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Modelling the building-related photovoltaic power production potential in the light of the EU's Solar Rooftop Initiative

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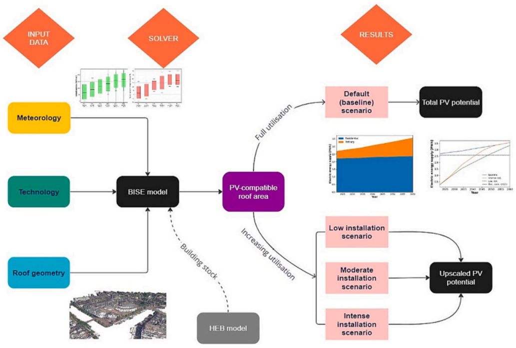
HIGHLIGHTS

- Germany, Italy and France have the highest technical potential of rooftop PV.
- Increase of around 25% in the technical potential was modelled until 2050.
- Current rooftop PV technical potential could satisfy all power need in the EU.
- Latest EU policies could mean huge step forward to a decarbonized building sector.

GRAPHICAL ABSTRACT



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ABSTRACT

Decarbonizing the building sector is key to meet the EU climate goals by 2050. Although the recent policies recognized the importance of on-site solar energy production in the energy transition, there are only a few modelling studies analyzing how much the gap between the technically possible and policy-driven power generation of rooftop photovoltaic (PV) panels can be reduced. This study, therefore, uses geospatial techniques and the high-resolution Building Integrated Solar Energy (BISE) supply model to estimate the main spatial and temporal characteristics of the rooftop PV energy production potential. To support decision-making, important implications of the Solar Rooftop Initiative action plan of the European Commission on the future dimension of the PV electricity supply are also assessed in the context of the achievable potential. The modelling results indicate that the current rooftop PV technical potential could be about 2.7 PWh, being in similar extent with the EU power consumption. The largest country-level PV potentials can be found in Germany, France, Italy and Poland, with an increase of 30% by 2060. Our findings also underline that by following the latest policies, major improvement could be achieved in the EU's rooftop solar energy production by around 2040, depending greatly on the structure and energy efficiency niveau of the future building stock.

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1. Introduction

In the EU, 40% of the total energy consumption and 33% of the CO_2 emissions are associated with the building sector [1]. To fulfil the EU climate strategy declared in the European Green Deal [2], which is the reduction of greenhouse gas emission by at least 55% until 2030 and reaching climate neutrality until 2050, huge efforts must be made, and several energy efficient solutions must be involved. One of the potential possibilities is the solar technology that can provide high-density clean energy both in space and time [3].

Solar energy systems have been showing significant progress in their reliability, efficiency and cost over the last decades [4]. At building level, photovoltaic (PV) panels, thermal (T) and hybrid (PV/T) collectors have become the most popular options, installed either on or integrated directly into the building material. Of these technologies, solar PVs had a much higher share (80%; 158.9 GW_p) in the installed capacity relative to the solar thermal (20%; 40 GW_{th}) in Europe in 2021 [5,6]. This fact is primarily attributed to the shorter payback time of PV panels than of thermal collectors in many climates [7] and, therefore, governments often prioritize this technology in financial support programs concerning energy transition [8].

Despite the rapidly growing rooftop PV segment, about 90% of the European building roofs are still unexplored in terms of solar energy [9], hence the untapped potential in generating clear energy is substantial. In coherence with this and with the energy transition goals, the European Commission (EC) released a Solar Energy Strategy [10] within the framework of the REPowerEU plan [11] in which, among others, the acceleration of rooftop PV installations is initiated. Precisely, this initiative focuses on overcoming administrative barriers (e.g., length of permitting for rooftop solar installations) and making rooftop PV installations mandatory for all new public, commercial and residential buildings as well as for all existing public and commercial buildings, with different deadlines. It would be equivalent with a 58 TWh of additional power generation and around 5 million new solar PV rooftops by 2025 [12]. This initiative fits perfectly into the strategy that plans to upscale the solar PV capacity (incl. Centralized and decentralized PVs) to 600 GW_{AC} by 2030 [10]. Since the power demand is expected to rise from 2760 to 6800 TWh by 2050 as a part of the EU's electrification strategy [13], the elevated power production of rooftop PVs can be one of the strongest pillars of this process. However, the dimension of the integration of new energy sources into the electricity market may depend largely on, for example, the sustainability of the stability of the grid [14,15], the availability of energy storage technologies [16] and the deployment of promising microgrid solutions [17,18].

In the light of previous studies regarding the technical potential of rooftop PV electric energy generation for the EU (e.g., [19–21]), the objectives of the EC, from the perspective of available and physically suitable rooftop area, seem to be very well supported [22], for example, employed different statistics (e.g., floor area per capita, population, number of floors per building type) for estimating the total and suitable roof area of 27 EU member states and found suitable areas of 2354 km^2 for residential and 703 km^2 for non-residential buildings. This resulted in total potential and installed capacity of 840 TWh and 951 GW_p by 2030, with the largest values in Germany, the UK and France. Considering the classification of [23], the available roof area was estimated with an even more sophisticated GIS (Geographic Information System) technique by [24]. In their analysis, they found the suitable roof area to be 7935 km^2 and 680.3 TWh/year of technical potential for 28 EU countries. This amount of electricity supply was concluded to satisfy 24.4% of the EU power consumption in 2016, with country-specific values over 50% in Croatia (50.8%), Portugal (52.3%), Bulgaria (59.8%), Romania (82.3%) and Cyprus (119.8%). Based on the predicted EU-wide economic potential of 16.8%, the authors, however, confirmed possible barriers due to the inadequate grid infrastructure, high operational costs, and limited availability of battery systems. Slightly higher PV potential and much lower suitable rooftop area were reported (705 TWh/year and 4015 km^2) in [25]. By taking all rooftop areas being available for PV installation, more ambitious numbers were estimated for the rooftop PV potential (2858 TWh/year) of the EU in the investigation of [26]. Additionally, this analysis revealed favorable levelized cost of electricity for the Mediterranean countries (e.g., Spain, Portugal and Italy; around 90 $/MWh), with higher prices and longer economic return towards the higher latitudes and Eastern Europe.

Country, region and city-specific assessments have been focusing on refining the EU-level results to estimate the share of rooftop PV electricity generation to the total electricity demand. However, due to different sources and accuracy of the sources of the input data, especially for the total and suitable roof area as well as for technological measures (e.g., efficiency and degradation of PV panels), the findings are quite diverse (Austria: 100%[1] [27]; Spain: 4% [28]; Andalusia (Spain): 78.9%[2] [29]; Apeldoorn (the Netherlands): 77% [30]; Athens (Greece): 49–87%[3] [31]; Catalonia (Spain): 5.6–31.1%[4] [32]; The Piedmont Region (Italy): 28% [33]; Valencia (Spain): 37%[5] [34]; Wroclaw (Poland): 30% [35] – sometimes even within a (non-EU) country (Switzerland: 28% [36]; 40% [37]; 91% [38]). If the electricity generation of PV panels is inspected, majority of the studies came to the same conclusion that residential buildings have the highest potential to satisfy the local demands among the building typologies [34,39].

As several authors pointed out [40–42], adapting GIS data and techniques in simulating and validating the building-related potential of PV energy supply could be a great tool across several scales. They also discussed that the quality of the data and the selected methodology have a decisive impact on the spatiotemporal characteristics of the outcomes. The above-mentioned studies for Switzerland showed an illustrative example for the importance of applied data and approach. Although each of the analyses employed very high-granularity digital elevation and digital surface models (DEMs and DSMs) as well as accurate building footprint data sets for deriving the crucial rooftop parameters, there are the best agreement in the results with the ones [43,44] included both GIS and machine learning technique (e.g., random forest, extreme learning machine ensembles and support vector regression). It is interpreted that results of solar PV-related estimations could be extremely sensitive to the applied scientific methods that vary on a wide spectrum in the literature. In many cases, however, the application of the most sophisticated procedures is constrained by the unavailability of accurate GIS data for even urban DSM and DEM layers. Data with inappropriate resolution, for example, make difficult to the identification of roof surfaces not optimal for PV installation [45].

Apart from gaps related to the lack of standardized input data and reliable methodology both in country-level and smaller scales, vast majority of the literature sources describe the rooftop PV electricity potential as ‘a most probable outcome’. Due to the high complexity of the modelling approach, less emphasis is put on investigating different possible future actions. If any scenario analysis exists, it often misses incorporating policy-driven processes that hold the most relevant information for decision makers and stakeholders.

To overcome some of the abovementioned gaps, this paper analyses not only the technical potential of how much electric energy can be generated by rooftop PVs in the EU, but also assesses the dimension of PV electricity supply resulted in the directives issued in the REPowerEU plan [11]. Using the high-resolution, GIS-based BISE (Building Integrated Solar Energy) energy supply model, this research showcases detailed modelling results on a wide spatial range, varying from country to building type levels. In addition to estimating the implications of the REPowerEU on PV power production at a significant spatiotemporal

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[1] Along with the existing green power generation

[2] Including all energy needs

[3] Only for space cooling

[4] Including all energy needs

[5] In certain periods, net zero energy balance is possible

disaggregation, the novelty of this study lies in that it develops a high-resolution database for key roof geometry parameters indispensable to derive the rooftop area suitable for installing PV panels. Hence, the contributions of this paper to the existing knowledge pool can be summarized as follows: (i) determining the total and suitable rooftop area across the EU member states using high granularity GIS datasets, (ii) providing detailed modelling outputs for the technical potential of the rooftop PV power production over a longer time frame based on the spatio-temporal dynamics of the EU building stock and (iii) estimating the future changes of the EU-level rooftop PV electricity production in the light of the latest policy packages.

2. Methodology

In order to estimate the technical potential of rooftop PV electricity generation in the EU, various data sources regarding meteorology, building footprints, roof parameters and solar panel technology are combined and integrated as an input into the hybrid BISE energy supply model [46–48]. Then simulations are performed to quantify the spatiotemporal distribution of the solar radiation income over building rooftops (i.e., the physical and urban potential) and the electric energy being converted from the solar energy absorbed by PV panels with a given technology (i.e., technical potential). Finally, different scenarios are constructed to conduct various electricity generation pathways and their implications on the energy transition goals of the EU. It must be noted that however, understanding the socio-economic segments of installing rooftop solar panels would be crucial to give a complex picture on what fraction of the technical potential could be realized in a cost-effective way, but this is beyond the scope of this paper.

In this section, first, the structure of the BISE model is presented. Secondly, the most essential data pre-processing steps in terms of meteorological, roof-related and technological inputs are shown. Finally, three PV installation scenarios and their main construction assumptions are introduced.

2.1. The Building Integrated Solar Energy (BISE) model

The BISE model encompasses an algorithm-based modelling framework that combines different GIS and relational (statistical/empirical) approaches to compute the future trends of the technically feasible solar energy generation on rooftops. This simulation tool can focus on PV and PV/Thermal systems; thus, it has the capability to give predictions on the building-related potential for both thermal energy and electricity.

The BISE considers 11 socio-economic regions of the world, with dedicated emphasis on the 27 EU member states and the United Kingdom (Fig. 1). The corresponding simulations cover the period from 2022 to 2060, with annual and optionally with hourly intervals. It means that the BISE outputs are suitable to reveal the seasonal and sub-seasonal (e.g., monthly, weekly and daily) characteristics of the solar energy supply. Initially, the outputs were generated in gridded format (with a spacing about 100 km) and then were aggregated to higher levels, including climate zones and countries.

