Renewable and Sustainable Energy Reviews 132 (2020) 110074

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

# On the potential contribution of rooftop PV to a sustainable electricity mix: The case of Spain

Antonio Gomez-Exposito *, Angel Arcos-Vargas, Francisco Gutierrez-Garcia

*University of Seville, Spain*

A R T I C L E I N F O

*Keywords:*
Self-supply
Regulation
Cities
Emissions
Renewables
Storage
Rooftop PV

A B S T R A C T

This work evaluates on a large-scale basis the potential contribution of rooftop PV to the future electricity mix. First, based upon an estimation of the available urban rooftop surface, the maximum PV distributed capacity is calculated for each conurbation. Then, several sustainable scenarios are considered, each comprising different shares of centralized renewables, rooftop PV and storage. For each generation scenario, the storage capacity that balances the net hourly demand is determined, and the portfolio combination that minimizes the cost of supplying electricity is obtained. The analysis is applied to mainland Spain, using public information and detailed granular models, both in time (hourly resolution) and space (municipal level). For the Spanish case, when the flexibility of hydro and biomass generation is taken into account, the least-cost portfolio involves rather modest storage capacities, in the order of daily rather than seasonal values. This shows that a sustainable, almost emissions-free electricity system for Spain is possible, at a cost that can be even lower than current wholesale market prices.

## 1. Introduction

Many countries are pledging for renewable electricity shares of 75–80% by 2030 and nearly 100% by 2050. In this context, the impact of a mostly renewable generation mix on power systems will ultimately depend on the share of centralized generation assets versus distributed ones, mainly composed of rooftop photovoltaics (PV) deployed in urban settlements.

Indeed, the cost reduction of small-scale renewable plants, energy storage systems (EES) [1] and electric vehicles (EV), the availability of smart meters and the growing social concern about environmental issues [2,3] have promoted a favorable state of opinion regarding self-sufficiency initiatives based on clean, behind-the-meter technologies. Germany, with over 1.5 million rooftop systems, Hawaii, and Australia constitute paradigmatic examples of this decentralized approach to electricity procurement [4,5]. On the other hand, relevant stakeholders are rather focusing their business models on the current centralized generation paradigm, which is tantamount to replacing large thermal units by renewable plants of similar size [6]. China and India, with PV plants exceeding 1 GW [7], are the best representatives of this model [8]. Fig. 1 represents the time evolution of centralized versus distributed global PV capacities, showing a clear trend for utility-scale PV plants to increase their share, probably due to the widespread adoption of capacity auctions in many countries.

Clearly, centralized plants feature lower capital costs, but distributed facilities provide other advantages for the whole system, including their lower grid requirements and, if installed on rooftops, reduced or null additional surfaces [10] At this crucial moment, when it is still uncertain whether the ambitious commitments pledged for the COP21 Paris agreement will be achieved [11], it is of outmost importance for policy makers, investors and grid planners to have an accurate estimate of the potential contribution of urban renewable resources to a decarbonized energy mix.

Table 1, provides a brief account of recently published works on these issues, including their contribution, strengths, and weaknesses [12–20]. A more detailed description of those works can be found in the Supplementary Note 1.

Related to the inclusion of rooftop PV systems, many analyses can be found in the literature. Those assessments are mainly focused on evaluating the technical potential of rooftop PV [21–32], performing a geospatial analysis of the availabre surface on buildings and the associated PV generation. Geospatial information systems (GIS) are commonly considered in the technical analysis with different input data and size. References [21,22] use LIDAR dataset from public sources

* Corresponding author. Camino de los descubrimientos s/n, 41092, Seville, Spain.
*E-mail address:* age@us.es (A. Gomez-Exposito).

https://doi.org/10.1016/j.rser.2020.110074
Received 13 February 2020; Received in revised form 3 July 2020; Accepted 6 July 2020
Available online 24 July 2020
1364-0321/

combined with government building data for the geospatial analysis of cities, while [23,24] consider just a district of the city and [25,26] the whole country. In Ref. [27], the Gangnam district in Seoul is evaluated with data collected and adapted to ArcMAP application by Korean government; likewise [28], assesses the PV potential of the Yongkang District with data provided by the Tainan City government in Taiwan [29]; uses public vectorial GIS data, provided by the Spanish government, for every Spanish municipality, classifying the buildings in several categories and performances in order to extrapolate for the entire Spanish territory. On the other hand [30], does not use GIS for the evaluation, its methodology being based on classifying the buildings depending on their shape and population characteristics.

Regarding the PV generation, most articles [21–32] obtain the information either from public sources (PVGIS, INSEL, satellite data, meteorological agencies, etc) or from own data sensors deployed in the case study area. However, some recent articles [31,32] go a step forward and combine this information with meteorological data, and then developing machine learning algorithms aimed at estimating the PV generation for every meteorological condition over the study area.

In addition, there also are articles which consider an economic analysis of the rooftop PV installation [33–36], complementing the technical evaluation. Reference [33] performs an economic analysis comparing the current PV scenario in a district of Seoul with the case of a complete PV system deployment on the available surface from 2008 to 2016. In Ref. [34], the total investment cost and annual savings are quantified after evaluating the PV potential of the Ludwigsburg County in South-West, Germany. The LCOE is also analyzed in Ref. [35] for USA, regarding additional renewable sources (biopower, hydrothermal, hydropower), and in Ref. [36] for the Spanish city of Seville, considering a new renewable generation scenario composed mainly of rooftop PV and storage systems.

Our work differs from previous ones in that it mainly focuses on the potential role and contribution of rooftop PV to the electricity mix, using Spain (about 30 million customers located in over 8000 municipalities) as a case study, which can be easily replicated in other countries. Distinguishing features of our work are: 1) it builds up a national electricity model by integrating the hourly PV production and demand data at the municipal level (bottom-up approach); 2) it takes advantage of existing buildings and electrical assets, incorporating society's expectations (elimination of nuclear energy and reduction of emissions); 3) it considers several combinations of generation and energy storage capacity, identifying the one that minimizes the total cost of serving electricity nationwide; 4) the extra demand arising from the electrification of the light-duty vehicles is included.

Clearly, the infrastructures and geographical conditions of each country will significantly condition the results, since part of the storage capacity requirements identified in this analysis can be supplied by manageable generation. Although there are other, quantitatively less important, low-emission technologies (biomass, cogeneration, …), hydraulic generation can play a more relevant role in this regard, mainly depending on its manageability, that is, the availability of pumping stations or large reservoirs. In order to duly assess this issue, a sensitivity analysis is carried out for different levels of hydraulic generation manageability, as this factor can have a significant impact on the resulting LCOE.

This work considers several scenarios, some of them including the current and foreseeable portfolio of sustainable generators, and determines suitable combinations of rooftop PV and storage ensuring that the net hourly demand is fully supplied. The costs associated to each scenario are estimated, which can help policy makers in shaping the best energy regulation and incentives to achieve a sustainable electricity mix.

## 2. Material and methods

As stated, the first goal of this work is to provide a thorough assessment of the potential contribution that rooftop PV can make to the electricity mix of a whole country in a decarbonized future, for which Spain is used as a relevant case study. The aim is to classify each conurbation as self-sufficient or not, in terms of rooftop PV production, and to estimate the storage capacity that will be required to achieve the energy balance for a given period (day, month, season), as well as the resulting costs.

The second goal is to evaluate the feasibility and cost of several brownfield sustainable scenarios, combining the foreseeable centralized generation with the rooftop PV that will be needed in each case to serve 100% of the demand. For each scenario, the storage capacity required to achieve the energy balance on an hourly basis is determined. Then, among all possible combinations of rooftop-PV and storage satisfying the expected demand, the one that minimizes the average cost of supplying electricity is obtained. The hourly demand, including that of the EV, is to be balanced by the hourly production of the partly manageable sustainable generation system, which calls for a certain storage capacity to cover possible gaps.

A diagram showing the input data, the main methodological steps and the scenarios considered is provided in Fig. 2.

Overall, four separate procedures are sequentially considered in this work, namely:

1. Determination of hourly demand profiles on a municipal basis: publicly available data bases, along with statistics regression analysis, are used to determine the annual electricity demand of each municipality, which is then split by days and hours in accordance with the typical load profiles provided by the Spanish TSO (REE) for each day of the year. Industrial loads and EV's are separately considered from the rest of consumption.

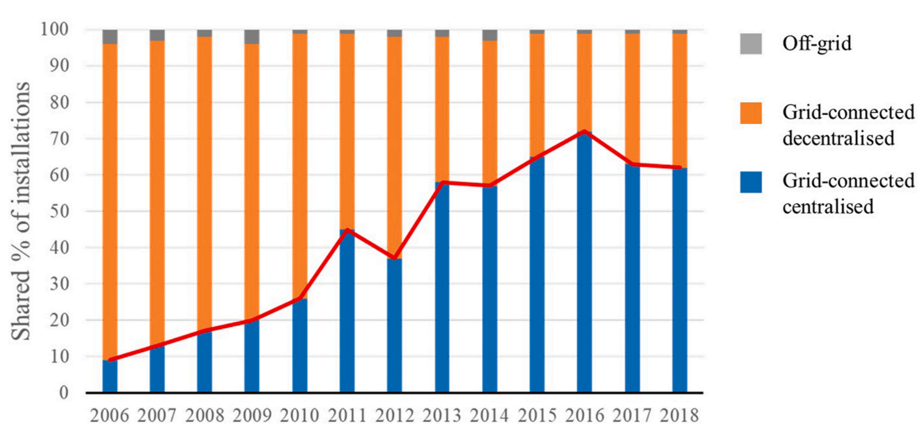


**Fig. 1.** Time evolution of centralized and distributed cumulative global PV capacities over the last decade. Source [9]: and own elaboration.

