes. At the beginning of the simulation, prepared data on PV production, total FEC, and the number of EVs connected to CSs and driving are imported. The consumption of the EVs, total energy stored in batteries, and the average state of charge (SoC) are calculated. For each step, i.e., every hour, the PV production and the total FEC are compared. The energy produced by the PV system is primarily used to cover the total FEC. In cases where the production of the PV system exceeds the demand, the overproduction of energy is stored in the batteries of the EVs. In the simulated system, the EVs are only charged when an overproduction of energy is produced. If energy is left over, then this is considered a system failure and is referred to as energy loss.

Conversely, if PV production is not sufficient to meet demand, then the energy from the EVs batteries is used as an additional source. If demand still cannot be met, then this is categorized as a system failure and referred to as an inability to supply the demanded load. In the context of EVs, restrictions are imposed such that they cannot be charged or discharged above or below certain limits of SoC. The algorithm of the model is shown in Figure 7.

As mentioned above, data are imported and the quantities of interest—the current average SoC and the total EV battery capacity—are calculated. For the first step, we assume an SoC of 50% and calculate the total capacity of the EV batteries according to Equation (1):

$$NRG_{total}(t=1) = SoC(t=1) \times N_{EVP}(t=1) \times 69\ \text{kWh}, \quad (1)$$

where $NRG_{total}(t=1)$ is the total capacity of the EV batteries at the first iteration, $SoC(t=1)$ is the SoC at the first iteration, which has a value of 0.5, N_{EVP} is the number of parked and connected EVs in the first iteration, and 69 kWh is the average EV battery capacity at the time the simulations were conducted [22]. In each step, the capacity of all EV batteries in the next step, $NRG_{total}(t+1)$, and the corresponding $SoC(t+1)$, are calculated using Equations (2) and (3):

$$NRG_{total}(t+1) = NRG_{total}(t) + PV_{prod}(t) - Load(t) + NRG_{charg}(t) - NRG_{cons}(t), \quad (2)$$

$$SoC(t+1) = {NRG_{total}(t+1)}\Big/{N_{EVP}(t+1) \times 69\ \text{kWh}}', \quad (3)$$

where $NRG_{total}(t+1)$ is the capacity of all EV batteries in the next step, $PV_{prod}(t)$ is the energy produced by the PV at time t, $Load(t)$ is the total FEC at time t, $NRG_{charg}(t)$ is the energy received by the EVs from charging at time t, and $NRG_{cons}(t)$ is the energy consumed by the EVs for driving at time t, calculated as presented in Equation (4). If the calculated values for the SoC are either greater or less than the specified limits determined for each simulation, then the SoC value is set to these values accordingly and this time interval is recorded as a system failure.

The energy consumed for driving at time t, $NRG_{cons}(t)$, is calculated using Equation (4):

$$NRG_{cons}(t) = N_{EVR}(t) \times 195^{\text{Wh}}/_{\text{km}} \times l_{trip}, \quad (4)$$

where $N_{EVR}(t)$ is the number of EVs on the road at time t, 195 Wh/km is the average value for the energy consumption of EVs [22] and l_{trip} is the average length of a personal vehicle trip, which is 15.6 km/trip and 17.95 km/trip for a working day and a non-working day, respectively [24].

In the end, a pure PV-EV system that only covers electricity consumption is simulated. The procedures are the same as those for the total FEC, except that the total FEC is replaced with the electricity consumption at every point where the total FEC is mentioned.

4. Results

In this section, some results of the case study simulations are presented. At the start, the results of the simulation of a pure PV-EV system are presented, and the section concludes with the results of a simulation in which the pure PV-EV system only covers the electricity demand of Slovenia.

4.1. Results for the Simulation of a Pure PV-EV System Covering the Total FEC

The simulations for the pure PV-EV system are performed according to the algorithm in Figure 7. The only constant in the simulation is the total FEC. The other variables are simulated with different values:

- For the number of EVs, simulations are run with values ranging from 10% to 200% of the total number of personal vehicles in Slovenia in 2022.
- For the SoC limit, 10%, 20%, and 30% as the lower limits and 70%, 80%, and 90% as the upper limits are used.
- For the surface size of the PV panels, a simulation from 0 to 700 km^2 is performed.