The model classifies the building stock into eight building types (i.e., single and multifamily buildings, educational buildings, hotels/restaurants, hospitals, retails, office and other buildings) and five building vintages (i.e., standard/existing, new, retrofitted, advanced new and advanced retrofitted). The shares of building types and building vintages vary at country-level and exhibit clear tendencies towards the end of the modelling era. The projection of these values relies on GDP, population data as well as on assumptions for retrofit and demolition rates. All information regarding the dynamics of building stock was transferred from the High Efficiency Building (HEB) model [49–51] and forwarded to the BISE to downscale climate zone/country-level inputs to the level of building types and vintages.

Fig. 1. Spatial distribution of the European countries considered in the BISE model.

The rest of the inputs of the BISE model can be categorized as meteorological, roof-related and technological parameters. Some of these inputs are fixed in time, but most of them are time-dependent, which means that they were added to the algorithms at every time step. In the model, a computational core handles the calculation of heat and power production separately. The corresponding algorithms were implemented in Python programing language (for more information, please refer to [52]) and result in files with netCDF format as outputs.

2.2. Estimation of meteorological inputs

Environmental variables have a great influence, for example, on the solar radiation received by the PV panel and control the efficiency of photovoltaic effect via the heat exchange between the PV cells and the overlying air layers [53]. The model parameterizes these mechanisms by implementing such meteorological inputs as Top-Of-Atmosphere radiation, global radiation, ambient air temperature and wind speed.

Since the simulations span a multi-decadal period, the change in the patterns of the climatic variables needs to be accounted for. For this reason, instead of creating typical (averaged) meteorological year profiles, climate projections were applied to represent the shift in their distributions until 2060. The projections were acquired from the CMIP-6 (Coupled Model Intercomparison Project) database [54]. Many of the available modelling products were sieved when their spatial ($\Delta x > 100$ km) and/or temporal ($\Delta t > 1$ day) resolution was too coarse. As a further criterion, only outputs with rather conservative ("middle of the road") CO_2 emissions growth and warming scenario (e.g., SSP – Shared Socioeconomic Pathway 2–4.5) were considered. At the end of this search process, the climate projections of the widely used model of the Deutsches Klimarechenzentrum (DKRZ) [55] were selected. Since a major objective of the BISE model is capturing the rooftop PV electricity production on hourly basis, the daily time steps of the DKRZ projections were split into hourly slices with the help of climate reanalysis data.

As the combination of observations and model outputs, reanalysis data provides robust information on the historic state of the climate [56]. In this study, the MERRA-2 (Modern Era Retrospective-Analysis for research and Applications) database [57] was employed to create mean hourly profiles for each meteorological input based on a 5-year period (2015–2019). In a three-step GIS workflow, the mismatch in the horizontal resolution between the different data sources was first resolved by re-gridding the reanalysis data. Then a four-dimensional vector (days: 365, hours: 24, x: 384, y: 192) per each variable was created, which represents its hourly weights (i.e., the hourly values normalized by the corresponding daily means). Lastly, assuming fixed profiles over each grid until 2060, the climate projection was transformed to a finer temporal representation, by multiplying the DKRZ projection with the hourly weights of the MERRA-2 data.

To demonstrate the reliability of the meteorological input data used by the BISE model, the mean monthly distribution of air temperature and global radiation was computed for the entire modelling period in randomly selected points in some of the European Koeppen–Geiger's climate zones [58] (Fig. 2). It can clearly be concluded that the climate-dependence of these inputs are well captured by the database. The mean annual air temperature values vary between 3 °C (Dfc) and 19.1 °C (Csa), with monthly minimum of −8.4 °C (Dfc) and maximum of 30.3 °C (Bsk). Showing a significant southward gradient, the mean annual values and monthly extrema of global radiation sums were estimated to be the largest for the point in the zone Dfc (890 kWh/m^2; min: 0 kWh/m^2; max: 169 kWh/m^2) and lowest for the point in the zone Csa (1950 kWh/m^2, min: 77 kWh/m^2; max: 224 kWh/m^2) (Fig. 2).

2.3. Extraction of building footprint data

Segmenting buildings from other artificial urban elements has a great importance in predicting the useful area suitable for installing rooftop PV panels. For many previous studies (e.g., [59,60]), the open-source building footprint data of Open Street Map (OSM) layers offered a reliable option to generate the map of building footprints. The OSM is global spatial database and has been created to build a detailed map of roads, buildings, railways, public places, water and administrative boundaries on community basis. In this dataset, the buildings can be defined to be accommodation, commercial, religious, amenity, sports, agricultural, technical buildings, carport(s) and other buildings. By the autumn of 2023, >200 million European buildings are recorded in the database. Despite the continuously improving coverage, one of the weaknesses of the OSM project is the spatial inhomogeneity of the quality and density of footprints [60,61].

A potential alternative or complementary open vector layers may be provided by the Microsoft Global Building Footprint (MGBF) database. In the MGBF dataset, the footprints were extracted from Airbus and Maxar imagery by means of deep neural network technique (i.e., semantic segmentation) [62]. After evaluating this dataset, the precision of the segmentation process was found to be over 90% (94.3% for Europe). Currently, about 160 million footprint polygons and 13.3 GB compressed data are downloadable from the GitHub page of the MGBF database for the EU member states.

In the earlier versions of the BISE model, the building footprint area was estimated by a supervised raster classification, using the built-up surface product of the Global Human Settlement Layer (GHSL) as the classifiable layer and building cadastral data as training data [48]. However, the raster layers of the GHSL are well applicable to extract footprints of larger buildings located in areas with lower building density, as a result of the 10-m resolution, capturing smaller buildings and buildings of compact built-up areas may be less accurate (Fig. 3). To overbridge the potential uncertainties related to the previous classification, the OSM and MGBG datasets were linked, and a new building footprint map was built to replace the GHSL-based building footprint polygons for the EU countries.

The most essential step in updating the building footprint map was to filter those footprints in both databases that represented the same building. For doing so, as an initial step, the format and the geographical coordinate system of both databases were set to be identical by means of Python packages. In the following, a so-called overlay analysis was performed in the QGIS software during which the percentage of geometrical overlapping was determined for each building footprint in each dataset. Then, by employing a filter algorithm, the building footprints with non-zero overlap percentages were eliminated from the database. After merging the remaining building footprints into a combined dataset, a new map was being created, containing all unique footprints, based on the OSM and GHSL datasets. By considering this combined database representative to the real distribution of buildings, the areas of the individual buildings were computed and exported to human-readable, tabular form (Fig. 4). As a result of the procedure above, about 80% of the OSM buildings were excluded, since these footprints were already available in the more extended MGSL database. Finally, the footprint area values were converted to m^2 dimension and aggregated for each EU member states.

2.4. Estimation of total and suitable rooftop area

In order to derive the total rooftop area for each member states, the building footprint areas were transformed by giving an estimation on their mean tilt angle and the share of flat and pitched roofs of the entire building stock. However, processing very detailed LiDAR (Light Detection And Ranging) data would be an adequate option to determine these critical parameters at urban scale or for a single country, in case of 27 member states it seemed to be better solution to apply an alternate, yet reliable technique. Since the aim of this study is to estimate the upper limit of the rooftop PV electricity production in a physically realistic way, it was assumed that the estimated tilt angles result in the highest annual insolation over PV panels. Precisely, for each relevant latitude of the EU countries, ideal PV and rooftop inclinations were calculated based on [63] as follows:

$$\beta = 1.3793 + \varphi[1.2011 + \varphi(-0.14404 + 0.000080509\varphi)] \tag{1}$$

where β is the ideal tilt of building roofs for solar applications and ϕ is the geographical latitude. To retrieve country-specific values, the means of the related angles were considered.

Furthermore, it was important to approximate the distribution of roof tilting for a given country and building type. Theoretically, the share of the flat and pitched roofs is the function of the climate and engineering traditions [64]. In Europe, there are abundant climate zones, including the variations of arid, warm, temperate and boreal climates. Therefore, as a first step, the typical values for the shares in each of the eight climate types of the Koeppen-Geiger's classification [58] were collected from the literature.

In summary, the climate zone-specific information was found to be incomplete and the analyzed study areas relatively small (Table 1), so the generalized numbers for the shares published in [65] were accepted. In this paper, the authors used data from EU projects, online tools, national statistics and literature sources. As an output, the share of flat and tilted roofs were revealed solely for residential buildings. For all commercial and public buildings, consequently, we assumed that rooftops have not any tilt. Then, the total roof area of flat roofs was taken equal to the building footprint area. In case of titled roofs, a simple trigonometric relationship was applied to transform the building footprint area to total roof area (RA).

The total roof area is generally much larger than the area physically suitable for installing solar PV panels. Analytically, the RA was reduced with a so-called utilization factor (U_F) [69] to consider the unfavorable effects of shading (C_{SH}), protected areas (C_{PROT}), construction areas (C_{CON}), service areas (C_{SA}), orientation/azimuth (C_{AZ}), slope/tilt angle (C_{SL}), panel separation (C_{GCR}) and share of solar panels/collectors (C_{PV}/C_{TH}) on the installation potential. The RA and U_F can be expressed with the following expressions:

$$U_F = C_{SH} \bullet C_{PROT} \bullet C_{CON} \bullet C_{SA} \bullet C_{AZ} \bullet C_{SL} \bullet C_{PV} \tag{2}$$

$$RA_{available\ t,r,p} = U_F \bullet RA_{t,r,p} \tag{3}$$

As indicated, the roof area physically suitable for installing PV panels ($RA_{available}$) was predicted in each year (t), country (r) and building type (p) by the BISE. Since most coefficients in Eq. (2) could have significant variability even within a single urban area, they were estimated based on literature findings (Table 1). In this analysis, south-facing gable (tilted) and flat roofs are always considered, therefore the C_{AZ} was set to

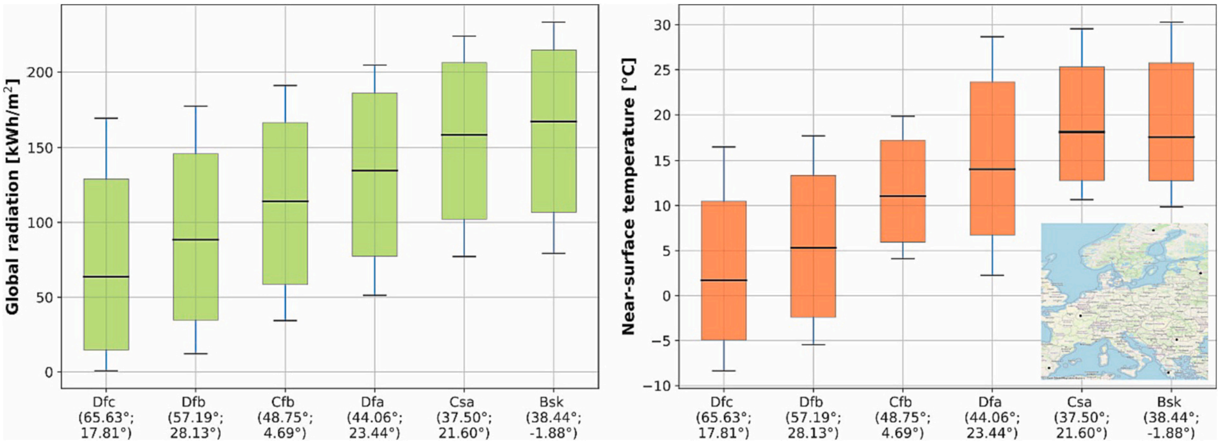

Fig. 2. Typical annual ranges of mean monthly radiation sums and near-surface temperature values (2022–2060) in randomly selected points (lower right map) of Europe, based on the meteorological database used in the BISE model. On the x-axis, the coordinates and Koeppen-Geiger climate zones of the selected points are included. For the description of the climate zones, please refer to [58].