2. Determination of hourly rooftop PV production on a municipal basis: starting from the total urban surface of each municipality, the available rooftop surface is estimated. Then, depending on the solar irradiance corresponding to each place, the expected hourly PV production is calculated for each municipality.
3. Hourly electricity balance on a municipal basis: based on the hourly electricity demand and the feasible PV production for each municipality, a balance is performed to determine which urban entities, over which periods of time, are self-sufficient, and how much storage is needed. Several scenarios are considered in this assessment, with and without EV demand, each differing in the amount of battery storage assumed, from daily to seasonal horizons. The most cost-effective combination of PV and battery storage is also determined at the national level for projected unitary costs.
4. Hourly electricity balance including the existing and foreseeable renewable and cogeneration assets: unlike in the previous item, dealing with the worst-case theoretical situation in which rooftop PV is the only electricity source, the existing and foreseeable renewable power (including pumped hydro), plus the highly efficient cogeneration systems, are duly considered for the hourly balance. This reduces the need for battery storage and the associated costs.

When applied to the Spanish case, the following main hypotheses are assumed:

- Only the continental Spain, accounting for 93% of the population and 94% of the national electricity demand, will be considered. This way, the analysis is restricted to a big and rather homogeneous interconnected system, avoiding the specifics of the Canary and Balearic islands.
- In the baseline scenario (EV's excluded), the electricity demand will be assumed to be about the same as that of 2018. Indeed, the decarbonized economy of the future will be more electrified, but also more efficient. So, at this stage, it is uncertain how much, if any, the electricity demand will grow in one or two decades from current levels. This way, when matching demand with production, we will use the actual hourly profiles from 2018.
- Likewise, it will be assumed that the number of EV's remains the same as in the current ICE fleet, over 23 million cars plus about 6 million EV equivalent, corresponding to buses, motorcycles and vans in 2018.

Each major procedure is described in more detail in the following subsections.

### 2.1. Determination of hourly demand profiles on a municipal basis

In this work, the hourly electricity demand is estimated on a granular (municipal) basis for two different scenarios: 1) base case scenario, in accordance with the actual demand (2018), implicitly assuming that the demand increase associated with other uses in the next two decades will be approximately compensated by expected efficiency gains, most notably those arising from the adoption of near-zero energy buildings, heat pumps, etc.; 2) same as base case scenario, but assuming 100% of the light-duty vehicle fleet is electrified, which is added to the current demand.

As the annual electricity demand is not available for all municipalities in Spain, it is estimated by means of an econometric model which resorts to the following data, taken from Instituto Nacional de Estadística [37]: population, annual per capita income, cadastral value (excluding industrial land), elevation above sea level (altitude) and climatic zone. The model is adjusted with complete information on electricity consumption available for the municipalities of Andalucía, Pais Vasco and Comunidad de Madrid [38–40].

To ensure consistency with the actual consumption, the estimations obtained for each municipality are scaled so that the sum extended to each region equals the actual demand provided by the System Operator [41] Once the annual demand at the municipal level is estimated, it must be prorated on an hourly basis throughout the 365 days of a year. To this end, it is assumed that the average load profiles provided by the Spanish Ministry [42] on an hourly basis are of application at the municipal level as well. Hourly profiles of the current demand, as well as those associated to the electric vehicles charging, are available from the Spanish System Operator [43,44], which in turn obtains this information from the smart meters of distribution companies.

Although there may be intra-hour variations not considered in this work, it is assumed that they can be duly balanced in real time by the flexibility mainly provided by the storage capacity (Li-Ion batteries and manageable hydraulic generation), through the ancillary services market.

A more detailed description of this procedure is provided in Supplementary Note 2.

In addition to the base case consumption, the demand arising from

**Table 1**
*Strengths & weaknesses of related works.*

| | Jacobson et al., 2013, 2018, Declucci and Jacobson 2012, & Jacobson and Declucci 2013. | DNV, 2018 | Ram et al., 2019 | Shell, 2018 |
|---|---|---|---|---|
| **Scope** | North America municipalities by 2050 | Worlwide by 2050 | Worlwide by 2050 | Worlwide by 2070, UE and USA by 2050 |
| **Contribution** | Development of a roadmap to transition to a renewable scenario based on 100% of Wind, Water and Sunlight generation. | Creation of a model to estimate the energy sources in the future | Technical feasibility and socio-economic viability analysis for a transition of the global electricity system to 100% renewable generation. | Definition of a pathway for decarbonising the global economy. |
| **Strengths** | 100% of renewable energy generation | Electrification of some part of transport and building consumption. | Hourly values of consumption and generation. | Electrification of transport by road and part of building end-use energy. |
| | | Calculation based on data from previous years adapting the estimation model to current scenario. | Transition to 100% renewable energy production.<br>Accurate storage system definition. | Transition to a 100% renewable scenario. |
| **Weakness** | Use of yearly annual values of consumption and production.<br>Electrification of all energy end-use and transport | Use of yearly annual values of consumption and production.<br>No decarbonization scope.<br><br>Regionally inaccurate. | No electrification of any other sector (transportation, building, etc).<br>Aggresive transition model. | Regionally inaccurate.<br><br>Very long time- scale simulation.<br>Use of yearly annual values for cosumption and production. |
| **Criticism** | Strong response from Trainer, T. (2012, 2013). | | | |

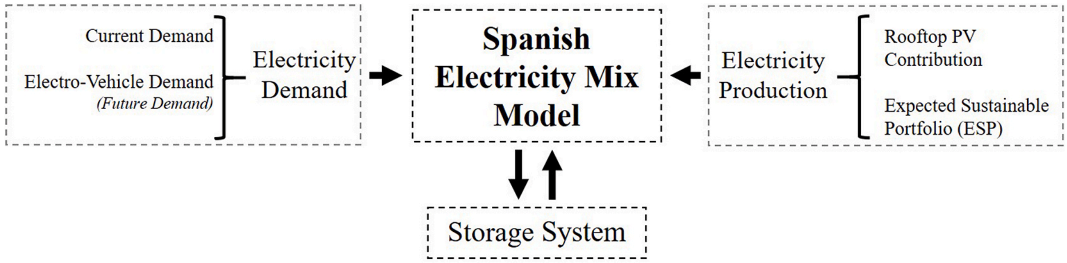


**Fig. 2.** Overview of the input data, processing blocks and results involved in the proposed assessment.

the electrification of 100% of the light-duty vehicle fleet is considered in this work. For this purpose, starting with the stock of vehicles (buses, motorcycles, vans, cars, etc.) for each municipality [45] all categories are transformed into an equivalent fleet of cars in terms of annual consumption. Then, hourly demand values are derived from data provided by the System Operator [44], which regularly monitors a pool of charging points. For the sake of simplicity, electric vehicles have been considered just as an additional conventional demand, although future research efforts should further analyze the contribution they will be able to make as new system resources (under V2G schemes), by establishing bi-directional energy flows. See the Supplementary Note 3 for more details on this procedure.

### 2.2. Determination of hourly rooftop PV production on a municipal basis

The second step of the proposed methodology is aimed at estimating the maximum hourly rooftop PV production on a municipal basis, for which two procedures are combined. On the one hand, it is necessary to estimate the total available rooftop surface on every municipality; on the other, the estimation of the solar potential is performed at every location, considering the surface slope and orientation. Overall, the resulting model is similar to the one developed in Ref. [46] which performs a geospatial assessment of rooftop solar PV for the European Union, yet on a more granular basis.

The assessment of the available rooftop surface is carried out using the application ArcGIS (Geographical Information System) along with cartographical data from the national geographical database ([47], for the study case analyzed). The following hypotheses have been adopted:

- The rooftops can be divided in two different types: pitched and flat roof.
- For pitched roofs, only the four main orientations are considered (South, East, West, North), with balanced roof distribution (i.e., 25% of pitched roof on average to each orientation).
- The surface utilization factor, i.e., the fraction of rooftops that can accommodate PV panels, is taken from a previous assessment performed for the city of Seville [36].

As analyzing the roofs of each municipality individually would be very time-consuming, the urban areas are clustered according to their size and climatic zone. Then, a canonical representative for each group is studied in detail and the results are extrapolated to all members of the cluster. A sample of municipalities are manually tested *a posteriori* to check the adequacy of this approach.

The information necessary for the calculation of the hourly electricity generation, with PV panels deployed on the rooftops, comprises three factors: 1) available surface for PV installation (estimated as explained in the Supplementary Note 4), 2) the performance of the PV panels, and 3) the hourly irradiation over the respective urban surfaces. By combining the hourly irradiation for each orientation and inclination, the available surface for each type of rooftop and the size and peak power of the deployed PV panels, the energy production over the whole year is obtained. A similar approach is developed by Ordoñez et al. in Ref. [48]. Who roughly estimate the rooftop PV contribution in Andalusia based on monthly values for each subregion.

The hourly distribution of PV electricity production is then estimated from the data provided by the Photovoltaic Geographical Information System (PVGIS) tool developed by the European Commission [49] PVGIS gives an hourly irradiation distribution, for a typical day of every month, depending on the geographic location, PV technology and the orientation and slope of the panels.

The irradiation values for the twelve canonical days are translated into available energy per kWp[1] through the energy conversion factor, also obtained from PVGIS tool. The hourly electricity production for the remaining days is obtained by means of an interpolation algorithm programmed in MATLAB and applied to every rooftop orientation. As the solar radiation hitting the north oriented rooftop surfaces is about a half of that received by those oriented to the south, only the pitched rooftops oriented to south, east and west, along with the flat ones, are considered when estimating the PV potential of urban rooftops (i.e., only 75% of the available pitched rooftops are actually accounted for).

Finally, by duly integrating all of the above factors, the maximum installable power and hourly electricity production throughout the year is estimated for each municipality and, as a byproduct, for every province and region of Spain. On average, each kWp of rooftop PV is estimated to yield about 1500 kWh/year, roughly 9% less than the 1650 kWh/year produced in 2018 by a utility-scale kWp in Spain. Further details of the procedure for estimating the surface area of rooftops, as well as the required information for the Spanish case, are provided in the Supplementary Note 4.