The calculations show that the average annual production of 217 km^2 of PV panels in Slovenia corresponds to the total annual consumption of the total FEC and of EVs. This theoretical result is tested on a model of a pure PV-EV system with a surface size of 217 km^2 and a 100% share of EVs.

Figure 8 shows that the theoretical result for a surface size of 217 km^2 does not fulfil the requirements for a pure PV-EV system. After running the simulations multiple times—1000 times in the case presented here—the average value for the number of times the system fails to provide the energy needed to cover the total FEC consumption is 5,645, or 64%, and the average number of times when energy cannot be saved is 1,189, or 14%. This means that in 78% of the hour intervals, we either fail to provide energy to cover the total FEC demand or fail to store overproduction. In the case of EV usage, the average value for the number of failed trips is 129, or 1%. The results for SoC limits of 20% and 80% are described.

From the analysis of Figure 8, diagram (a), we can see that failures in the storage of overproduced energy occur from February to November. On the other hand, failures in the provision of sufficient energy to meet energy demand and in the use of EVs, because the batteries do not contain enough energy, occur all year round.

Diagrams (b) and (c) show situations that frequently occur in winter and summer. Diagram (b) shows a close-up of the simulation for 6 January, one of the days with the lowest PV production, on which various types of failures occur.

The hours in which the energy demand cannot be met are shown by blue dots. On most winter days, the energy demand is only covered during the short periods of overproduction and up to two hours afterward. Diagram (b) also shows a case in which there is not enough energy available for the use of EVs. This is shown by a black dot.

Diagram (c) shows a close-up of the simulation for 28 July, the day with the highest PV production. The cases in which the surplus energy produced cannot be stored are visible. They are shown by red dots. On most summer days, the same thing happens, namely that the system cannot store any energy in the last hours of overproduction. On the other hand, the energy demand is covered throughout the day.

Figure 9 shows the simulation results for a pure PV-EV system where the surface size of the PV panels varies from 200 to 700 km^2, the SoC limits are 20% and 80%, and the share of EVs is given for seven different values between 80% and 200%. Figure 9 also shows that as the size of the PV surface increases, the number of failures in meeting energy demand (shown in red) decreases, and the number of failures in energy storage (shown in green) increases, as expected. In addition, a larger share of EVs have smaller failure rates. Furthermore, in Figure 9 we can analyze the intersections between the red line for failures to meet demand and the green line for energy storage failures, which correspond to the same share of EVs. We refer to these intersections as balance points. The observed trend for the balance points is that with a larger share of EVs, they move towards smaller values for PV surface size and the number of failures decreases.