Fig. 3. Comparison of building footprints in the GHSL-based (red polygons) and OSM + MGBF-based (yellow polygons) classifications over a randomly selected rural region of Hungary (bottom left map). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

0.5 and 1 for titled and flat roofs, respectively. Also, the building stock was projected without protected rooftops ($C_{PROT} = 1$). In C_{SL}, the latitudinal deviation of β was included. The influence of rooftop obstacles on space availability (e.g., HVAC systems on office buildings) was controlled via the C_{CON} and C_{SA} variables. Finally, the very complex shading patterns could be formed over building rooftops were estimated via the shading coefficient of the U_F (C_{SH}) that was later fixed over the modelling period.

The C_{SH} coefficients were generated relying on very accurate LIDAR data collected from random countries representing specific climate zones of Europe. From the LIDAR data, a 3-D surface model was created for each urban area (Fig. 5), based on which the buildings were segregated from other surface elements. As a next step, a building rooftop (surface) analysis was performed using the WhitetoolBox[6] Python package to retrieve the mean annual 'hillshade' factor for all buildings of a selected city. Table 2 indicates that buildings in cities with colder climates (i.e., less radiation over the years) have more shaded rooftops compared to the Mediterranean region, which results in less unshaded (and PV-suitable) rooftop area in the earlier case. By assuming that shading could be similar at climate-zone level, the results of the LIDAR data analysis were extended to other rooftops located in the same climate (here the climate classification of the HEB model was considered [51]) as the reference ones (Table 2).

The disaggregation of the rooftops by years, countries and building types were carried out with the help of the HEB model. Precisely, annual shares of floor areas for the given t, r and p level were gathered from this

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[6] https://www.whiteboxgeo.com/manual/wbt_book/available_tools/lidar_tools.html#LidarRooftopAnalysis

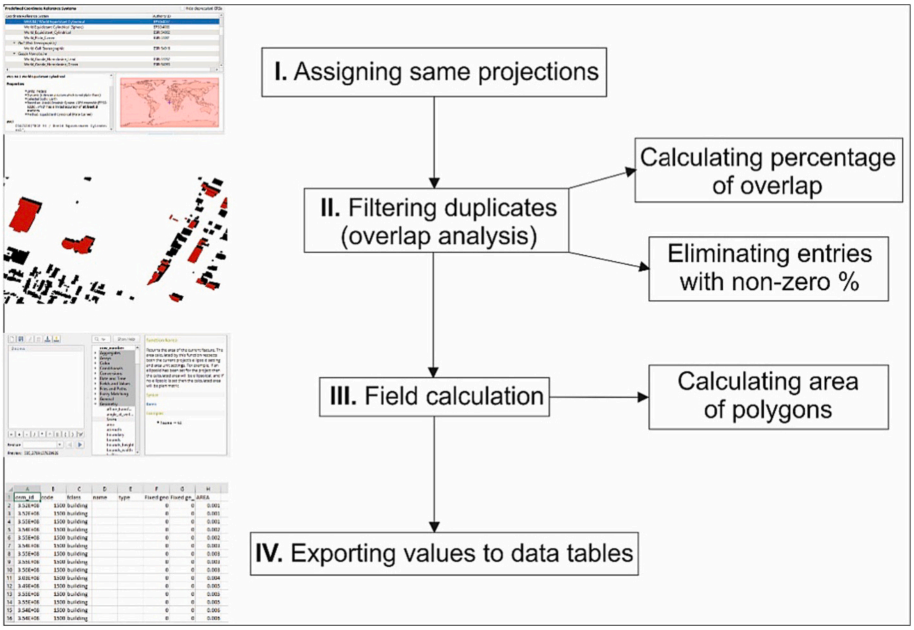

Fig. 4. Flowchart of generating building footprint data in the BISE model using the OSM and MGBF databases.

Table 1
Share of flat and pitched roofs published in the reviewed literature. The other coefficients used in Eq. (2) are summarized in [52]. For the description of the climate zones, please refer to [58].

Country (region/ urban area)	Percentage of flat and pitched roofs	Dominant climate zone	Reference
Germany (Baden-Wuerttemberg)	Flat: 9% Pitched: 91%	Dfb	Mainzer et al. [66]
Spain (Andalusia)	Flat: 38–40% Pitched: 60–62%	Csa/Csb	Ordónez et al. [29]
Spain (Canary Island)	Flat: 70–95% Pitched: 5–30%	Bwk	Schallenberg-Rodríguez [67]
Sweden (Vasterås)	Flat: 18% Pitched: 82%	Dfb	Yang et al. [68]
EU-27 + UK	Flat: 45% Pitched: 55%	–	Gevorgian et al. [65]

model ($f_{t,r,p}$) and were employed to generate the $RA_{t,r,p}$ values. Then, the final $RA_{\text{available } t,r,p}$ was retrieved by solving Eq. (3). It is also important to mention that the building footprint-based RA values were assumed to be valid for the initial year of the modelling period (RA_{2022}). In the rest of the modelling era (between 2023 and 2060), RA was calculated with the HEB-based $f_{t,r,p}$ shares being aggregated to each t, r and p level as:

$$RA_{t,r,p} = \frac{f_{t,r,p}}{f_{2022,r,p}} \bullet RA_{2022,r,p} \tag{4}$$

Naturally, if there is an increase (decrease) in the share of a given year relative to the year 2022, the $RA_{t,r,p}$ becomes proportionally larger (lower). From the modelling year 2023, Eq. (4) was always computed initially to finally get the $RA_{\text{available } t,r,p}$.

2.5. *Definition of parameters for solar PV panels*

To specify the technological parameters required by the BISE algorithm, data sheets of the products of the most popular PV panel manufacturers were reviewed. The purpose of this process was to find rooftop panels with the highest performance in terms of electric efficiency ($\eta_{r,elec}$), temperature coefficient (β_p) and nominal power (P_{max}), which was mostly motivated by two reasons concerning the length of the modelling period. Over the 39 years, the performance of PV panels will probably be growing remarkably, therefore applying high-quality PV panels may not

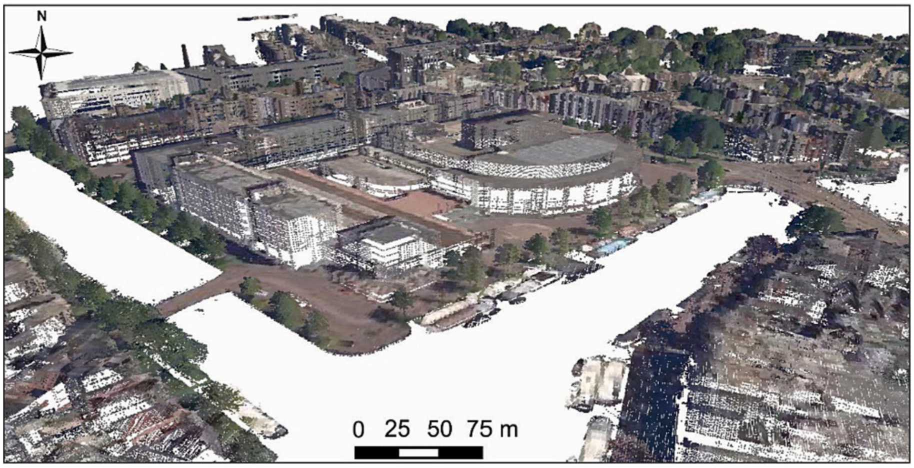

Fig. 5. An example of the LIDAR-based 3D surface models (Rotterdam, the Netherlands) created to estimate roof-specific modelling inputs.

Table 2
Estimated shading over buildings in reference urban areas of specific European climate zones. The CID refers to the climate ID used in the climate classification of our HEB model. Footnotes indicate the data sources for LIDAR data for a given urban area.

Reference urban area	Climate zone (HEB classification)	Other climate zones to extend	Shading (%)
Tampere (Finland)[a]	CID 1 – Only heating (Very high heating demand)	–	61%
Zürich (Switzerland)[b]	CID 2 – Only heating (High heating)	–	42%
Rotterdam (The Netherlands)[c]	CID 3 – Moderate heating demand	–	47%
Marseille (France)[d]	CID 6 – Heating and cooling (Moderate heating and low cooling demand)	CID 7 – Heating and cooling (Moderate heating and cooling demand) & CID 9 – Heating and cooling (Low heating and moderate cooling demand)	38%
Málaga (Spain)[e]	CID 10 – Heating and cooling (Low heating and cooling demand)	CID 18 – Heating, cooling and dehumidification (Low and moderate heating and cooling demand)	29%

[a] https://tiedostopalvelu.maanmittauslaitos.fi/tp/kartta?lang=en
[b] https://www.swisstopo.admin.ch/en/geodata/height.html
[c] https://app.pdok.nl/ahn3-downloadpage/
[d] https://geoservices.ign.fr/lidarhd
[e] http://centrodedescargas.cnig.es/CentroDescargas/locale?request_locale=en

underestimate the future technical potential too much. Secondly, the efficiency of PV systems usually drops by about 0.2% annually [70], which means that the degradation of most panels would be too high to consider only one installation cycle. A few cutting-edge PV panels, however, can guarantee even 40-year power warranty and 25-year product warranty for the inverter.

The SunPower-Maxeon6 440 (SPR-MAX6–440-E3-AC) prototype is one of these highly developed products [71] that was used to represent the rooftop PVs during the simulations. The specification of the SPR-MAX6–440-E3-AC is summarized in Table 3. This PV panel is covered by high-transmission anti-reflective tempered class and consists of 66 monocrystalline IBC (interdigitated back contact) N-type cells. It converts direct current to altering current with a factory-integrated microinverter. As the inputs of the BISE, only the parameters listed in Table 3 were employed.

2.6. Scenario configuration

Beyond the estimation of the technical potential of the rooftop PV electricity production, this study intends to quantify how much different policies for PV installation could contribute to the increase in the rooftop solar electricity supply to the total power production. In order to analyze one recent of them, three scenarios were constructed by using the BISE's roof area and PV potential projections.

During the definition of the scenarios, the first step was to subdivide the building categories of the BISE model to assign different building vintages. As all previous disaggregation stages, this procedure was also performed with the help of the HEB model from which the possibilities of future shares of the five building vintages (i.e., standard/existing, new, retrofitted, advanced new and advanced retrofitted) were transferred for each building types (for the definition of HEB vintages and scenarios, please refer to [51]). The BISE scenarios were designed by following their original HEB names to be 'Low installation', 'Moderate installation' and 'Intense installation'. Then the recently announced EU Solar Rooftop Initiative was translated to the current building vintage types as follows:

Table 3
Technical specification of the rooftop PV panel used during the simulations [71].

Model: *SPR-MAX6–440-E3-AC*	
Attribute	Value
Nominal power (P_{max})	440 W
Nominal electric efficiency ($\eta_{r,elec}$)	22.8%
Temperature coefficient (β_p)	−0.29%/°C
Max. continuous output power ($P_{max,inv}$)	366 VA
Microinverter efficiency ($\eta_{r,inv}$)	95.6%
Size	1.9 m^2

- All new commercial/public buildings will be installed with rooftop PVs from 2026.
- All existing and retrofitted commercial/public buildings will be installed with rooftop PVs by 2027.
- All new residential buildings will be installed with rooftop PVs from 2029.

To obtain a scenario that prescribes regulation for all possible building vintage types of the BISE model, the above points of the Solar Rooftop Initiative were completed with three additional assumptions:

- All advanced (retrofitted + new) buildings (residential + commercial/public) will be installed with rooftop PVs from 2022.
- All retrofitted buildings (residential) will be installed with rooftop PVs from 2030.
- 33% of the existing buildings (residential) will be installed with rooftop PVs by the end of the modelling period, characterized by logarithmic pace (own assumption).

Naturally, different shares of building vintages can make the installation rates and thus the calculated potentials very divergent (Table 4). During the modelling activity, all buildings were assumed to be 'standard' in 2022. After this year, however, various building vintage shares were defined to create the different installation scenario cases. In the meantime, other, building-independent input variables (e.g., technological and meteorological) were kept identical in each scenario. After performing all experiments, the results were aggregated to country and EU-level to be able to easily compare them with annual electricity consumption data and with the default ('Baseline') simulation.