### 2.3. Hourly electricity balance between rooftop PV and demand on a municipal basis

Given the hourly demand for each municipality, and the hourly production of the maximum PV power installable on its rooftops, the net hourly balance is obtained simply by subtracting those two magnitudes. As will be seen below, the annual PV production exceeds the demand on an aggregated basis, which means that, with the introduction of sufficient storage capacity, capable of dealing with daily and seasonal imbalances, it is theoretically possible to design a self-sufficient electric energy system, free of emissions and requiring no additional land (in the sequel, this will be termed the *greenfield* scenario). A complete review on the storage size determination for renewable energy systems is presented in Ref. [50].

For each demand scenario (with and without EV's included), the associated costs (LCOE) are computed following the same methodology as in Ref. [48] to be compared with current wholesale or retail electricity prices. The cost parameters and data involved in the calculation of the LCOE are provided in Table 2.

[1] Peak Power (measured in kWp): It is the sum of the peak power of the PV modules installed in a solar facility. It is normally higher than the nominal power, determined by the rating of the AC/DC inverter.

### 2.4. Hourly electricity balance including the foreseeable sustainable assets

Last but not least, the expected sustainable portfolio (ESP), comprising the existing and authorized renewable and cogeneration facilities, are additionally considered in the hourly electricity balance (in the sequel, this will be termed the *brownfield* scenario). The installed capacity, technology, hourly production and level of manageability (i.e., fraction of energy shiftable in time) associated with each of these assets are assumed to be the same as in 2018, which is deemed representative enough for the last few years.

The hourly electricity produced by the unmanageable technologies, as provided by the market operator (OMIE), is subtracted from the gross demand, yielding the net demand to be served by the manageable centralized assets in combination with rooftop PV and battery storage. In order to determine the least-cost capacity of rooftop PV and storage, capable of filling the gap between the ESP production and the demand on an hourly basis, a rather complex constrained optimization problem could be formulated. Alternatively, an iterative procedure exploring a sufficiently large number of PV-storage combinations (complete search estrategy) is adopted in this work.

The outer loop of this process begins with the minimum PV capacity that produces enough electricity to serve the annual demand gap (for this purpose, an average utilization factor of 17% is adopted). This is determined by subtracting the available manageable generation from the annual net demand (as defined above), and adding an estimate of the annual losses incurred by the battery storage system. Then, the inner loop determines the minimum storage capacity required to fully achieve the hourly balance. After each inner loop iteration, the PV capacity is slightly increased, in an attempt to reduce the storage requirements, and the inner loop is run again. The outer loop stops when further increases of PV capacity are not useful to decrease the associated storage capacity.

The flowchart of Fig. 3 provides further details on the exhaustive search strategy adopted to obtain feasible PV-storage combinations satisfying the hourly balance.

As the results are very sensitive to the fraction of hydro generation which is assumed to be manageable, the process is repeated for varying degrees of hydro manageability.

The following hypotheses are established regarding the “expected sustainable portfolio” (ESP) of generation capacity in the brownfield scenario:

- Only the current biomass and cogeneration plants remain in the thermal generation category, along with onshore wind turbines, hydro plants, PV and concentrated solar power in the centralized renewables category. This way, the CO2 emissions of the electricity sector would come only from the approximately 5.7 GW of existing cogeneration plants, which are assumed to remain in the mix owing to their relatively higher efficiencies.
- In order to estimate the amount of additional storage capacity that will be needed to balance the demand, it is most important to discriminate which centralized plants are manageable. In this work, it is initially assumed that 85% of the hydropower production (i.e., excluding run-of-the-river power plants) and 100% of electricty from biomass facilities are manageable, but lower values will be subsequently considered. As cogeneration is under the control of the incumbent industries, no flexibility is assumed for this technology.
- As of writing, the projected PV and wind generation capacity with authorized connection points amounts to an additional increase of 86% and 904%, respectively, with respect to the power installed by the end of 2018. Such significant increase of PV and wind installed power modifies the current renewable generation portfolio, which calls for duly reconsiderating the whole generation/storage system.
- For the brownfield scenarios, the demand is assumed to be the same as for the greenfield case, considering both the current electric consumption and the electrification of the entire Spanish fleet of light-duty vehicles. The estimation of the energy consumption is calculated as stated previously in section 2.1.

**Table 2**
Costs and expected life of PV and storage equipment.

| Technology | Unitary cost | Expected life (Year) | Efficiency (%) |
|---|---|---|---|
| PV | 1 €/Wp | 25 | – |
| Storage | 100 €/kWh | 13.7 [1] | 95 |

Source [2,3]: and own elaboration

Table 3 provides the installed power, the expected capacity increase and the two components (manageable and not manageable) of the annual electricity generation corresponding to each technology. The hourly electricity produced by the unmanageable technologies in 2018, as provided by the market operator (OMIE), is assumed in this work.

## 3. Results

### 3.1. Rooftop PV potential for self-consumption at the municipal level

The main outcome of the procedure described in Section 2.1, a color contour map of the mainland Spain showing the annual electricity demand at the municipal level, is represented in Fig. 4. Fig. 5 gives an idea of how the electricity consumption is distributed among the whole set of municipalities. Note that the 666 largest municipalities (8% of the total) consume 80% of the electricity.

The rooftop PV production for each municipality, calculated in accordance to the methodology presented in Section 2.2, can be represented likewise. Fig. 6 shows the potential annual electricity production over the Spanish mainland territory for each municipality with more than 1000 inhabitants. The most productive municipalities are obviously the big cities, as they span larger areas, but also those located in the southern regions, where the solar radiation is higher. Due to its size, Madrid would be the main producer of Spain, with a maximum estimated production of nearly 7800 GWh.

Table 4 provides the maximum rooftop PV power that can be installed and the annual electricity production classified by provinces, as well as the aggregated national values (234 GWp and 291 TWh, respectively). The losses due to shadow effects are considered as 10%.

Fig. 7 shows the resulting annual electricity balance (surplus in blue, deficit in red) for each municipality. Note that all the ingredients necessary to perform such a theoretical assessment (demand and rooftop PV production on a municipal and hourly basis) have been laid out above. Over 95% of the analyzed municipalities have a potential for rooftop PV production exceeding their annual demand.

Given that the total annual production exceeds the base case demand, it would be theoretically possible to design an electrical supply system solely based on rooftop PV installations, that uses the current distribution and transmission grids to match the geographical unbalances, and that resorts to not yet existing storage facilities to shift energy in time as needed (see more details below).

The annual net balance does no give a clue of what happens on a temporal (daily, monthly or seasonal) basis, which is a valuable byproduct of the study undertaken in this work. Fig. 8 offers further insights into how the energy unbalances take place, both by provinces and months. The provincial results have been obtained by aggregating the municipal results presented in Fig. 7. Note that, despite the fact that the annual production of the maximum installable rooftop PV is higher than the overall national demand, during the winter months this is not the case. It turns out that 11 provinces (including Madrid and Barcelona) lack enough rooftop surface to be self-sufficient in terms of PV electricity production. At the national level, the country would not be self-sufficient over the quarter November–January, whereas Seville (the province with highest annual surplus) would be self-sufficient all the year round and Asturias (the one with highest deficit) would be always deficient if PV was deployed only on rooftop surfaces.