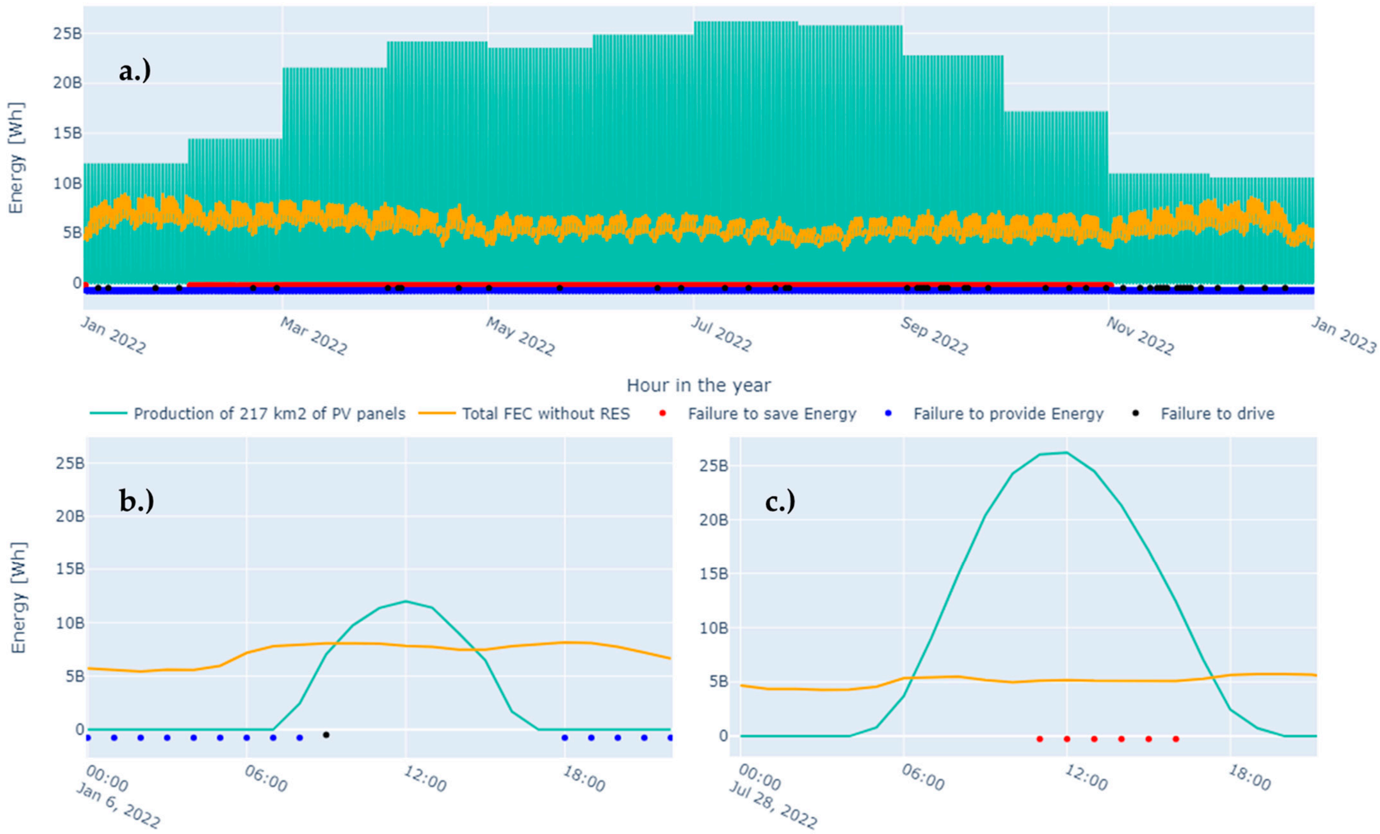

Figure 8. Results of the simulation of a pure PV-EV system with a surface size of 217 km^2 and a share of 100% of EVs, with limit values of 20% and 80% for the SoC of the EV batteries. The diagrams show the PV production and the total FEC. In addition, the hours when failures occur are marked with colored dots. (**a**) The diagram for the entire year of 2022 with a PV panel surface size of 217 km^2 and a share of 100% EVs is shown. (**b**) Close-up of the simulation for 6 January. (**c**) Close-up of the simulation for 28 July.