3. Results

In the subsections below, the most important modelling results are summarized. As an initial step, the PV-compatible roof area estimations are shown for the whole EU and different member states. Based on the dynamics of the building rooftops over the simulation period, the estimations carried out for the rooftop PV technical potential are then presented. Lastly, within the framework of a scenario analysis, these 'baseline' values are compared with the predicted expansion in the rooftop PV power supply induced by the EC's Solar Rooftop Initiative for the largest economies of the EU.

3.1. Estimation of roof area available for PV installation

In Fig. 6, the roof area suitable for PV installation is presented in an

Table 4
Share of building vintages used in the three scenarios. These shares were implemented from the HEB model [51].

Scenario/vintage (year)	Low installation			Moderate installation			Intense installation		
	2030	2045	2060	2030	2045	2060	2030	2045	2060
Standard	78%	42%	15%	71%	14%	0%	71%	14%	0%
New	9%	25%	37%	9%	10%	8%	7%	7%	0%
Retrofitted	10%	28%	40%	14%	26%	5%	12%	11%	0%
Advanced	2%	5%	7%	6%	50%	88%	10%	69%	100%

aggregated form and building type-wise for the entire EU. Estimations show that the EU-level available roof area is anticipated to grow from 10.56 billion m^2 in 2022 to 13.74 billion m^2 in 2060, resulting in a 30.11% increase (Fig. 6a). Fig. 6b shows that when referring to building categories, the available roof area in residential buildings is predicted to stay nearly constant (from 8.66 billion m^2 in 2022 to 9.10 billion m^2 in 2060, an increase of 5.1%) over the analysis period, while in commercial buildings, a grow of 144.2% (from 1.90 billion m^2 in 2022 to 4.64 billion m^2 in 2060) is modelled.

When evaluating the available roof area for the member states (plus the UK), Fig. 7 shows that the countries with the highest (absolute) available roof area include Germany (with simulated changes from 2.21 billion m^2 in 2022 to 2.57 billion m^2 in 2060), France (with simulated changes from 1.46 billion m^2 in 2022 to 2.00 billion m^2 in 2060), Poland (with simulated changes from 0.89 billion m^2 in 2022 to 1.25 billion m^2 in 2060) and Italy (with simulated changes from 0.86 billion m^2 in 2022 to 0.97 billion m^2 in 2060). In the meantime, the highest growth rates are found for such countries as Ireland (with simulated changes from 0.15 billion m^2 in 2022 to 0.32 billion m^2 in 2060; an increase of 110.1%), Luxembourg (with simulated changes from 0.015 billion m^2 in 2022 to 0.027 billion m^2 in 2060; an increase of 77.4%), Romania (with simulated changes from 0.48 billion m^2 in 2022 to 0.85 billion m^2 in 2060; an increase of 76.7%) and Cyprus (with simulated changes from 0.047 billion m^2 in 2022 to 0.077 billion m^2 in 2060; an increase of 64.7%). Finally, the few countries where the available roof area is simulated to decrease in the period considered are Latvia (with simulated changes from 0.056 billion m^2 in 2022 to 0.048 billion m^2 in 2060; a decrease of 14.1%) and Croatia (with simulated changes from 0.12 billion m^2 in 2022 to 0.11 billion m^2 in 2060; a decrease of 5.6%).

3.2. Estimation on the technical potential of rooftop PV electricity production

The modelled technical potential of rooftop PV electricity supply in EU-27 and the UK for the period 2022–2060 shows an increase of 32.4% (from 2.69 PWh to 3.56 PWh in 2060) (Fig. 8). By comparing with the results for the available roof area (Fig. 6), it is clearly seen that this potential, as expected, has a robust correlation with the changes in the PV-compatible roof area.

Again, as a result of the projections given for the available roof area (Fig. 7), countries with the largest building stock are typified by the highest PV potentials: Germany (with simulated changes from 0.54 PWh in 2022 to 0.65 PWh in 2060; an increase of 20%), France (with simulated changes from 0.38 PWh in 2022 to 0.55 PWh in 2060; an increase of 45%), Italy (with simulated changes from 0.23 PWh in 2022 to 0.28 PWh in 2060; an increase of 22%) and Poland (with simulated changes from 0.21 PWh in 2022 to 0.30 PWh in 2060; an increase of 43%) (Fig. 9). Countries with highest expansion in their building stock and PV potentials, on the other hand, include Ireland (with simulated changes from 0.035 PWh in 2022 to 0.070 PWh in 2060; an increase of 99.6%), Luxembourg (with simulated changes from 3.9 TWh in 2022 to 7.3 TWh in 2060; an increase of 89.9%), Romania (with simulated changes from 0.13 PWh in 2022 to 0.24 PWh in 2060; an increase of 84.4%) and Malta (from 3.5 TWh in 2022 to 5.8 TWh in 2060; an increase of 63.3%). And finally the most profound decreases are revealed for Latvia (with simulated changes from 0.013 PWh in 2022 to 0.011 PWh in 2060; a decrease of 15%), Croatia (with simulated changes from 0.032 PWh in 2022 to 0.031 PWh in 2060; a decrease of 5.4%) and Lithuania (with simulated changes from 0.027 PWh in 2022 to 0.26 PWh in 2060; a decrease of 1.33%). It must be noted that the findings, however, indicate higher overall electricity generation potential of rooftop PVs in countries with millions of buildings and significant available roof area (e.g., Germany and Poland), the normalized potential (i.e., the total potential normalized by total suitable rooftop area) could be much higher in the southern member states (e.g., Greece, Portugal and Malta), due to climatic reasons.

Fig. 10 shows the PV potential estimations for all building types considered in the model, which can be described by a general growth in all analyzed types. Nonetheless, it is interesting to conclude that the electric generation potential in commercial buildings are anticipated to grow about 150% in all tertiary building types, while the values in residential buildings could rise by only 32.2% for multifamily buildings (from 0.43 PWh in 2022 to 0.57 PWh in 2060) and 0.71% for single family houses (1.77 PWh in 2022 to 1.79 PWh in 2060). Precisely, the power supply potential is modelled to grow in educational buildings from 0.069 PWh in 2022 to 0.17 PWh in 2060, in the 'others' category from 0.12 PWh in 2022 to 0.29 PWh in 2060, in offices from 0.040 PWh in 2022 to 0.10 PWh in 2060, in hospitals from 0.061 PWh in 2022 to 0.15 PWh in 2060, in hotels and restaurants from 0.036 PWh in 2022 to 0.088 PWh in 2060 and in retails from 0.16 PWh in 2022 to 0.39 PWh in 2060. However, the estimated numbers suggest that the largest rooftop PV potential in single family houses, the importance of such commercial sub-types as offices and retails could be increasingly pivotal in the future.

Fig. 11 illustrates the PV technical potential by building types for the six countries with the greatest aggregated PV potential. As discussed above, the electricity generation potential of rooftop PV panels is predicted with the lowest growth over the period 2022–2060 for residential buildings. To conduct residential buildings in details, the share of multifamily buildings in the total potential yields growth in Germany (from 16.5% to 19.2%) and in Italy (from 13.4% to 18.7%), stagnation in Spain (at around 31%) and decrease in France (from 17.2% to 13.4%). Meanwhile, the relevance of single family buildings decreases in all considered countries. In commercial buildings, the share of the rooftop PV technical potential increases for all building sub-types, independently from the member states considered. In all countries and all building types, the share of tertiary potential doubles relative to that of in 2022. Since the projections for the future dynamics of roof types are the function of socio-economic drivers (i.e., population and GDP) in the BISE model, the modelling estimations for the building-type based PV potential might have non-negligible uncertainties.

3.3. Scenario analysis in terms of the future rooftop PV technical potential

Fig. 12 presents the results for the simulated rooftop PV power production potential, considering different PV installation scenarios for the EU-27 and the UK, compared to the total EU electricity consumption in 2021. As it can be seen, the Baseline scenario considers the electric energy supply potential, being in parity with the total EU electricity consumption, to be 2.67 PWh in 2022. While in 2060, the PV potential is shown to grow to 3.56 PWh, which is substantially higher than the current level of consumption. On the other hand, the Low and the

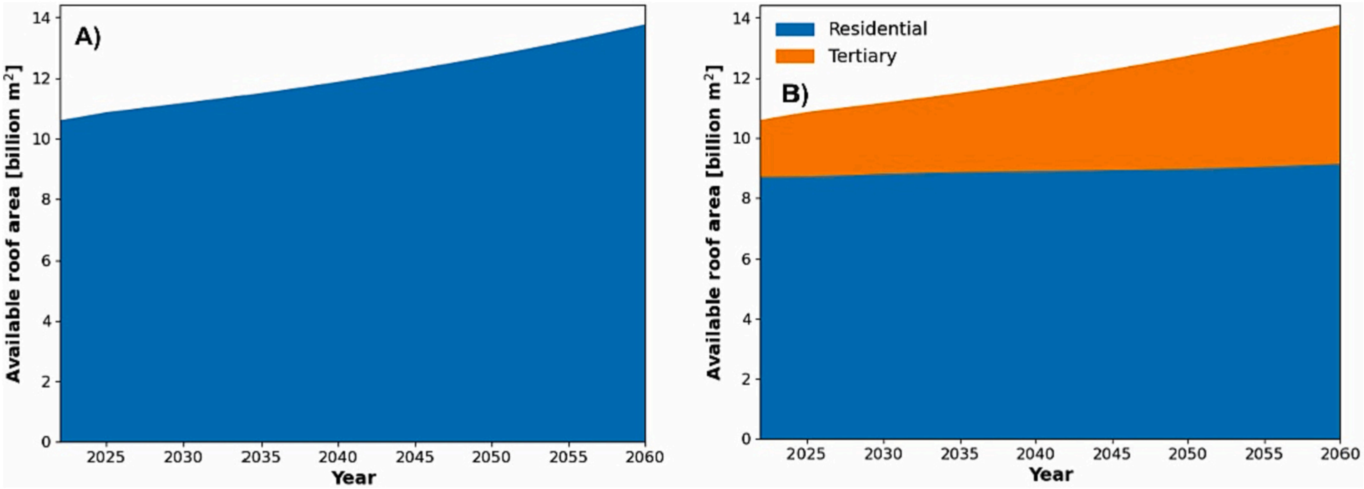

Fig. 6. Projected roof area availability (A – aggregated, B – by main building categories) for the EU-27 and the UK between 2022 and 2060.

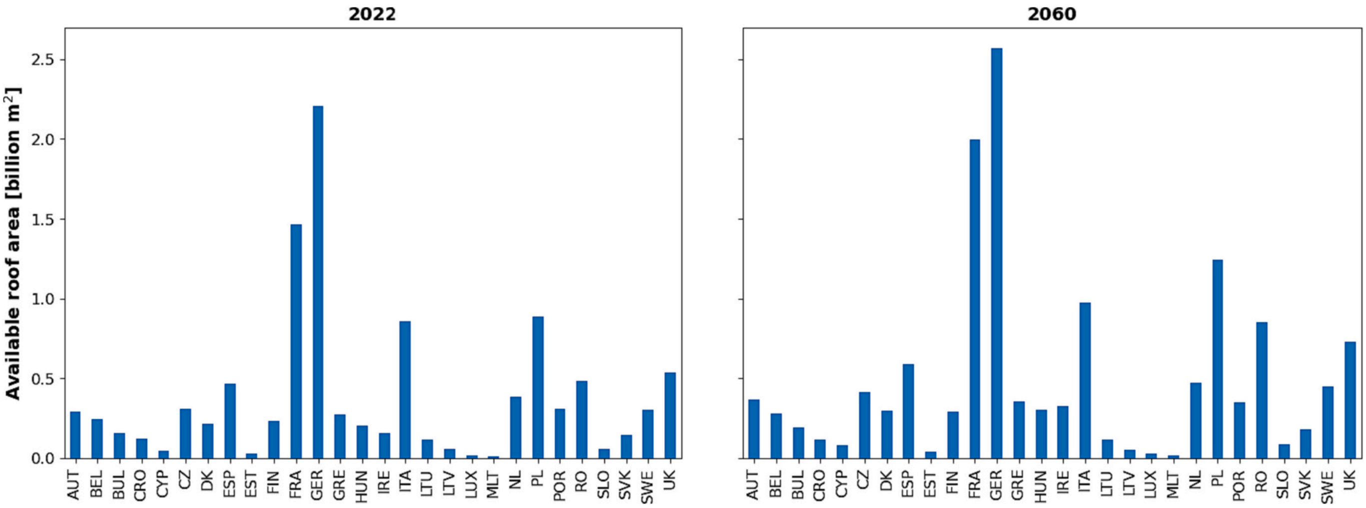

Fig. 7. Projected roof area availability for the EU-27 countries and the UK by 2022 and 2060.