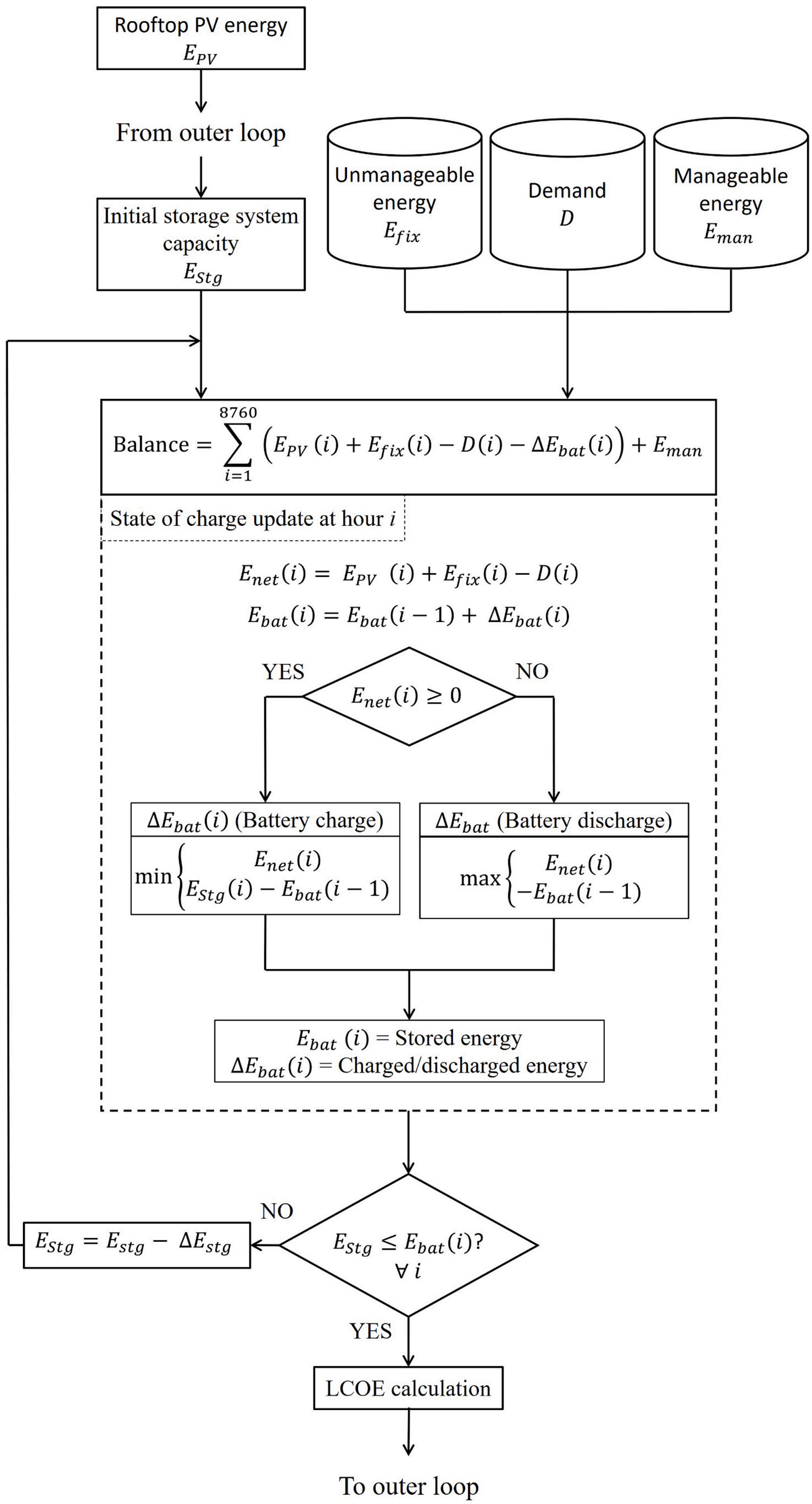


**Fig. 3.** *Determination of feasible PV-storage combinations satisfying the hourly balance.* As mentioned above, the balance depends on the demand, including the current consumption and the EV demand; the unmanageable energy comprising the existing and authorized renewable and cogeneration facilities; the energy produced by the new rooftop PV system; the storage system which is charged/discharged to meet the hourly balance (considering losses); and the manageable energy (part of hydro and biomass) used in the worst hours.

**Table 3**
*Installed capacity and annual production of the generation portfolio assumed in the brownfield scenario.*

| Energy Source | Installed Sustainable Power in 2018 (GW) | Additional Expected Power (GW) | Total Expected Sustainable Power (GW) | Non-Manageable (TWh) | Manageable (TWh) | Total (TWh) |
|---|---|---|---|---|---|---|
| Cogeneration | 5.7 | **0.0** | 5.7 | 19.9 | **0.0** | 25.6 |
| Biomass | 0.2 | 0.0 | **0.2** | 0.0 | 0.7 | 0.7 |
| Wind | 23.5 | **20.2** | 43.7 | 80.7 | 0.0 | 80.7 |
| PV | 4.7 | 42.5 | 47.2 | 66.5 | 0.0 | 66.5 |
| Hydro | 20.7 | 0.0 | 20.7 | 4.8 | 27.2 | 32.0 |
| Thermo Solar | 3.9 | 0.0 | 3.9 | 3.9 | 0.0 | 3.9 |
| Total | 58.7 | 62.7 | 121.4 | 181.4 | 27.9 | 209.3 |

Source [41]: and own elaboration

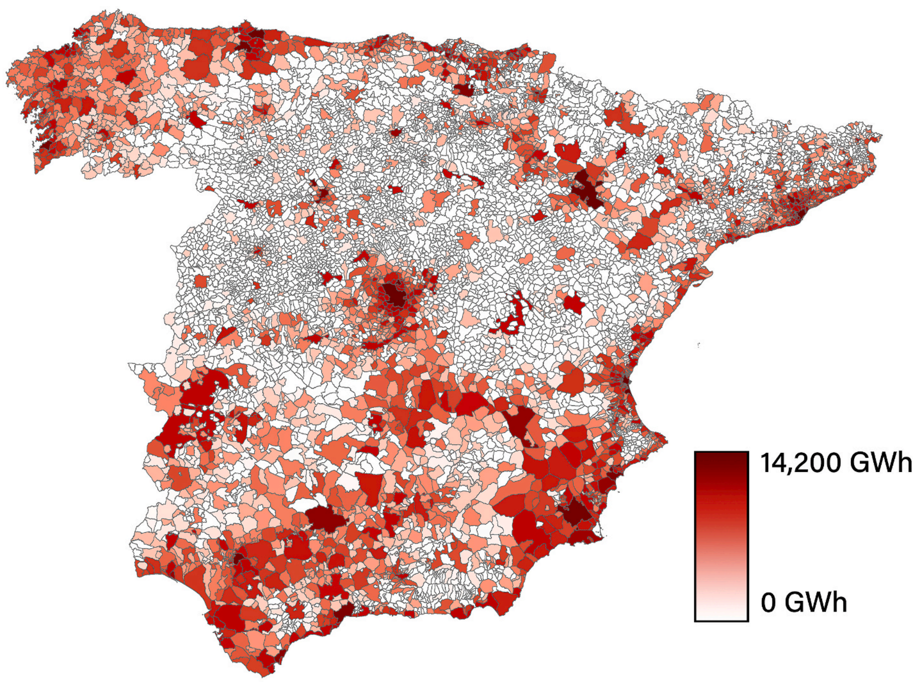


**Fig. 4.** *Annual electricity demand at the municipal level (higher demands in red).* (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

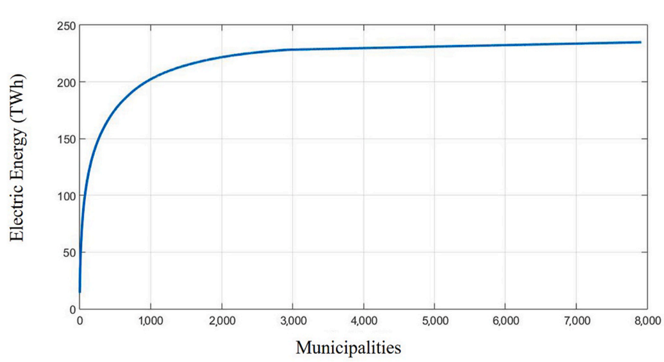


**Fig. 5.** Lorenz curve showing the distribution of electricity consumption among municipalities.

In a future scenario with all vehicles electrified (trucks excluded), we should add to the equation the 60.8 TWh of electricity that would yearly consume the equivalent fleet of cars (nearly 30 million equivalent cars) [41,42]. Even in this case, there is sufficient rooftop surface area to accomplish the annual energy balance (295 TWh of total demand), for which a small fraction of north-faced roofs should be used. In the sequel, all scenarios will include the EV demand, unless otherwise noticed.

### *3.2. Greenfield scenarios: rooftop PV plus battery storage only*

The future scenarios analyzed in this paper are not aimed to reflect a specific year, but rather refer to a hypothetical medium-term horizon in which the huge potential of both renewable sources and EV's has materialized to a large extent. This will likely happen at some time in the decade from 2030 to 2040, depending mainly on yet unveiled technological advances and how ambitious the implemented policies are.

To begin with, we consider an idealized or "thought" scenario intended to answer, among others, the following major questions:

1) Would PV panels, massively deployed on the rooftop surfaces of today's urban settlements, produce sufficient electricity to totally satisfy the annual demand of a whole country?
2) If so, when and where will energy unbalances (surplus or deficit) arise, and how much energy storage will be strictly needed to restore the required balance on specified time horizons (daily and seasonal)?