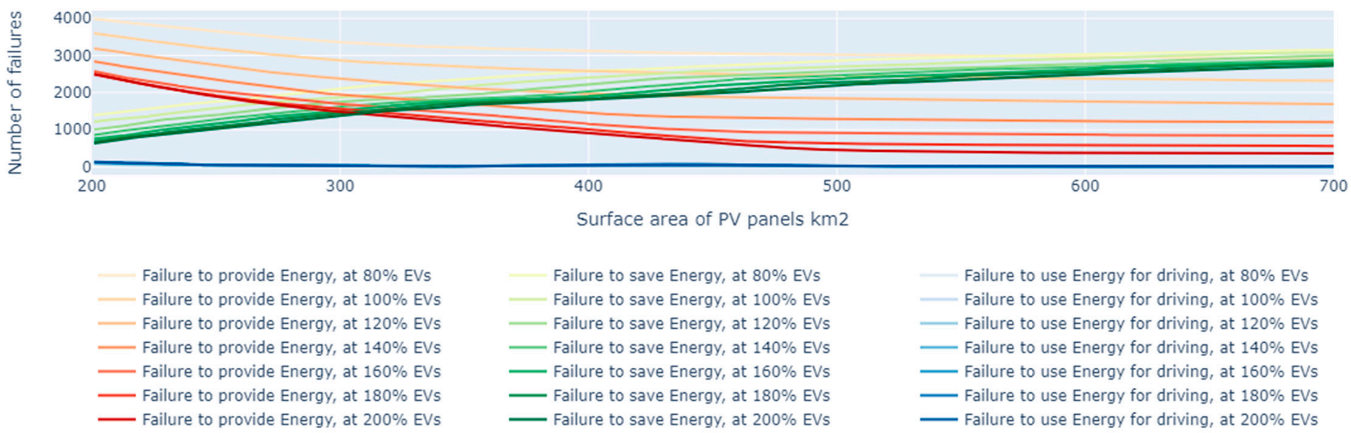

Figure 9. Results for a pure PV-EV system. The figure shows the cases for thresholds at 20% and 80% of the SoC of the EV batteries. The results for the number of failures in a year as a function of the surface size of the PV system for different shares of EVs are shown, as indicated in the figure legend. Each type of failure is shown in a different color, and the darker the color, the greater the share of EVs.

The number of failures to provide sufficient energy for the hourly demand of the total FEC is relatively small only if the surface size is larger than 500 km^2. As a reminder, the estimated value for a total suitable surface size for the installation of PV systems in Slovenia is 280 km^2 [25]. This result, for surface sizes larger than 500 km^2, is despite the fact that the share of EVs is 200% of the number of personal vehicles in 2022 in Slovenia.

4.2. Results for the Simulation of a Pure PV-EV System Covering Electricity Demand

To further investigate this, the simulations in which the total FEC is replaced with electricity consumption are conducted. Figure 10 shows the simulation results for a surface size of 63 km^2 with PV panels. The PV surface size is calculated as the average annual PV production equal to the annual electricity consumption and the EV consumption. Figure 10 shows that the theoretical result for a surface size of 63 km^2 does not meet the requirements of a pure PV-EV system.