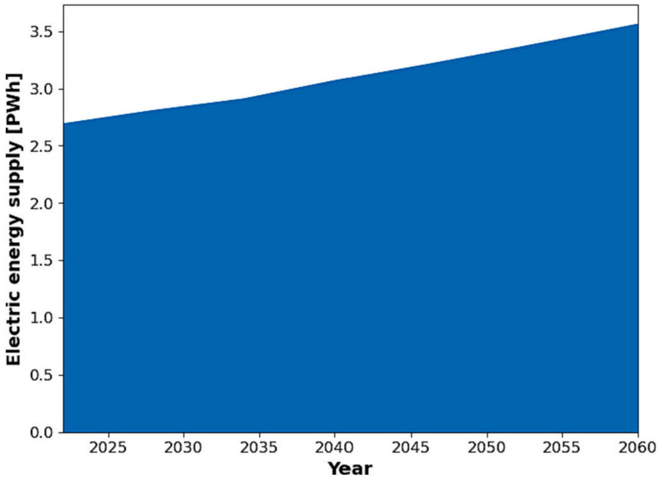

Fig. 8. Simulated rooftop PV technical potential for the EU-27 and the UK between 2022 and 2060.

Intense installation scenarios project an electric energy supply potential of 0.27 PWh in 2022, followed by a steep increase up to 2060 in both cases. The Intense installation scenario, however, results in slightly higher potential relative to the Low installation case, with estimated supply potentials of 3.56 PWh and 3.33 PWh, respectively. In other words, if the actions of the Solar Rooftop Initiative are followed, the expected outcome would be very different (in relative sense: 7%), depending on the structure of the building stock. With the slow introduction of energy-efficient (advanced, nearly net zero) buildings to the stock (i.e., Low installation scenario), huge potential might remain untapped, and a delay of about 5 to 10 years can happen in achieving a more significant level of rooftop PV energy production niveau.

The country-level differences are illustrated again for the member states with the largest buildings stock (Fig. 13). In Germany, the rooftop PV technical potential given by the Baseline scenario is found to be higher than its electricity consumption (with a trend very similar to that of the EU-27 and the UK) already in 2022. By considering the Low and Intense installation scenarios, the estimated potential could reach the current consumption level after 2040, but several years earlier if a more ambitious installation pace is followed. Experiments for France and Poland show a similar trend until 2060 than that of concluded for Germany. A major distinction, however, is that the PV technical potential for these member states could be lower than the total electricity

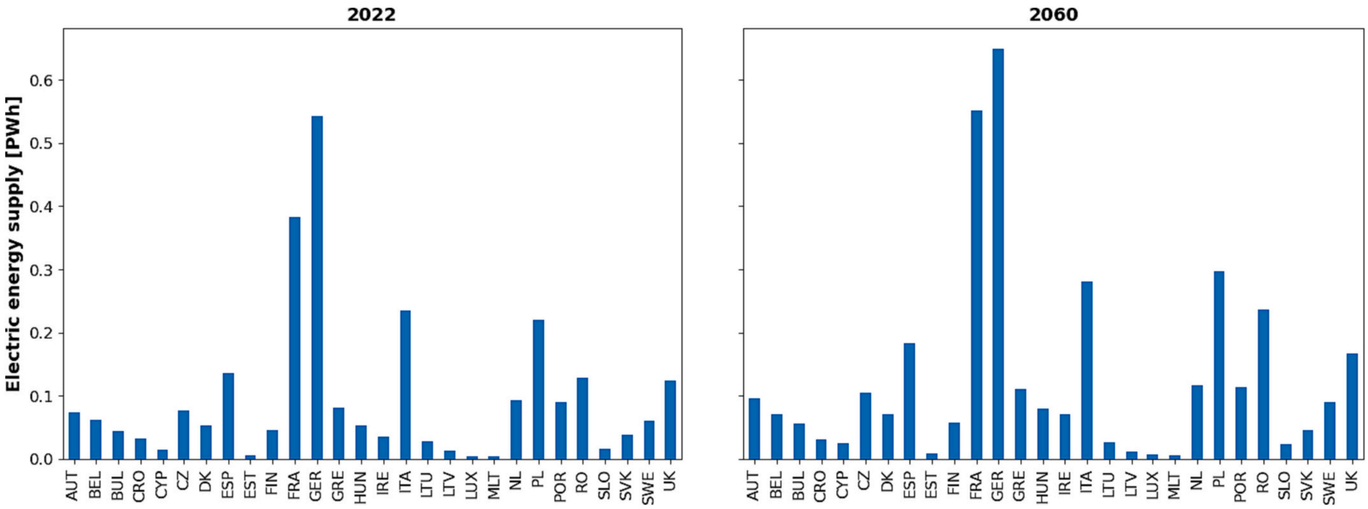

Fig. 9. Simulated rooftop PV technical potential for the EU-27 countries and the UK by 2022 and 2060.

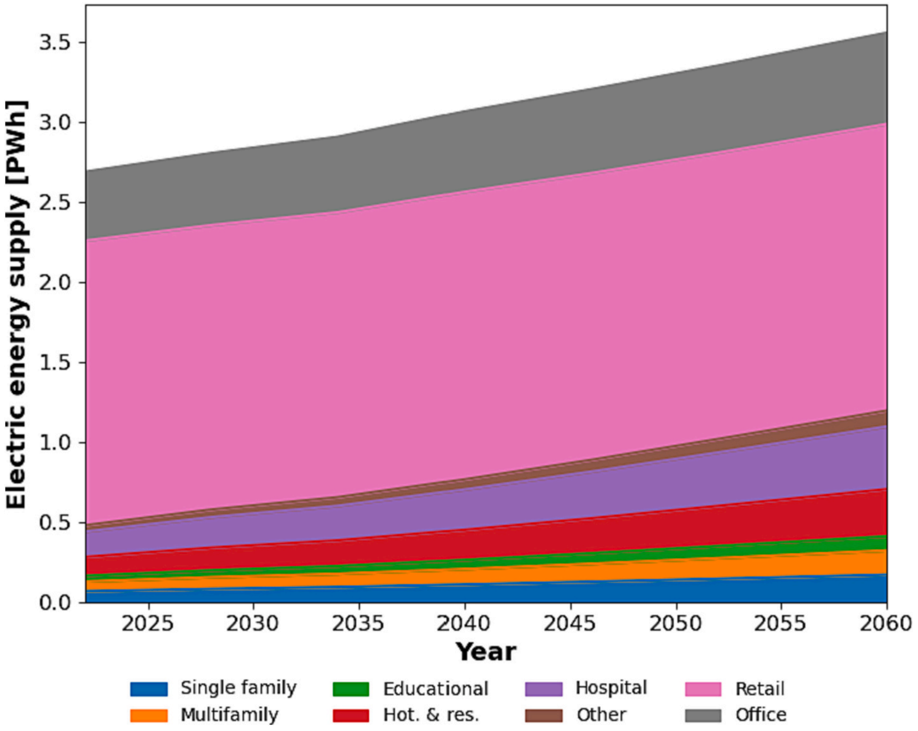

Fig. 10. Simulated rooftop PV technical potential by building types for the EU-27 and the UK between 2022 and 2060.

consumption in the initial years of the analysis period. In Poland, the PV power supply is estimated to grow rapidly in each of the presented scenarios, with a peak in the modelled growth rate by around 2035. This culmination occurs later in France, especially when the curve for the Low installation case is seen.

For the UK, Italy and Spain, the relative differences between the scenarios are in agreement with those found for the cluster of countries analyzed above, which is also the consequence of distinct installation rates applied. For these countries, on the other hand, the rooftop PV power generation potential is predicted to be well below the electricity consumption until 2060, with any of the modelled scenarios considered. These gaps between the potentials and consumptions might be rectified, first, by the slight underestimation of roof area availability (e.g., in Spain) and/or unfavorable climatic drivers (e.g., the UK). Secondly, the assumption for the ideal roof angle (lower angles towards lower latitudes) could increase the C_{GCR} factor of the U_F (please refer to Eq. (2)), which consequently reduces the fraction of PV-compatible roof area and hence curtails the potential in the Mediterranean regions.

It is important to emphasize that the default version of the BISE model, as highlighted in Section 3.4, excludes the effects for degradation and efficiency changes of the installed PV panels due to the highly unpredictable nature of future technological progress. Nevertheless, to obtain a generalized picture on how much the modelled rooftop PV power generation potential is sensitive to the fixation of these technological factors, a new set of modelling experiments is made, using the results illustrated in Fig. 12 as reference runs. Since the PV panel prototype employed during the modelling activity (and other state-of-the-art panels) represents an advanced technology (Table 4) and is characterized by a typical degradation of about 0.2%/year, one lifecycle can be assumed for each rooftop PV panel considered in the model. It