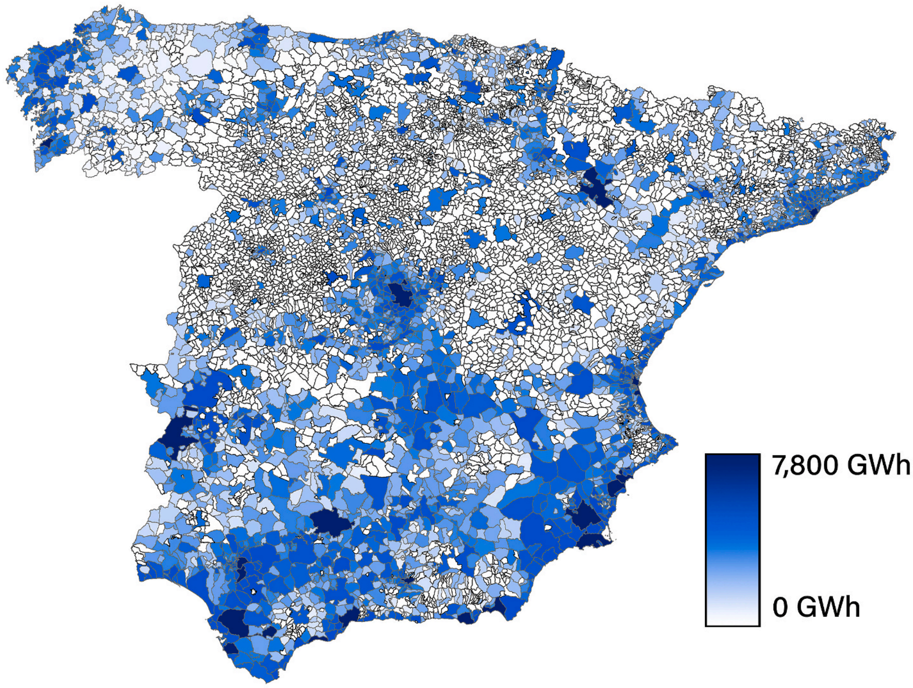


**Fig. 6.** Potential annual roftoop PV production on a municipal basis.

**Table 4**
Maximum rooftop PV power and annual production by mainland Spanish provinces.

| Provinces | Installed PV power (MWp) | Annual production (GWh) | Equivalent hour | Provinces | Installed PV power (MWp) | Annual production (GWh) | Equivalent hour |
|---|---|---|---|---|---|---|---|
| Álava | 994 | 984 | 1101 | La Rioja | 1229 | 1300 | 1175 |
| Albacete | 2901 | 3673 | 1407 | Leon | 4256 | 5158 | 1346 |
| Alicante | 10,718 | 14,070 | 1459 | Lerida | 2689 | 3194 | 1320 |
| Almeria | 5309 | 7623 | 1595 | Lugo | 1760 | 1790 | 1130 |
| Asturias | 2959 | 2834 | 1064 | Malaga | 7844 | 10,700 | 1516 |
| Ávila | 1221 | 1467 | 1334 | Madrid | 18,420 | 24,129 | 1456 |
| Badajoz | 5565 | 7154 | 1428 | Murcia | 10,894 | 14,219 | 1450 |
| Barcelona | 21,609 | 27,038 | 1390 | Navarra | 7642 | 8077 | 1174 |
| Burgos | 2118 | 2317 | 1216 | Orense | 2060 | 2283 | 1231 |
| Cáceres | 2835 | 3591 | 1407 | Palencia | 1102 | 1283 | 1293 |
| Cádiz | 6135 | 8541 | 1547 | Pontevedra | 5471 | 6007 | 1220 |
| Cantabria | 3768 | 3352 | 989 | Salamanca | 1769 | 2172 | 1364 |
| Castellón | 3552 | 4509 | 1411 | Segovia | 1492 | 1746 | 1300 |
| Ciudad Real | 4365 | 5574 | 1419 | Sevilla | 11,040 | 15,123 | 1522 |
| Córdoba | 4740 | 6267 | 1469 | Soria | 705 | 849 | 1337 |
| Cuenca | 1789 | 2166 | 1345 | Tarragona | 6139 | 7591 | 1374 |
| Gerona | 6324 | 7449 | 1309 | Teruel | 808 | 1015 | 1396 |
| Granada | 6640 | 8936 | 1495 | Toledo | 7821 | 9766 | 1387 |
| Guadalajara | 2067 | 2530 | 1360 | Valencia | 13,264 | 17,307 | 1450 |
| Guipúzcoa | 1845 | 1689 | 1018 | Valladolid | 2615 | 3123 | 1327 |
| Huelva | 3816 | 5414 | 1576 | Vizcaya | 3779 | 3373 | 992 |
| Huesca | 1305 | 1624 | 1382 | Zamora | 857 | 1047 | 1357 |
| Jaén | 4640 | 6083 | 1457 | Zaragoza | 3837 | 4689 | 1358 |
| La Coruña | 9573 | 10,090 | 1171 | | | | |
| | | | | Total | 234,282 | 290,917 | 1242 |

3) What would the electricity cost be in such idealized scenario, compared with the average cost of today's wholesale and retail electricity markets?

By applying the procedures described in the Methods section to a case study (in this work the whole mainland Spain), the right answer can be given to the questions posed above. The goal is to provide a thorough, granular and accurate assessment of the potential contribution the distributed rooftop PV can make to the electricity mix in a decarbonized future. Not only is a system-wide perspective provided, but the energy balance is also carried out by hours for each municipality. This way, for a given period (month, season, year) each conurbation can be classified as self-sufficient or not in terms of rooftop PV production, and the associated storage capacity and cost can be quantified.

As shown above, overall a maximum of 234 GWp of PV panels can be accommodated on an estimated available surface of 1134 km$^2$ of

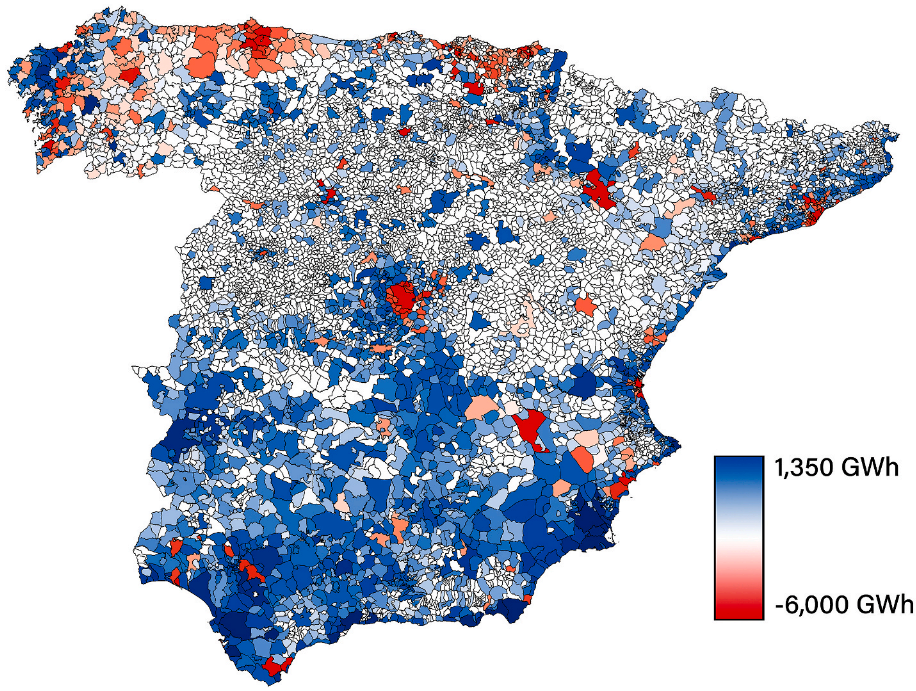


**Fig. 7.** Annual electricity unbalance on a municipal basis for the greenfield theoretical scenario.

rooftops (this excludes north-faced roofs), representing about 46% of the total urban surface and just 0.22% of the national surface. Such installed capacity can deliver annually around 290 TWh of electricity (1240 equivalent hours on average), theoretically sufficient to supply the 235 TWh consumed by mainland Spain in 2018 [41].

As evidenced by Fig. 8, though, noticeable seasonal unbalances arise, which may differ significantly among provinces or regions. If no other source of firm power is available, then some energy storage will be required to shift PV power from day to night and, depending on the location, from summer to winter. In this work, several storage scenarios are considered, ranging from the most exigent case in which all excess of solar energy in summer must be shifted to the winter, to the case in which there is no storage at all, including in between the more realistic one in which the storage devices are dimensioned just to trade energy on a daily basis. A total of forty different storage scenarios have been analyzed and the results are summarized in Fig. 9. The percentage of annual electricity supplied by the rooftop PV system is shown for increasing storage capacities. Note the strongly non-linear evolution of the demand coverage as the storage capacity increases, with a very high slope until the daily storage needs are satisfied, and then a "saturation" region (small slope) for the remaining scenarios, until 100% seasonal coverage is achieved.

In absence of storage, the coverage of the demand barely exceeds 41% (50% if EV's were excluded[2]). Note that the storage capacity required to cover 100% of the demand in this theoretical greenfield scenario (34.5 TWh) would be infeasible or disproportionately expensive with current technology. However, by ensuring sufficient daily storage (489 GWh) nearly 90% of the demand could be served.

The costs (LCOE) associated to all scenarios are computed and represented in Fig. 10, assuming Li-ion batteries are used for storage. Only an interval around the least-cost storage capacity has been represented, as the costs associated with cases warranting 100% of demand coverage (seasonal storage) are extremely high (around 900 €/MWh). It is worth noting that, while the optimal storage capacity (435 GWh) is insufficient to ensure the daily balance in the worst case, both costs are relatively close (between 50 and 52 €/MWh, of the same order of magnitude as today's wholesale European markets). Therefore, the daily storage capacity can be considered also sufficiently optimal for practical purposes, which is good news.

### 3.3. Brownfield scenarios: inclusion of the foreseeable sustainable assets

The *greenfield* case constitutes just a reference scenario providing local and global upper limits to the potential share of distributed PV generation, as well as the storage capacity required to achieve daily or seasonal balances. However, more credible *brownfield* scenarios should duly consider existing and planned sustainable generation plants if a realistic assessment is to be performed of the feasibility of the resulting mix and the required investments.

In this regard, in addition to the existing renewable assets, a long-term future scenario should also consider the wind and PV capacity which has already been granted a connection point to the grid. As shown in the former section, the foreseeable capacity and annual production of such "expected sustainable portfolio" (ESP), are currently much higher than those projected by the Spanish government in the recently issued Integrated National Plan of Energy and Climate (PNIEC) [51]. Unlike the PNIEC, this work excludes any thermal generation, except for the biomass facilities and 5.7 GW of existing cogeneration plants, the latter being kept in the mix owing to their relatively higher efficiencies. In order to estimate the additional storage capacity that will be needed to balance the hourly demand, it is most important to discriminate which centralized plants are manageable. Initially, this work assumes that 85% of the hydropower production (run-of-the-river power plants excluded) and 100% of biomass electricty are manageable.

In total, 209.3 TWh are expected to be produced by the centralized fleet of ESP generators, of which only 27.9 TWh are initially assumed to be manageable. In absence of any other resource, this is clearly insufficient to serve the foreseeable demand (295 TWh, EV including). Moreover, a detailed hourly analysis shows that, despite the manageable fraction of energy being used in an optimal fashion, there are intervals of time for which the net demand is negative, which calls for unmanageable generation curtailment. The data collected in Table 5 shows that

[2] The results of the base case analysis, excluding the demand of EVs, are included in the Supplementary Note 5.