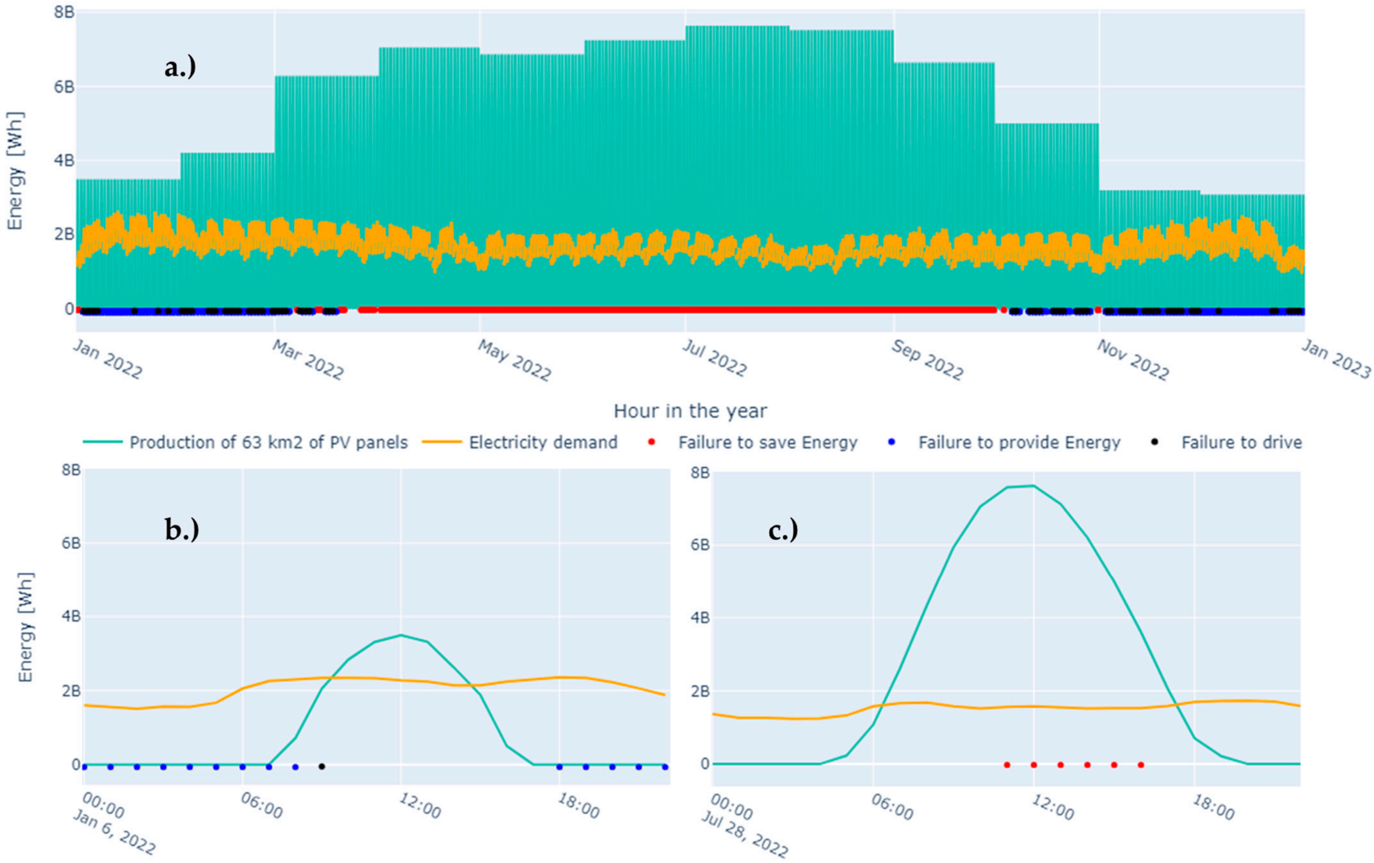

Figure 10. Results of the simulation of a pure PV-EV system covering only the electricity demand with a surface size of 63 km^2 and a share of 100% of EVs, with limit values of 20% and 80% for the SoC of the EV batteries. The diagrams show PV production and hourly electricity demand. In addition, the hours when failures occur are marked with colored dots. (**a**) The diagram for the entire year of 2022 with a PV panel surface size of 63 km^2 and a share of 100% EVs is shown. (**b**) Close-up of the simulation for 6 January. (**c**) Close-up of the simulation for 28 July.

After running the simulations multiple times—1000 times in the case presented here—the average value for the number of times the system fails to provide energy for electricity consumption is 5653, or 65%, and the average number of times when energy cannot be stored is 915, or 10%. This means that in 75% of the hour intervals, the system either fails to provide energy to cover electricity demand or fails to store overproduction. In the case of EV usage, the average value for the number of failed trips is 83, or 1%. The results for SoC limits of 20% and 80% are described.

From the analysis of Figure 10, diagram (a), we can see that failures in the storage of overproduced energy regularly occur from March to October, with few occurrences outside this time interval. On the other hand, failures in the provision of sufficient energy to meet energy demand and in the use of EVs, because the batteries do not contain enough energy, occur only until April and from October on.

Diagrams (b) and (c) show extreme situations that frequently occur in winter and summer. When comparing diagrams (b) and (c) from Figures 8 and 10, we see the resemblance.

Diagram (b) shows a close-up of the simulation for 6 January, one of the days with the lowest PV production, on which various types of failures occur. The hours in which the energy demand cannot be met are shown by blue dots. On most winter days, the energy demand is only covered during the short periods of overproduction and a few hours later. Diagram (b) also shows a case in which there is not enough energy available for the use of EVs. This is shown by a black dot.

Diagram (c) shows a close-up of the simulation for 28 July, one of the days with the highest PV production. The cases in which the surplus energy produced cannot be stored are visible. They are shown by red dots. On most summer days, the same thing happens, namely that the system cannot store any energy in the last hours of overproduction. On the other hand, the energy demand is covered throughout the day.