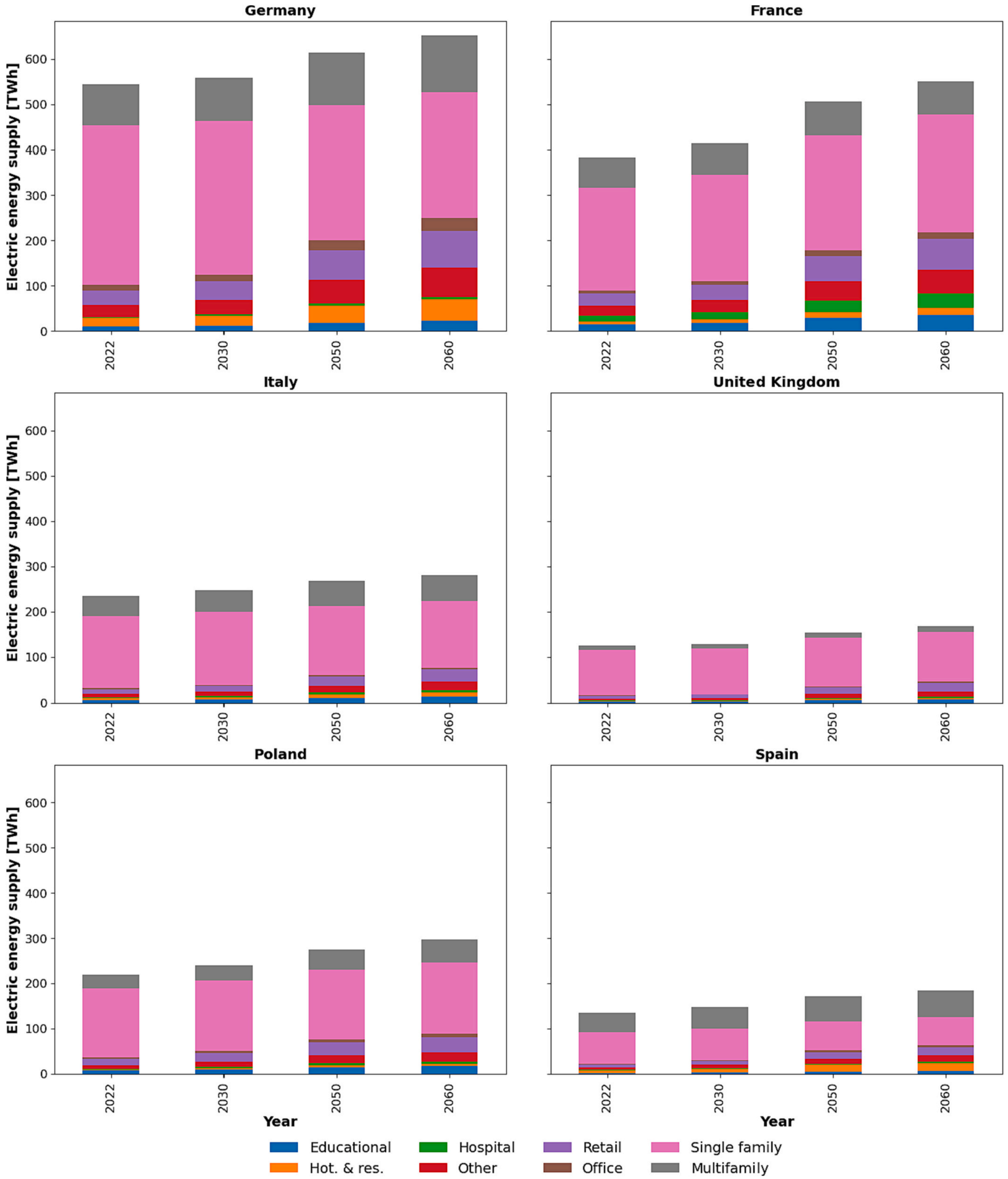

Fig. 11. Simulated rooftop PV technical potential by building types for countries with the largest aggregated potential by 2022, 2030, 2050 and 2060.

realistically means that among the technological attributes mentioned above, only the efficiency shift could impact the future values of the PV potential. Therefore, this experiment was designed to express the changes in the panel's efficiency with different linear trends (by increases of 0.2, 0.35 and 0.5%/year), while the degradation was fixed at a rate of 0.2% per annum.

The outputs of this analysis show that the considered efficiency rise of rooftop PV panels has the most pronounced impact on the power generation potential in the Baseline run (Fig. 14). The estimated difference is found to be the highest between the default case (no

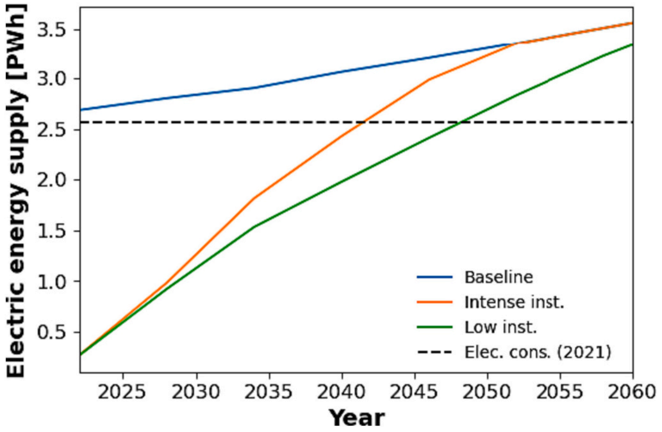

Fig. 12. Simulated rooftop PV power generation resulted by different PV installation scenarios for the EU-27 and the UK between 2022 and 2060. The dashed black line indicates the total EU electricity consumption in 2021.

degradation and efficiency change is defined) and the one with a degradation and efficiency progress of 0.2%/year. Quantitatively, the gap between these experiments is simulated to be 0.2 PWh (7%) by 2060 in the Baseline scenario. However, the High and Low installation scenarios are less influenced by this effect, the corresponding simulations with non-zero efficiency changes depict larger variabilities (2045: 6 TWh) than that of in the Baseline case (2060: 4.6 TWh).

In the comparison of the experiments for the High and Low installation scenarios, it can be concluded that by incorporating the temporal changes for the degradation and the efficiency of PV panels into the model, the likelihood to reach the 'real' technical PV potential given by the Baseline runs is much lower if the installation rate follows the Low installation scenario, and meanwhile the efficiency of producing green power is limited in contrast with the High installation case (Fig. 14). Another important conclusion, as the reverse in the magnitudes of the estimated potentials for the runs with the lowest degradation and efficiency progress rates of the High installation and Baseline scenarios after 2050 demonstrates (Baseline: 3.1 PWh; High installation: 3.2 PWh), if rooftop PV panels become widespread too quickly (i.e., in the Baseline scenario), the aggregated degradation effect could be elevated during the initial years. In the meantime, rising amounts of rooftop areas turn into unavailable for the installation of increasingly developed PV panels, compared to the case (i.e., High installation scenario) when PV systems are gradually established.

4. Comparison of BISE's rooftop PV potential to literature results

After reviewing relevant literature sources, our rooftop PV potential outputs were evaluated against other published results to ascertain the ability of the BISE model in capturing a reasonable magnitude for this measure. Because of the clear data lacking for building type-specific PV potential in the literature, these outcomes could not be directly compared. Owe to the availability of country-level references, however, the different potentials of rooftop PV power generation could contrasted for both the EU and certain member states.

Based on Table 5, it can be concluded that the estimated reference values range from 0.7 to 3.2 PWh for the EU. The technical potential of 2.7 PWh simulated by the BISE seems to be one of the largest. Although, due to the diversity of the methods, input data, reference time and simplifications applied in the reviewed investigations, the range of literature values can be interpreted as an inherent uncertainty factor for the estimated potentials. If the studies are grouped by the technique used to derive the available roof area, as a crucial parameter during the estimation, papers with statistical approach (e.g., [20,22]) obtained generally lower potential. On the other edge, the largest potential was estimated by [72] in which the suitable roof area was created by sophisticated XGboost machine learning technique. [24] found a rooftop PV potential that is slightly below 1 PWh and hence 80% lower than that of [72]. It is slightly surprising, because both analyses rely on similar GIS data (e.g., CORINE Land Cover and building footprint/cadastre) but on distinct methodological considerations.

Our values show the lowest deviation from the paper employs big data and artificial intelligence approach [72]. The agreement, therefore, is the consequence of the degree of sophistication in estimating suitable roof area values (reference: 7.6 billion m^2; this study: 10.6 billion m^2). On the other hand, [72] converted the roof area to potential by employing annual and monthly conversion factor (i.e., kWh produced by each kWp installed capacity per day) of the World Bank, while the BISE predicts the energy conversion in every hour of a given day, which may lead to slight temporal differences.

During the rooftop PV potential estimation, the technological specification of the reference PV panel is also essential. For example, the older studies calculated with lower PV efficiency (e.g., [73]: 10.5%), which resulted in lower rooftop PV potential (Table 4). In fact, this could partly be the explanation why the literature values for Spain ([28]: 14.7% efficiency and 70% lower potential) and Germany [74]: 14% efficiency and 70% lower potential) were reported to be much larger relative to our estimation. On the other hand, the BISE estimation of 200 TWh/year for the Italian potential is in a great agreement with the value of [75] in which the applied efficiency were defined to be very similar (22%).

5. Summary, discussion and final remarks

Employing on-site solar energy production in European buildings may be one of the feasible solutions towards the clean energy transition. In this paper, the technical potential of rooftop PV energy supply was calculated and projected with the BISE model by using different scenarios up to 2060. In the Baseline scenario, where all suitable building rooftop area was assumed to be installed with solar PVs, the EU-level technical potential was estimated to be around 2.7 PWh along with an increase of 33% until the end of the modelling period. This growth was related to the anticipated 'PV-compatible' rooftop area expansion, with a corresponding change from 10.56 billion m^2 in 2022 to 13.74 billion m^2.

At country level, the largest rooftop PV potential was revealed for countries with the highest rooftop availability (i.e., Germany and France), not for countries with the highest solar radiation (i.e., Spain or Greece). For the same reason, the lowest potential was found for countries with less building and suitable rooftop area. Nevertheless, if the aggregated potentials would be normalized by the rooftop availability, the (geographical/resource) PV potential is the highest in the southern countries of the EU (e.g., Spain, Portugal, Italy, Greece and Cyprus).

As a result of the projected building stock characteristics, residential buildings were simulated with the highest contribution to the total rooftop PV technical potential in 2022, although the biggest growth was found for such non-residential buildings as offices and retails. At this point, it is noteworthy that rooftop PVs might rather be suitable instruments to satisfy the in-situ energy demand and for low-rise residential buildings. Despite the high aggregated potential carried out by this analysis for high-rise, multi-story tertiary buildings, their individual (building-level) rooftop PV potential could be lower relative to single family buildings, due to their much lower roof to floor ratios.

Apart from the 'Baseline case', some relevant implications of the EC's Solar Rooftop Initiative were tested in the form of two rooftop PV installation scenarios. This analysis demonstrated that among the major economies of the EU, Germany and France could theoretically have the opportunity to balance their entire power demand by rooftop PV electricity production, although the installation pace and the building types within the stock could have a major influence on the timing. In the UK, Italy, Spain and Poland, contrarily, just a smaller fraction of the total

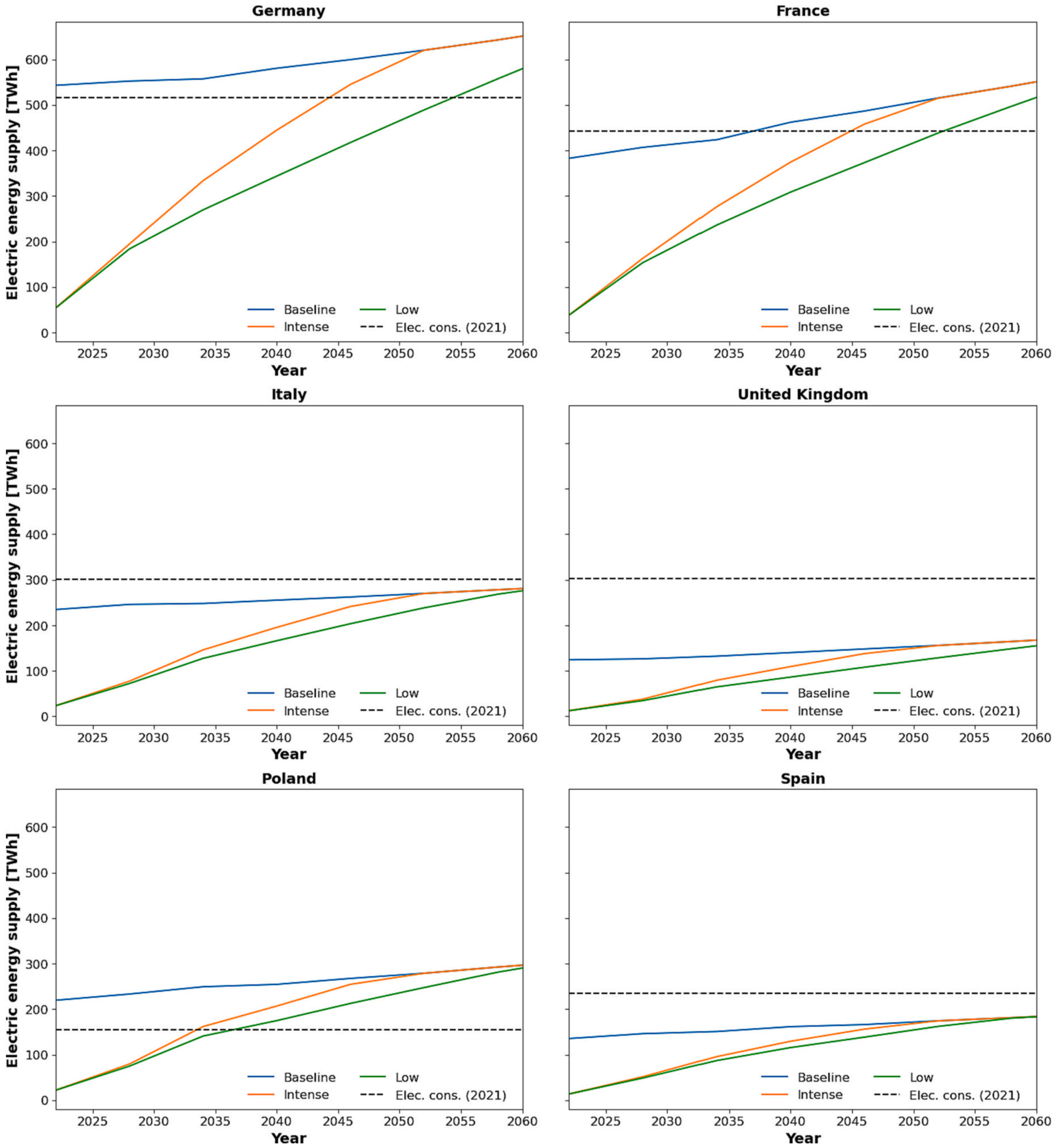

Fig. 13. Simulated rooftop PV power generation resulted by different PV installation scenarios for countries with the largest aggregated PV potential between 2022 and 2060. The dashed black lines indicate the country-level electricity consumption in 2021.