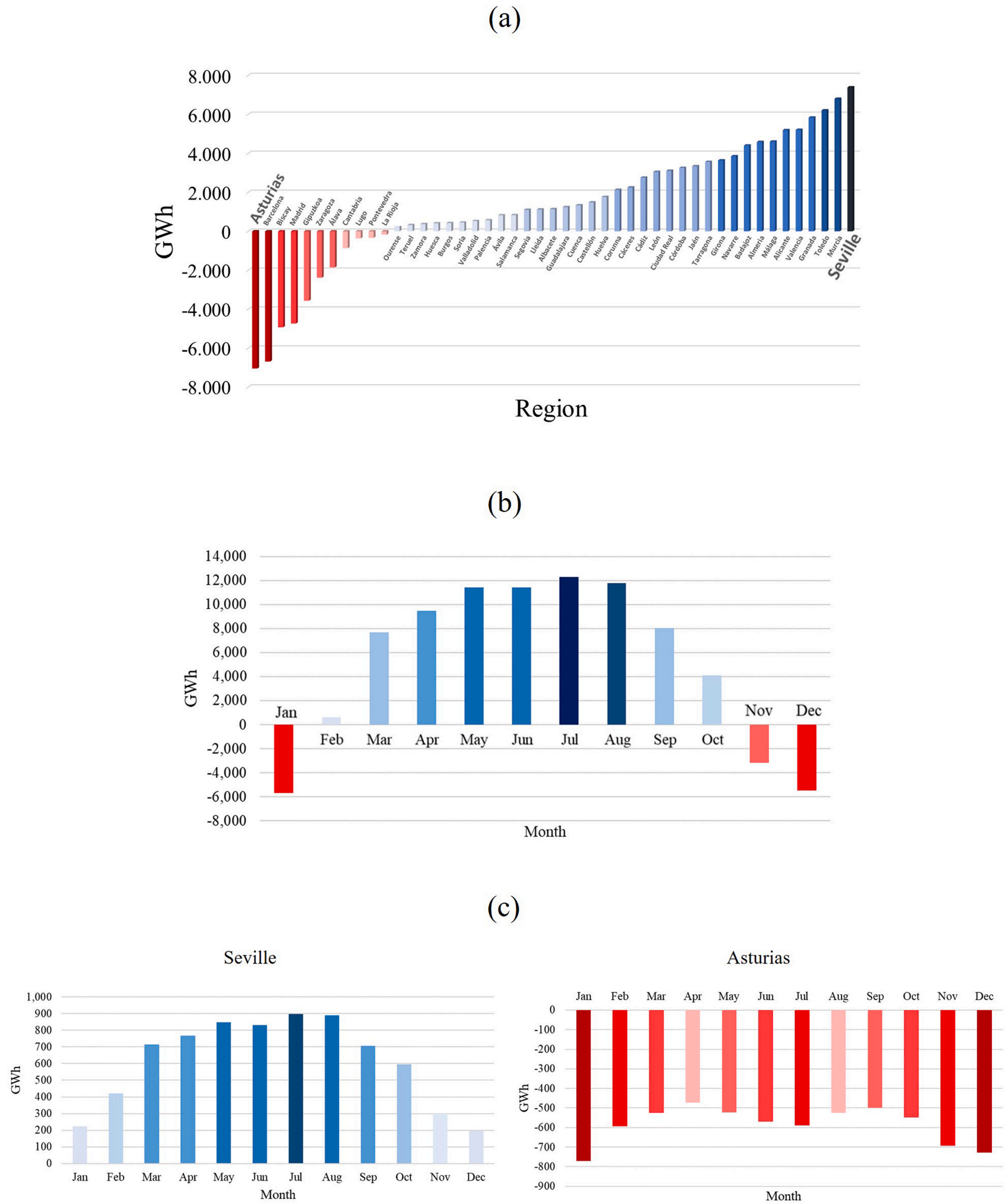


**Fig. 8.** Annual electricity balance by provinces for the base case (a), monthly electricity balance for the total mainland Spain (b), and for the two provinces with the greatest unbalance, Seville (surplus) and Asturias (deficit), (c).

nearly 100 TWh (32%) remain userved in this case, whereas 5.5% of the ESP electricity should be curtailed.

We assume that the additional electricity required to close the gap between the ESP production and the expected demand (i.e., the residual demand) is produced exclusively by rooftop PV. For the sake of sizing the associated storage system, it is also assumed that the manageable energy can be arbitrarily shifted in time, as long as the required power is lower than the rated power of the involved generators (the details of how the hourly balance is carried out in this case can be found in Section 2.4). Unlike in the greenfield scenario, comprising only distributed assets, a single national balance is performed in this case, as there is no reasonable way of splitting or decomposing the production of centralized assets on a municipal basis. This implicitly assumes that the transmission system is designed so that the electricity can flow across the Spanish geography as required. Table 6 provides the breakdown of battery storage and PV costs in the optimal case.

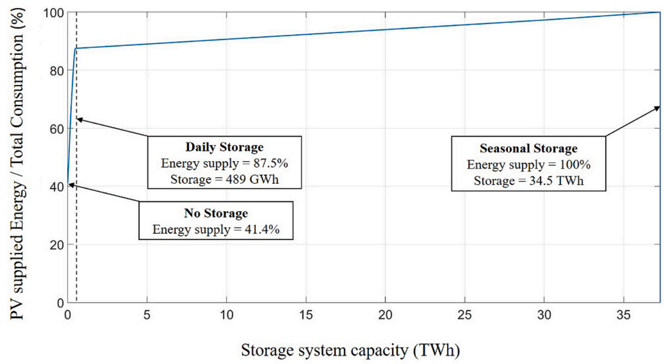


**Fig. 9.** Demand coverage vs. installed storage capacity (EV demand included).

Fig. 11 represents the isoquant curve of all rooftop PV-storage combinations that can feed the total net demand, clearly showing two asymptotic values. Assuming unlimited rooftop surface for PV production, the minimum energy storage capacity is 190 GWh, while the minimum PV power capable of serving the remaining net demand, including the losses due to charge-discharge battery cycles, is 66 GWp. The figure also shows the resulting LCOEs for all isoquant combinations. Note that the minimum cost (55.8 €/MWh) is achieved for a rooftop PV capacity of 75 GWp and a storage system of 298 GWh. Such cost is slightly lower than the average wholesale market price in 2018 in Spain (56.4 €/MWh). Moreover, the resulting *mix* is virtually emission-free and, being distributed to a larger extent, would reduce the overall system losses and network requirements.

One of the parameters most affecting the results presented in Fig. 11 is the fraction of hydro electricity which is manageable. In order to assess the sensitivity of the results to this parameter, the analysis is repeated for decreasing levels of hydro manageability (from 40 to 85%). Fig. 12 represents the LCOEs for the additional isoquant rooftop PV-storage curves, showing how the minimun cost evolves for each level of hydro manageability. As expected, the lower the proportion of manageable hydro, the higher the cost, as more rooftop PV and storage must be added to the system. It should be highlighted that, at the point of lowest cost, the contribution of storage to the total LCOE is close to 40%, which represents a significant, albeit manageable, fraction.

## 4. Discussion

Table 7 summarizes the main results for each of the five scenarios considered in the paper, including the optimal combination of rooftop PV and storage, the percentage of demand coverage, curtailed energy (which could be used for other purposes, such as water desalination or $H_2$ production), as well as the associated costs. For the computation of the averge LCOE, it has been assumed that the cost of the electricity provided by the ESP assets corresponds to the average cost of the whosale market in 2018.

Regarding the greenfield scenarios, the following conclusions are worth stressing:

- In Spain, the available urban surface (excluding north-faced rooftops) can theoretically accommodate enough PV panels to deliver 100% of the annual electricity consumed in 2018. However, this would require unacceptably expensive amounts of seasonal battery

**Table 5**
Annual demand, production and balance for the brownfield scenario in absence of rooftop PV and battery storage.

| Current scenaio | | Energy (TWh) | Total Energy (TWh) |
|---|---|---|---|
| Demand | Current Demand | 234.9 | 295.7 |
| | EV Demand | 60.8 | |
| Production | Managebale energy | 27.9 | 209.3 |
| | Non-Managebale energy | 181.4 | |
| Balance | Total demand | | 295.7 |
| | Used energy | | 197.8 (94.5%) |
| | Unserved demand | | −97.9 |

**Table 6**
Rooftop and storage capacity, production and costs in the least-cost brownfield scenario.

| Assessment | Technology | Unite of measurement | Value |
|---|---|---|---|
| New systems | Installed rooftop PV power | [GWp] | 75.0 |
| | Rooftop PV usuful energy | [TWh] | 93.0 |
| | Storage capacity | [GWh] | 298.0 |
| Investment | PV | [M€] | 75,000 |
| | Storage | [M€] | 29,800 |
| | Total | [M€] | 104,800 |
| Depreciation | PV (25 years depreciation) | [M€/Year] | 3000 |
| | Storage (13.7 years depreciation) | [M€/Year] | 2175 |
| | Total | [M€/Year] | 5175 |
| LCOE | – | [c€/kWh] | 5.58 |

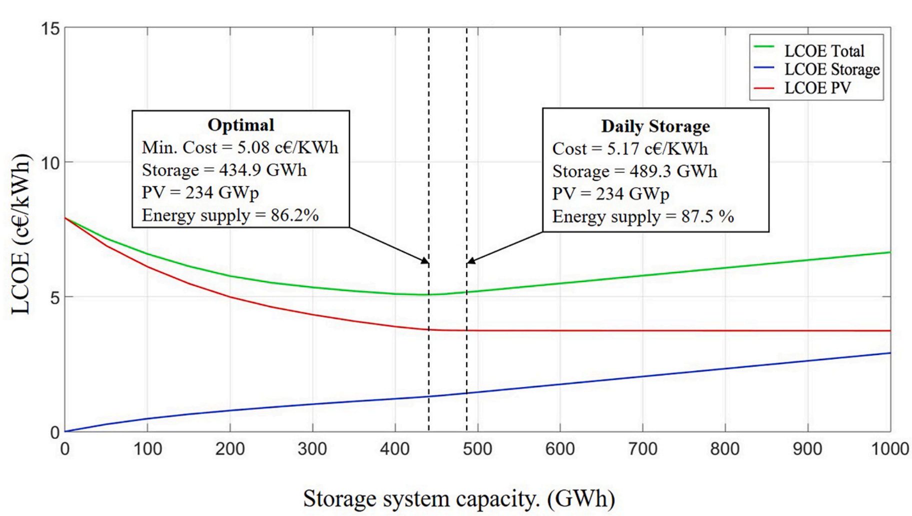


**Fig. 10.** LCOE estimation vs. battery capacity storage.

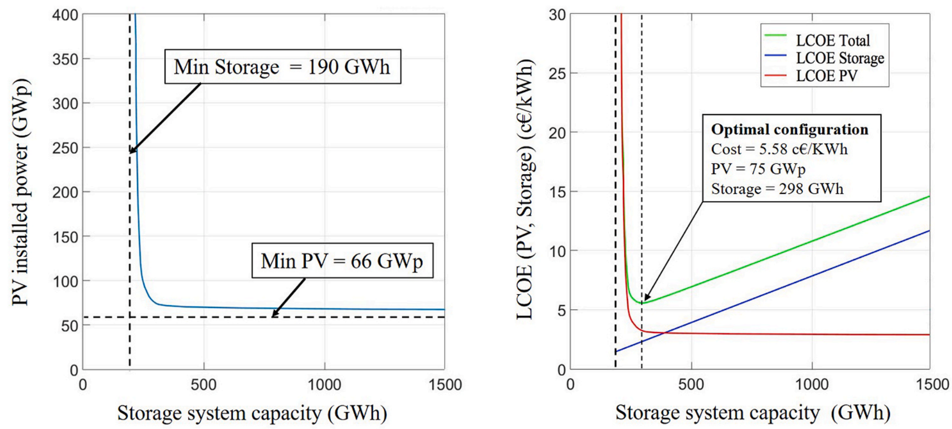


**Fig. 11.** *Isoquant curves showing all possible combinations of rooftop PV and storage capacity serving 100% of the net residual demand in the brownfield scenario (left) and related LCOEs (right).* This scenario assumes that 85% of hydro is manageable. The combination leading to minimum LCOE is marked up on the right diagram.