Figure 11 shows the simulation results for a pure PV-EV system that covers the electricity demand, for which the surface size of the PV panels is varied from 1 to 200 km^2, the SoC is limited to 20% and 80%, and the number of EVs is presented for five different values ranging from 20% to 100% shares. From Figure 11, we can conclude that only for surface sizes larger than twice the theoretical size of 63 km^2 do failures occur less than 10% of the time for a 100% share of EVs. Additionally, as the size of the PV surface increases, the number of failures in meeting energy demand (shown in red) decreases, and the number of failures in energy storage (shown in green) increases, as expected. In addition, a larger share of EVs have lower failure rates.

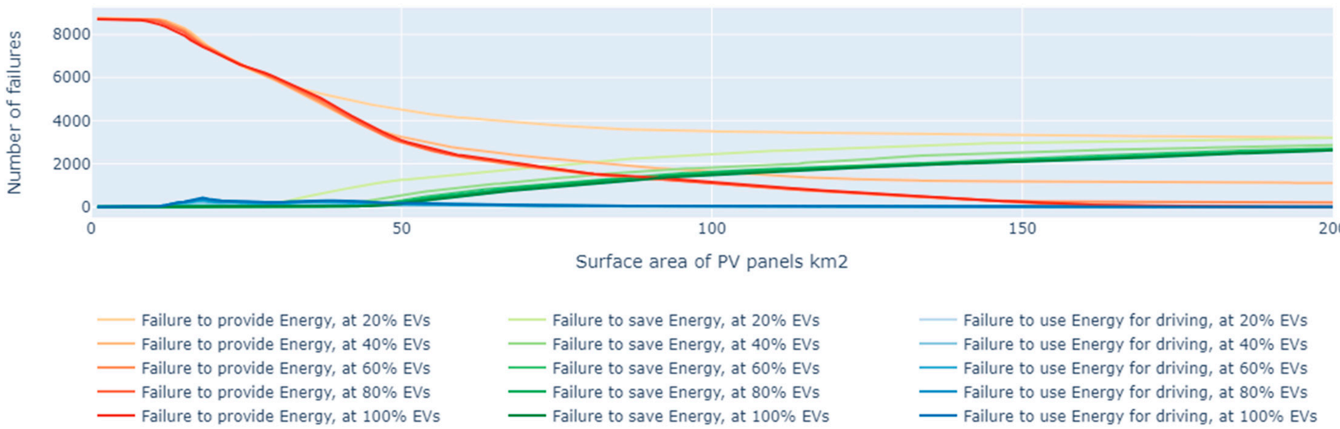

Figure 11. The results for a pure PV-EV system to meet electricity demand. The figure shows the cases limiting values at 20% and 80% of the SoC of EV batteries. Presented are the number of outages as a function of the surface size of PV panels for different shares of EVs.

Additionally, in Figure 11 the points of intersection between the lines for the number of failures to provide sufficient energy to cover demand and the corresponding number of failures to store energy can be observed. These are the points of balance between failures. The objective is to bring the y-value of the balance point as close as possible to 0. The trend for the balance points in Figure 11 indicates that with a larger share of EVs, the PV surface size and number of failures decrease.

5. Discussion

In this study, we investigated the concept of a pure PV-EV system in which the entire energy demand is covered exclusively by a PV and EV batteries are used as the only storage solution. The focus was on the technical feasibility of such a system in Slovenia. Although economic feasibility was not considered in this study, it remains a decisive factor for future investigations into the feasibility of pure PV-EV systems.

To assess the feasibility of a pure PV-EV system in Slovenia, data were collected and processed through cleaning and modeling. We developed a model using Python, as shown in Figure 7, to simulate different scenarios with different shares of EVs and PV surface sizes. During each hourly step of the simulation, PV production and total FEC were compared. Excess energy when PV production exceeded demand was stored in the EV batteries. Any excess energy that exceeded the storage capacity was recognized as an energy loss. Conversely, if PV production was insufficient, then the energy stored in the EV batteries was utilized. If demand could still not be met, then this was categorized as a system failure.