power consumption can be supplied by rooftop PV, independently from the installation efforts. Nonetheless, buildings consume only about one-third of the total electricity in the EU, therefore it does not mean that the building-level balance between the demand-supply side balance is impossible. It rather dictates that some countries need to make more efforts if they pick the rooftop PV technology as a key tool in energy transition.

To extend the discussion on the EU and country-level possibilities of rooftop PV, the estimated power production potential is compared with consumption statistics (Table 6). Based on Eurostat data [76], the total EU-level electricity consumption was 2.57 PWh in 2021. The results of the BISE model showcase that aggregated to the entire EU and to annual basis, cutting-edge PV panels could theoretically balance this energy demand if all suitable rooftop area would be installed by solar systems. Nevertheless, at country-level the possibilities, as partly seen earlier, may be very divergent.

For the Scandinavian countries (i.e., Finland and Sweden), it was found that the PV technical potential is much lower than the consumption (Table 6), which could be the consequence of low annual radiation income at the higher latitudes of Europe. Same conclusion can be drawn for Estonia. In case of Belgium and France, the explanation of the slight difference between the potential and consumption is not connected with the climate but rather with the large magnitude of demand side or with the underestimation of the potential via the total roof area. The latter assumption could be especially valid for Spain and Italy where the mean climatic potential (areas with annual solar radiation over 1500 kWh/m^2) is among the largest ones within the EU.

In countries, for which the potential was estimated to be higher than the consumption, the largest excesses of production occur in Lithuania, Cyprus, Slovakia, Romania, Portugal and Croatia (Table 6). For

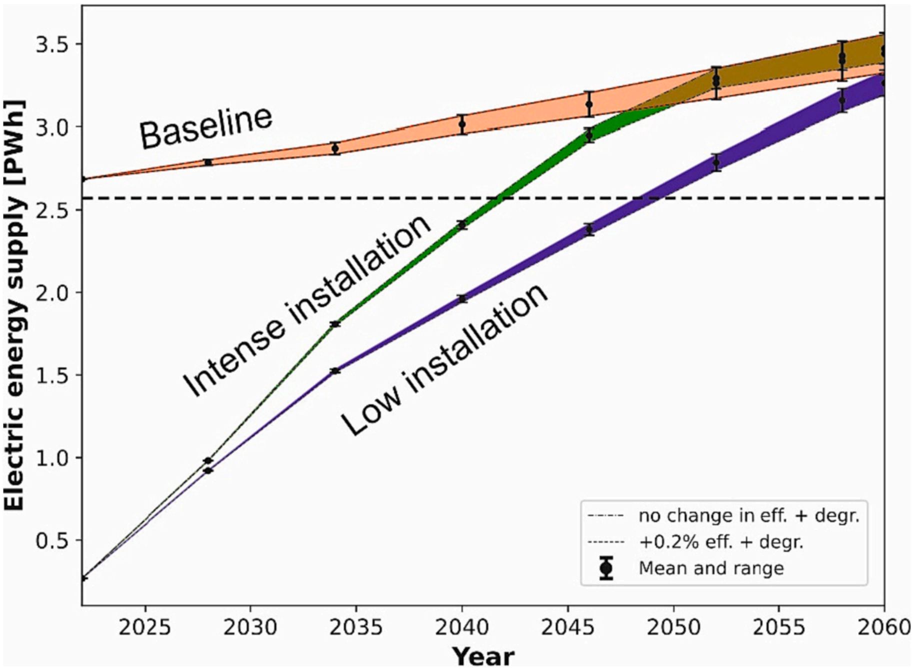

Fig. 14. As in Fig. 12., but includes simulation results with the assumption of +0.2%/year efficiency rise and degradation for rooftop PV panels. The shaded areas express the level of uncertainty caused by the different assumptions for these technological measures.

Table 5
Comparison of the rooftop PV technical potential of the BISE model to values exist in the literature. Please note that the PV electric efficiency in the BISE model was assumed to be 22.8%.

Study	Region/ country	Temporal validity (reference ↔ current study)	Assumed electric efficiency of PV module	Estimation by reference study [PWh]	Estimation by BISE model [PWh]
Hoogwijk [73]	EU-27 + UK	2004 ↔ 2022	10.5%	1.2[a]	2.7
Gernaat et al. [25]	EU-27 + UK	2020 ↔ 2022	17%	0.7	2.7
Joshi et al. [72]	EU-27 + UK	2021 ↔ 2022	10%	2.9[b]	2.7
Defaix et al. [22]	EU-27[c]	2030 ↔ 2022	19.7%	0.8[d]	2.7
Bódis et al. [24]	EU-27 + UK	2016 ↔ 2022	14%[e]	0.7	2.7
Mainzer et al. [74]	Germany	2013 ↔ 2022	14.5%	0.15[f]	0.5
Mazzer and Moser [75]	Italy	2021 ↔ 2022	22%	0.2	0.2
Izquerdo et al. [28]	Spain	2011 ↔ 2022	14.7%	0.04	0.14

[a] Sum of decentralized PV potential for Eastern Europe and OECD Europe.
[b] Aggregated to the whole European continent.
[c] Includes the UK and excludes Croatia.
[d] Total BIPV potential (i.e., roof + facade).
[e] Balance-of-system and degradation losses.
[f] Estimated for residential buildings.

Table 6
Comparison of BISE's technical roof to the EUROSTAT electricity data [76].

Country	Estimated rooftop PV potential [TWh]	Electricity consumption in 2021 [TWh]	Share of potential to the consumption (%)
Austria	73.7	66.1	111
Belgium	61.0	83.7	73
Bulgaria	43.5	31.7	137
Croatia	32.3	16.8	192
Cyprus	14.7	4.7	314
Czechia	77.1	61.9	125
Denmark	52.2	34.4	152
Estonia	6.0	8.6	69
Finland	45.2	83.2	54
France	382.8	442.5	86
Germany	543.1	515.8	105
Greece	80.6	49.8	162
Hungary	53.4	43.9	122
Ireland	35.0	29.8	118
Italy	234.7	300.6	78
Lithuania	27.0	6.9	390
Latvia	12.9	12.0	108
Luxembourg	3.9	6.5	60
Malta	3.5	2.5	139
Netherlands	93.1	113.4	82
Poland	219.5	154.0	143
Portugal	90.1	48.2	187
Romania	128.3	50.7	253
Slovenia	15.8	25.7	61
Slovakia	37.5	13.5	277
Spain	135.4	235.0	58
Sweden	60.2	130.0	46
EU-27	2,680	2,572	104

Portugal, Cyprus and Croatia, the favorable ratio can be attributable to the abundant radiation availability. In Romania and Slovakia, the share of the electricity in the total energy consumption is below the EU average, hence in this case the relatively low level of consumption can be balanced by rooftop PV electricity. For Lithuania, the overestimation of the potential seems to be the most likely explanation. Among the largest economies in the EU, it must be highlight again that the highest possibility to offset the consumption with building-integrated solar energy was found for Poland and Germany.

One of the most burning questions for the future is obviously that how much of this rooftop PV potential can be exploited in an economically feasible way. Although estimating the economic potential is beyond the scope of this research, the literature confirms that most of the green power of rooftop PV panels is producible at competent cost in the EU. As [77] concludes, about 70% of the potential they calculated can be used to replace 'unclean' electricity. As a result of the sky-rocketing energy prices globally, the return on investment for PV has decreased to a year in many member states.[7] Therefore, the time has come to be even more ambitious in upscaling the PV installation capacity in the EU. As [24] highlights, countries as France, Germany, Portugal and Belgium have the highest opportunity for contributing to the outburst of cost-competitive rooftop PV.

Upscaling the installation rates and making the installation costs reasonable in the highest possible number of EU countries are seemingly met with the goals of the European Commission, which was declared under the Solar Rooftop Initiative. Our model shows that the future extent and composure of the building stock will be key of how fast rooftop PV becomes a standard at buildings. As the scenario analysis indicates, there could be a significant variability in the level of energy production, depending on the share of buildings with advanced construction. The maximization of energy supply by solar PVs could only be feasible by gradually transforming the building stock to be energetically self-sufficient.

Based on the building type projection of the BISE model, promoting self-sufficiency and PV technology would be the most profound for residential buildings, thanks to their large fraction in the entire stock. However, due to the anticipated increase in the share of tertiary buildings, it is also necessary to force rooftop PV installations for these categories. In this regard, we note again that majority of the commercial/public buildings have multiple floors, their respective roof to floor ratio is small, which implies that the installation of PV panels on building facades might also facilitate substantial potential.

Irrespective to the applied way of installing method, the owners of tertiary buildings can usually utilize the benefits of PV systems at a shorter payback period than that of the residential sector. Financial and willingness factors could also be huge barriers to increase the volume of PV installation for family buildings. It is particularly true in the less developed economic regions of the EU where the building stock is the oldest and the most energy inefficient. Consequently, as many member states correctly identified, long-term funding strategies on deep renovation (including PV installation), favorable country-level feed-in tariff schemes and regulatory incentives (e.g., green certificates and removing administrative barriers) must be established to be able to effectively shift from old, dominantly fossil fuel-based technologies to sustainable solutions. To make rooftop solar PVs more competitive for the as many actors of the residential sector as possible, a successful subsidizing policy should be complemented with upscaling of the European share in manufacturing solar panels, inverters and batteries. By shortening the supply chain, not only the security of production can be guaranteed, but also the prices of PV products could be controlled better.

However, the current study analyzed the year-to-year tendency of the rooftop PV potential, the intra-annual ratio of power production and consumption can be quite different. It means that there are many periods over the year when mismatch occurs (e.g., winter: consumption > production; summer: consumption < production). To obtain a balance at building level, on the one hand, the energy surplus can be fed into the grid and recall later at no-production hours. On the other hand, there are energy storage solutions that are still quite expensive. It can already be seen that the extremely increasing power production of rooftop PVs poses remarkable and complex challenges for the electricity grid to ensure its stability and reliability in the EU. The ideal grid operation can be obtained by maintaining a power transmission system that has the capacity for limiting unwanted periods of large frequency/voltage deviations, high transformation losses, transmission line overload, synchronism losses, increased power oscillation and outages [15]. If only the building segment of the PV sector is highlighted, microgrid systems could offer realistic solutions to keep the national electricity power grid operable and to satisfy the local demand at all times. As the initial costs of electricity storage devices has been dropping significantly over the recent years, microgrid systems have become increasingly cost-efficient [78] and can operate with the adequate stability under various configurations [79]. Consequently, it can be hypothesized that by further subsidizing the widespread of battery technologies among building owners can result in high number of prosumer communities. Several great examples are already seen in many member states (e.g., Germany and France), yet, the more effective utilization of the available rooftop PV potential can only be unlocked by making the best-practices available for the less developed EU in a cost-effective manner.