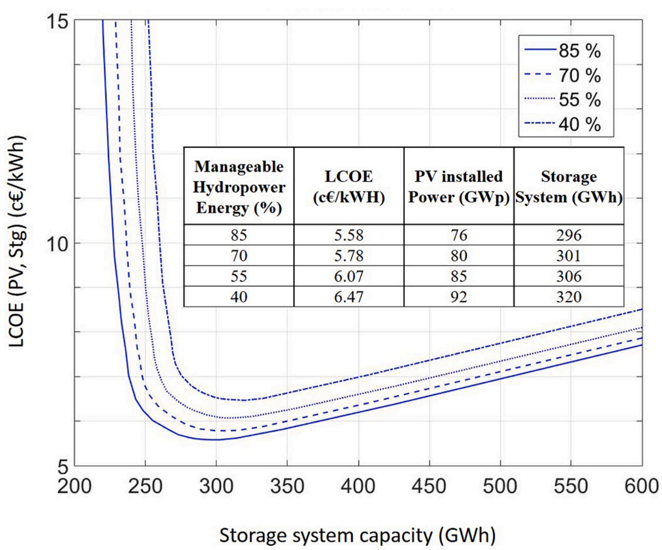


**Fig. 12.** *Minimun LCOE for each level of hydro power manageability.*

storage. The least-cost rooftop PV-storage combination (234 GWp of PV and 294 GWh of storage) can supply 91% of the current demand at an estimated cost of 55 €/MWh.

- When 30 million equivalent vehicles are assumed to be electrified, the least-cost rooftop PV-storage combination involves 55% more storage (455 GWh) but the LCOE is lower (51 €/MWh). Should the energy stored by EV batteries be partially used as an additional grid resource (V2G scheme), the storage capacity could be drastically reduced (this possibility is not explored in this work).
- In both cases, a significant fraction of the rooftop PV production must be curtailed or used for other purposes (86 TWh in the base case and 30 TWh when the EV is considered).

When the sustainable centralized assets (ESP) are included in the balance (brownfield scenarios), the following conclusions are drawn:

- As expected, the ESP assets alone would be insufficient to satisfy the demand. Assuming 85% of the hydro production is flexible enough, still nearly 32% of the demand cannot be served.
- The least-cost rooftop PV-storage combination capable of serving, along with the ESP centralized fleet, 100% of the demand at an average cost of 56 €/MWh, comprises just 75 GWp of PV and 298 GWh of storage.
- Should the rate of hydro manageability be reduced from 85 to 40%, the least-cost capacity of rooftop PV and battery storage would increase to 92 GWp and 320 GWh, respectively, and the average cost would reach 60 €/MWh.
- Interestingly enough, in all cases the optimal combination of PV and battery storage leads to storage capacities which are in the order of the energy consumed on a daily basis. Therefore, expensive seasonal storage is not needed at all, as long as a minimum amount of manageable capacity is available. In fact, the average costs are similar to those of the Iberian wholesale market in 2018.
- The high share of manageable hydro energy leads to a significant cost reduction, due to the decrease of the seasonal storage capacity needed to match the demand in the worst days. Indeed, this is possible for the particular energy generation portfolio of Spain. In other regions lacking enough hydro resources, likely more expensive storage alternatives should be considered. Another possibility partly alleviating the problem would be to oversize to a certain extent the renewable generation system.
- The resulting generation and storage portfolio has enough firm capacity (power) to deal with the respective peak demand, even if the non-manageable ESP is fully ignored.
- The distributed PV installed capacity arising in the brownfield model is well below the one considered in Ref. [52], below which there would be no congestion problems on transmission and distribution systems.
- From the figures collected in Table 7, it turns out that the storage should be dimensioned on average for less than 5 h of rated power, of the same order as the latest generation of stationary batteries currently being deployed worldwide.

## 5. Conclusion

This paper has first shown that the Spanish urban surfaces can accommodate enough rooftop PV capacity to potentially feed the current electricity demand plus the consumption of the light-duty vehicle fleet, should it be electrified. Very costly seasonal storage would be needed to serve 100% of the demand in this theoretical greenfield scenario. However, if approximately 10% of the demand could be served by other flexible means, then the remaining 90% could be satisfied solely by PV plus a reasonable daily storage capacity. The adopted methodology is based on public data, with hourly and municipal resolution and can be applied to any other country.

Then, other more realistic scenarios, additionally considering the expected sustainable portfolio of mostly centralized generation assets, are also analyzed. For each scenario, the storage capacity that minimizes the average cost of supplying electricity is obtained. The most relevant

**Table 7**
*Least-cost combination of rooftop PV-battery storage capacities under different sustainable scenarios.*

| Scenario | | Annual Load | | Manageable ESP. | | Unmanageable. | | | | Battery Storage | | Served Energy | Curtailed Energy | LCOE | Whosale Market | Average Energy Cost |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | ESP | | PV | | | | | | (New system) | 2018 | |
| | | Energy | Peak | Energy | Rated | Energy | Rated | Energy | Peak | Energy | Peak | | | | | |
| | | TWh | GW | TWh | GW | TWh | GW | TWh | GWp | GWh | GW | % | TWh | €/MWh | €/MWh | €/MWh |
| Greenfield | Base case | 235 | 41 | | | | | 291 | 234 | 294 | 60 | 91% | 80 | 55.2 | 56.4 | 55.3 |
| | Base case + EV | 296 | 55 | | | | | 291 | 234 | 435 | 94 | 88% | 31 | 50.8 | 56.4 | 51.5 |
| Brownfield (EV included) | ESP only (Hydro is 85% manageable) | 296 | 55 | 28 | 18 | 181 | 104 | | | | | 67% | 12 | 55.8 | 56.4 | 56.0 |
| | ESP + PV + Storage (Hydro is 85% manageable) | 296 | 55 | 28 | 18 | 181 | 104 | 103 | 75 | 296 | 61 | 100% | 16 | 55.8 | 56.4 | 55.8 |
| | ESP + PV + Storage (Hydro is 40% manageable) | 296 | 55 | 13 | 8 | 196 | 114 | 126 | 92 | 320 | 66 | 100% | 64 | 64.7 | 56.4 | 64.7 |

conclusion is that the least-cost combination of generation assets (centralized renewables, rooftop PV and storage) that satisfies the foreseeable demand (EVs included) leads to daily rather than seasonal storage capacities, with associated LCOEs of the same order as the average cost of the Iberian wholesale market. The presence of sustainable manageable generation plays a relevant role when defining the storage capacity needs, hydraulic generation (pumping and/or reservoirs) being the best exponent in countries like Spain.

In a nutshell, this work has proven that a sustainable, emissions-free electricity system is possible, for a big country such as Spain, by suitable and affordable combinations of centralized and distributed generation, the latter one providing up to nearly 45% of the demand, along with relatively modest amounts of storage capacity, mainly dimensioned for daily cycles.

## Credit author statement

Antonio Gomez-Exposito, Conceptualization, Methodology, Supervision. Angel Arcos-Vargas, Conceptualization, Methodology, Validation. Francisco Gutierrez-Garcia, Data curation, Visualization, Investigation, Methodology, Writing and Editing.

## 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.


## Acknowledgements

This research was funded by the 2020 PAIDI plan managed by the Consejeria de Economia y Conocimiento within the EU- FEDER Andalusia 2014–20 program (project S2V, US-1265887).


## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2020.110074.

## References


[1] Sisternes De, Fernando J, Jenkins Jesse D, Botterud Audun. The value of energy storage in decarbonizing the electricity sector. Appl Energy 2016;175:368–79.

[2] Sussams L, Leaton J. Expect the unexpected: the disruptive power of low-carbon technology. Grantham Institute at Imperial College London 2017. https://www.imperial.ac.uk/grantham/publications/expect-the-unexpected-the-disruptive-power-of-low-carbon-technology.php.

[3] Bloonberg New Energy Finance. New energy outlook 2018. https://about.bnef.com/new-energy-outlook/; 2019.

[4] Bronski P, Creyts J, Guccione L, Madrazo M, Mandel J, Rader B, Crowdis M. The economics of grid defection: when and where distributed solar generation plus storage competes with traditional utility service. Rocky Mountain Institute 2014:1–73.

[5] Hoffmann W. PV as a major contributor to the ~100% renewably powered world and solving the climate battle. In: Petrova-Koch V, Hezel R, Goetzberger A, editors. High-efficient low-cost photovoltaics. vol. 140. Springer, Cham: Springer Series in Optical Sciences; 2020.