Based on the results presented, a pure PV-EV system is not feasible in a country like Slovenia. If we want to cover the FEC, then we need a sufficient energy source and enough capacity to store PV overproduction for times of underproduction or non-production. A simulation of a pure PV-EV system for Slovenia has shown that the theoretically calculated results comparing PV production in one year with the annual demand for energy and EVs, 217 km^2 of PV installations and 100% EV share, are not sufficient to sustain the system. This is because the capacity of the EV batteries is not sufficient to store overproduced energy and supply enough energy in times of demand. Above all, the system is unable to transfer the energy surplus from the summer months with higher overproduction to the winter months with higher energy demand. We propose further simulations in which the limits for SoC for summer and winter are set to different values in order to investigate this obstacle of the pure PV-EV system further.

The simulated values for a pure PV-EV system that could represent a reasonably low number of failures are larger than 500 km^2 of PV and require a 200% share of EVs compared with the Slovenian personal vehicle fleet in 2022. These values for PV surface sizes are larger than 280 km^2, which is the estimated value of the surface size suitable for PV installation [25]. The share of EVs is also unattainable. In comparison, the current surface size of installed PV systems is estimated to be 3.08 km^2 and the EV share in Slovenia in 2022 is approximately 3%. These results of a pure PV-EV system are unattainable in the near future.

For a pure PV-EV system that only covers the electricity demand, the results are realizable. The calculated theoretical result is that a PV with a surface size of 63 km^2 has an average annual yield that can cover the entire electricity demand and consumption of EVs. The simulation results show that a larger surface size of PVs is required. In the case of 100% EVs, satisfactory results are obtained for surface sizes of less than 280 km^2, at approximately 150 km^2.

Another encouraging fact is that in our study we simulated the total electricity demand and did not exclude the demand currently met by RESs. If this is taken into account, then we can reduce the share of EVs or the surface size of installed PV systems.

These simulations of a system covering only electricity demand also showed problems in bridging between winter and summer months. In these simulations, there were only a few months in which both energy storage and energy supply failed. In general, these failures did not occur together in the system covering only electricity demand.

The simulations also confirmed some of the logical thoughts when thinking about a pure PV-EV system, namely that as the surface size of the PV increased, the number of failures in meeting energy demand decreased, and the number of failures in energy storage increased (see Figures 9 and 11). The energy storage failures occurred in the last hours of overproduction because the batteries of the EVs were already full. The same conclusion arises when demand could not be met in the last hours of underproduction because the EV batteries were already empty, as shown in Figures 8 and 10.

The results presented here can serve as a starting point for further investigations of pure PV-EV systems as well as for more in-depth studies on meeting the energy or electricity demand in countries using only solar energy or other RESs and EVs as energy storage. In addition, PV-EV systems can be analyzed for their ability to participate in the energy market and ensure grid stability. The simulation can also be extended to other flexible loads such as heat pumps and batteries.

6. Conclusions

A pure PV-EV system produces all of the energy required to meet the system's needs solely by the PV system and uses the EV batteries as the only storage system. This system was used in the simulations presented here for Slovenia at the national level. Several important conclusions can be drawn from the results of our research.

First, the great importance of V2G: EVs as BESSs have great potential, especially considering the efficiency of modern lithium ion batteries, which reaches about 90% [14], and considering that on average a vehicle is idle about 95% of the time [15].

Our study for Slovenia has shown that the required surface size of installed PV systems and the number of EVs needed are not feasible. If this scenario is considered for Slovenia in the future, then other RESs should be included and the number of EVs should be kept within a realistic range, and additional BESS would be needed to cover the energy demand.

Finally, the study has shown that a pure PV-EV system would be sufficient to cover only the electricity demand in Slovenia. The surface size and number of EVs are within the estimated surface size suitable for the installation of PV systems [25] and the total number of personal vehicles in 2022 [24].

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