[6] Leonard MD, Michaelides EE, Michaelides DN. Energy storage needs for the substitution of fossil fuel power plants with renewables. Renew Energy 2020;145:951–62.

[7] Xin-gang Z, Zhen W. Technology, cost, economic performance of distributed photovoltaic industry in China. Renew Sustain Energy Rev 2019;110:53–64.

[8] International Energy Agency. World energy outlook. Paris, France: International Energy Agency; 2019.

[9] International Energy Agency. Trends 2015 in photovoltaic applications. Report No. IEA-PVPS T1–36, https://iea-pvps.org/wp-content/uploads/2020/02/5319-iea-pvps-report-2019-08-lr.pdf; 2019.

[10] Unfccc. Paris decision. FCCC/CP/2015/L.9/Rev.1. Available from: https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf; 2015.

[11] Yushchenko A, De Bono A, Chatenoux B, Patel MK, Ray N. GIS-based assessment of photovoltaic (PV) and concentrated solar power (CSP) generation potential in West Africa. Renew Sustain Energy Rev 2018;81:2088–103.

[12] Jacobson MZ, Howarth RW, Delucchi MA, Scobie SR, Barth JM, Dvorak MJ, Jones R. Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight. Energy Pol 2013;57: 585–601.
[13] Jacobson MZ, Cameron MA, Hennessy EM, Petkov I, Meyer CB, Gambhir TK, Miccioli ML. 100% clean and renewable Wind, Water, and Sunlight (WWS) all-sector energy roadmaps for 53 towns and cities in North America. Sustainable Cities and Society 2018;42:22–37.
[14] Det Norske Veritashas–Dnv. Energy transition outlook 2018. 2018. A global and regional forecast of the energy transition to 2050.
[15] Ram M, Bogdanov D, Aghahosseini A, Gulagi A, Oyewo AS, Child M, Caldera U, Sadovskaia K. Farfan, J., barbosa LSNS., fasihi M., khalili S., dalheimer B., gruber G., traber T., de caluwe F., fell H.-J., breyer C. Global energy system based on 100% renewable energy – power, heat, transport and DesalinationSectors. Lappeenranta, Berlin: Study by Lappeenranta University of Technology and Energy Watch Group; 2019. March 2019.
[16] Shell. SkySshell Scenarios: Meeting the goals of the paris agreement. 2018.
[17] Trainer T. A critique of Jacobson and Delucchi's proposals for a world renewable energy supply. Energy Pol 2012;44:476–81.
[18] Trainer T. 100% renewable supply? Comments on the reply by jacobson and delucchi to the critique by trainer. Energy Pol 2013;57:634–40.
[19] Delucchi MA, Jacobson MZ. Response to "A critique of Jacobson and Delucchi's proposals for a world renewable energy supply" by Ted Trainer. Energy Pol 2012; 44:482–4.
[20] Jacobson MZ, Delucchi MA. Response to Trainer's second commentary on a plan to power the world with wind, water, and solar power. Energy Policy, 57, 641-643 2013.
[21] Jakubiec J, Alstan Reinhart, Christoph F. A method for predicting city-wide electricity gains from photovoltaic panels based on LiDAR and GIS data combined with hourly Daysim simulations. Sol Energy 2013;93:127–43.
[22] Suomalainen Kiti, Wang Vincent, Sharp Basil. Rooftop solar potential based on LiDAR data: bottom-up assessment at neighbourhood level. Renew Energy 2017; 111:463–75.
[23] Strzalka Aneta, Alam Nazmul, Duminil Eric, Coors Volker, Eicker Ursula. Large scale integration of photovoltaics in cities. Appl Energy 2012;93:413–21.
[24] Santos T, Gomes N, Freire S, Brito MC, Santos L, Tenedório JA. Applications of solar mapping in the urban environment. Appl Geogr 2014;51:48–57.
[25] Buffat René, Grassi Stefano, Raubal Martin. A scalable method for estimating rooftop solar irradiation potential over large regions. Applied Enery 2018;216: 389–401.
[26] Gagnon Pieter, Margolis Robert, Melius Jennifer, Phillips Caleb, Elmore Ryan. Rooftop solar photovoltaic technical potential in the United States: a detailed assessment. National renewable energy laboratory. www.nrel.gov/publications; 2016.
[27] Hong Taehoon, Lee Minhyun, Koo Choongwan, Jeong Kwangbok, Kim Jimin. Development of a method for estimating the rooftop solar photovoltaic (PV) potential by analyzing the available rooftop area using Hillshade analysis. Appl Energy 2017;194:320–32.
[28] Ko Li, Wang Jen-Chun, Chen Chia-Yon, Tsai Hsing-Yeh. Evaluation of the development potential of rooftop solar photovoltaic in Taiwan. Renew Energy 2015;76:582–95.
[29] Izquierdo Salvador, Rodrigues Marcos, Fueyo Norberto. A method for estimating the geographical distribution of the available roof surface area for large-scale photovoltaic energy-potential evaluations. Sol Energy 2008;82:929–39.
[30] Kurdgelashvili Lado, Li Junli, Shih Cheng-Hao, Attia Benjamin. Estimating technical potential for rooftop photovoltaics in California, Arizona and New Jersey. Renew Energy 2016;95:286–302.
[31] Assoulinea Dan, Mohajeri Nahid, Scartezzini. Large-scale rooftop solar photovoltaic technical potential estimation using Random Forests. Appl Energy 2018;2017:189–211.
[32] Assoulinea Dan, Mohajeri Nahid, Scartezzini Jean-Louis. Quantifying rooftop photovoltaic solar energy potential: a machine learning approach. Sol Energy 2017;141:278–96.
[33] Lee Minhyun, Hong Taehoon, Jeong Kwangbok, Kim Jimin. A bottom-up approach for estimating the economic potential of the rooftop solar photovoltaic system considering the spatial and temporal diversity. Appl Energy 2018;232:640–56.
[34] Rodríguez Romero, Duminil Laura, Eric Sánchez Ramos, José, Eicker, Ursula. Assessment of the photovoltaic potential at urban level based on 3D city models: a case study and new methodological approach. Sol Energy 2017;146:264–75.
[35] Brown Austin, Beiter Philipp, Heimiller Donna, Davidson Carolyn, Denholm Paul, Melius Jennifer, Lopez Anthony, Hettinger Dylan, Mulcahy David, Porro Gian. Estimating renewable energy economic potential in the United States: methodology and initial results. National renewable energy laboratory. www.nrel.gov/publications; 2016.
[36] Arcos-Vargas A, Gomez-Exposito A, Gutierrez-Garcia F. Self-sufficient renewable energy supply in urban areas: application to the city of Seville. Sustainable Cities and Society 2019;46:101450.
[37] Instituto Nacional de Estadística. www.ine.es; 2019.
[38] Andalucía Junta de. Sistema de Información multiterritorial de Andalucía (SIMA). https://www.juntadeandalucia.es/institutodeestadisticaycartografia/sima/index2.htm; 2019.
[39] Comunidad Autonoma del Pais Vasco. Indicadores municipales de sostenibilidad: consumo eléctrico anual del municipio (kWh/habitante). https://datos.gob.es/es/catalogo/a16003011-indicadores-municipales-de-sostenibilidad-consumo-electrico-anual-del-municipio-kwh-habitante; 2019.
[40] Comunidad Autonoma de Madrid. Anuario estadístico de la Comunidad de Madrid. 1985-2019 industria y energía. http://www.madrid.org/iestadis/fijas/estructu/general/anuario/ianucap12.htm; 2019.
[41] Red Eléctrica de España – REE-. Series estadísticas del sistema eléctrico español. 2019.
[42] Ministerio para la Transición Ecológica. Boletin Oficial del Estado. Viernes 4 de enero de 2019. Resolución de 21 de diciembre de 2018, de la Dirección General de Política Energética y Minas, por la que se aprueba el perfil de consumo. 2019.
[43] Red Eléctrica de España – REE-. Demand profiles. https://www.ree.es/es/perfiles-de-consumo; 2019.
[44] Red Eléctrica de España – REE-. Control centre for the electric vehicle (cecovel). https://www.ree.es/en/red21/electric-vehicle/cecovel-the-electric-vehicle-control-centre; 2019.
[45] Ministerio del Interior. Direccióm general de Tráfico. Tablas estadísticas. http://www.dgt.es/es/seguridad-vial/estadisticas-e-indicadores/parque-vehiculos/tablas-estadisticas/; 2019.
[46] Bódis K, Kougias I, Jäger-Waldau A, Taylor N, Szabó S. A high-resolution geospatial assessment of the rooftop solar photovoltaic potential in the European Union. Renew Sustain Energy Rev 2019;114:109309.
[47] Ministerio de Fomento. Instituto Cartofráfico Nacional. Cartografía y datos geográficos. https://www.fomento.gob.es/areas-de-actividad/instituto-geografico-nacional/cartografia; 2019.
[48] Ordóñez J, Jadraque E, Alegre J, Martínez G. Analysis of the photovoltaic solar energy capacity of residential rooftops in Andalusia (Spain). Renew Sustain Energy Rev 2010;14(7):2122–30.
[49] European Comission. Photovoltaic geographical information system (PVGIS). Downloaded from, http://re.jrc.ec.europa.eu/pvgis/; 2012.
[50] Yang Y, Bremner S, Menictas C, Kay M. Battery energy storage system size determination in renewable energy systems: a review. Renew Sustain Energy Rev 2018;91:109–25.
[51] Ministerio para la Transición Ecológica. Plan nacional integrado de Energía y clima (PNIEC) 2021-2030. BOE núm. 52 de 01 de Marzo de 2019;2019.
[52] Tevar G, Gomez-Exposito A, Arcos-Vargas A, Rodriguez-Montanes M. Influence of rooftop PV generation on net demand, losses and network congestions: a case study. Int J Electr Power Energy Syst 2019;106:68–86.