Despite the major uncertainties of the future trends in the building stock and PV potential, this study gives a robust modelling evidence on that the latest rooftop PV policy packages of the EU could lead to a major upscale in the current on-site power generation. Still, further research must be done to bridge some of the literature knowledge gaps as well as the limitations of this modelling work. Our future research agenda, therefore, to improve our suitable roof area estimations by extending the sample areas for which LIDAR data is processed. Moreover, we intend to create learning curves for the most important technological parameters of PV panels and explicitly include the efficiency progress in the model. By doing so, the BISE model can capture the influence of the progress of solar technology on the technical potential over the next decades. Finally, extending the functionality of the BISE model with wall-integrated PV simulations is important, which would help to better explore the various possibilities of different building-integrated solutions.

CRediT authorship contribution statement

Gergely Molnár: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Luisa F. Cabeza:** Writing – original draft, Visualization. **Souran Chatterjee:** Writing – original draft, Supervision, Methodology. **Diana Ürge-Vorsatz:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Diana Urge-Vorsatz, Souran Chatterjee, Gergely Molnar reports financial support was provided by European Commission. Diana Urge-Vorsatz, Souran Chatterjee reports financial support was provided by Japan Ministry of Economy Trade and Industry. Luisa F. Cabeza reports financial support was provided by Catalan Government.

Data availability

Data will be made available on request.

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[7] https://www.pv-magazine.com/2022/10/14/wind-solar-payback-times-under-a-year-in-some-parts-of-world-says-rystad/ (accessed on 8th December 2022)

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References

[1] Remeikienė R, Gasparėnienė L, Fedajev A, Szarucki M, Đekić M, Razumienė J. Evaluation of sustainable energy development progress in EU member states in the context of building renovation. Energies 2021:14. https://doi.org/10.3390/en14144209.

[2] European Commission. EU green deal. 2020.

[3] Carbon Tracker. The Sky's the Limit: Solar and wind energy potential is 100 times as much as global energy demand. 2021.

[4] Gul M, Kotak Y, Muneer T. Review on recent trend of solar photovoltaic technologyvol. 34; 2016. https://doi.org/10.1177/0144598716650552.

[5] EurObservER. Solar thermal and concentrated solar power barometer 2022. 2022.

[6] EurObservER. Photovoltaic barometer. 2022.

[7] Huang L, Zheng R. Energy and economic performance of solar cooling systems in the hot-summer and cold-winter zone. Buildings 2018:8. https://doi.org/10.3390/buildings8030037.

[8] Solar Heat Europe. Energising Europe with solar heat – a solar thermal roadmap for Europe. 2022.

[9] SolarPower Europe. EU market outlook for solar power 2020–2024. 2020.

[10] European Commission. EU solar energy strategy. 2022.

[11] European Commission. REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition. 2022.

[12] CAN Europe. Engaging citizens and local communities in the solar revolution rooftop solar PV country comparison report. 2022.

[13] Fraile D, Vandenberghe A, Klonari V, Ramirez L, Pineda I, Tardieu P, et al. Getting fit for 55 and set for 2050 | WindEurope. 2021.

[14] Zsiborács H, Pintér G, Vincze A, Birkner Z, Baranyai NH. Grid balancing challenges illustrated by two European examples: interactions of electric grids, photovoltaic power generation, energy storage and power generation forecasting. Energy Rep 2021;7:3805–18. https://doi.org/10.1016/j.egyr.2021.06.007.

[15] Medina C, Ana CRM, González G. Transmission grids to Foster high penetration of large-scale variable renewable energy sources -a review of challenges, problems, and solutions. Int J Renew Energy Res 2022;12:146–69. https://doi.org/10.20508/ijrer.v12i1.12738.g8400.

[16] Abdelghany MB, Al-Durra A, Zeineldin H, Gao F. Integrating scenario-based stochastic-model predictive control and load forecasting for energy management of grid-connected hybrid energy storage systems. Int J Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.05.249.

[17] Garcia-Torres F, Bordons C, Tobajas J, Marquez JJ, Garrido-Zafra J, Moreno-Munoz A. Optimal schedule for networked microgrids under deregulated power market environment using model predictive control. IEEE Trans Smart Grid 2021; 12:182–91. https://doi.org/10.1109/TSG.2020.3018023.

[18] Merabet A, Al-Durra A, El-Saadany EF. Improved feedback control and optimal management for battery storage system in microgrid operating in bi-directional grid power transfer. IEEE Trans Sustain Energy 2022;13:2106–18. https://doi.org/10.1109/TSTE.2022.3184165.

[19] Defaix PR, van Sark WGJHM, Worrell E, de Visser E. Technical potential for photovoltaics on buildings in the EU-27. Sol Energy 2012;86:2644–53. https://doi.org/10.1016/j.solener.2012.06.007.

[20] Gernaat DEHJ, de Boer HS, Dammeier LC, van Vuuren DP. The role of residential rooftop photovoltaic in long-term energy and climate scenarios. Appl Energy 2020; 279:115705. https://doi.org/10.1016/j.apenergy.2020.115705.

[21] Jäger-Waldau A, Kougias I, Taylor N, Thiel C. How photovoltaics can contribute to GHG emission reductions of 55% in the EU by 2030. Renew Sustain Energy Rev 2020:126. https://doi.org/10.1016/j.rser.2020.109836.

[22] Defaix PR, van Sark WGJHM, Worrell E, de Visser E. Technical potential for photovoltaics on buildings in the EU-27. Sol Energy 2012;86:2644–53. https://doi.org/10.1016/j.solener.2012.06.007.

[23] Castellanos S, Sunter DA, Kammen DM. Rooftop solar photovoltaic potential in cities: how scalable are assessment approaches? Environ Res Lett 2017:12. https://doi.org/10.1088/1748-9326/aa7857.

[24] 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. https://doi.org/10.1016/j.rser.2019.109309.

[25] Gernaat DEHJ, de Boer HS, Dammeier LC, van Vuuren DP. The role of residential rooftop photovoltaic in long-term energy and climate scenarios. Appl Energy 2020: 279. https://doi.org/10.1016/j.apenergy.2020.115705.

[26] Joshi S, Mittal S, Holloway P, Shukla PR, Gallachóir Ó, B, Glynn J.. High resolution global spatiotemporal assessment of rooftop solar photovoltaics potential for renewable electricity generation. Nat Commun 2021;12:1–15. https://doi.org/10.1038/s41467-021-25720-2.

[27] Fina B, Auer H, Friedl W. Cost-optimal economic potential of shared rooftop PV in energy communities: evidence from Austria. Renew Energy 2020;152:217–28. https://doi.org/10.1016/j.renene.2020.01.031.

[28] Izquierdo S, Montañés C, Dopazo C, Fueyo N. Roof-top solar energy potential under performance-based building energy codes: the case of Spain. Sol Energy 2011;85: 208–13. https://doi.org/10.1016/j.solener.2010.11.003.

[29] 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;14:2122–30. https://doi.org/10.1016/j.rser.2010.01.001.

[30] Kausika BB, Dolla O, WGJHM Van Sark. Assessment of policy based residential solar PV potential using GIS-based multicriteria decision analysis: a case study of Apeldoorn, the Netherlands. Energy Procedia 2017;134:110–20. https://doi.org/10.1016/j.egypro.2017.09.544. Elsevier Ltd.

[31] Zambito A, Pernigotto G, Pezzutto S, Gasparella A. Parametric urban-scale analysis of space cooling energy needs and potential photovoltaic integration in residential districts in South-West Europe. Sustain 2022:14. https://doi.org/10.3390/su14116521.

[32] Torres-Rivas A, Palumbo M, Jiménez L, Boer D. Self-consumption possibilities by rooftop PV and building retrofit requirements for a regional building stock: the case of Catalonia. Sol Energy 2022;238:150–61. https://doi.org/10.1016/j.solener.2022.04.036.

[33] Bergamasco L, Asinari P. Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surface area: application to Piedmont Region (Italy). Sol Energy 2011;85:1041–55. https://doi.org/10.1016/j.solener.2011.02.022.

[34] Gómez-Navarro T, Brazzini T, Alfonso-Solar D, Vargas-Salgado C. Analysis of the potential for PV rooftop prosumer production: technical, economic and environmental assessment for the city of Valencia (Spain). Renew Energy 2021; 174:372–81. https://doi.org/10.1016/j.renene.2021.04.049.

[35] Jurasz JK, Dąbek PB, Campana PE. Can a city reach energy self-sufficiency by means of rooftop photovoltaics? Case study from Poland. J Clean Prod 2020:245. https://doi.org/10.1016/j.jclepro.2019.118813.

[36] Assouline D, Mohajeri N, Scartezzini JL. Quantifying rooftop photovoltaic solar energy potential: a machine learning approach. Sol Energy 2017;141:278–96. https://doi.org/10.1016/j.solener.2016.11.045.

[37] Walch A, Castello R, Mohajeri N, Scartezzini JL. Big data mining for the estimation of hourly rooftop photovoltaic potential and its uncertainty. Appl Energy 2020; 262:114404. https://doi.org/10.1016/j.apenergy.2019.114404.

[38] Buffat R, Grassi S, Raubal M. A scalable method for estimating rooftop solar irradiation potential over large regions. Appl Energy 2018;216:389–401. https://doi.org/10.1016/j.apenergy.2018.02.008.

[39] Kozlovas P, Gudzius S, Ciurlionis J, Jonaitis A, Konstantinaviciute I, Bobinaite V. Assessment of technical and economic potential of urban rooftop solar photovoltaic systems in Lithuania. Energies 2023;16. https://doi.org/10.3390/en16145410.

[40] Gassar AAA, Cha SH. Review of geographic information systems-based rooftop solar photovoltaic potential estimation approaches at urban scales. Appl Energy 2021;291:116817. https://doi.org/10.1016/j.apenergy.2021.116817.

[41] Zhong T, Zhang Z, Chen M, Zhang K, Zhou Z, Zhu R, et al. A city-scale estimation of rooftop solar photovoltaic potential based on deep learning. Appl Energy 2021; 298:117132. https://doi.org/10.1016/j.apenergy.2021.117132.

[42] Sun T, Shan M, Rong X, Yang X. Estimating the spatial distribution of solar photovoltaic power generation potential on different types of rural rooftops using a deep learning network applied to satellite images. Appl Energy 2022;315:119025. https://doi.org/10.1016/j.apenergy.2022.119025.

[43] Assouline D, Mohajeri N, Scartezzini JL. Quantifying rooftop photovoltaic solar energy potential: a machine learning approach. Sol Energy 2017;141:278–96. https://doi.org/10.1016/j.solener.2016.11.045.

[44] Walch A, Castello R, Mohajeri N, Scartezzini JL. Big data mining for the estimation of hourly rooftop photovoltaic potential and its uncertainty. Appl Energy 2020; 262:114404. https://doi.org/10.1016/j.apenergy.2019.114404.

[45] Massano M, Macii E, Lanzini A, Patti E, Bottaccioli L. A GIS open-data co-simulation platform for photovoltaic integration in residential urban areas. Engineering 2023;26:198–213. https://doi.org/10.1016/j.eng.2022.06.020.

[46] Petrichenko K. Net-zero energy buildings: Global and regional perspectives. Central European University; 2014.

[47] Petrichenko K, Ürge-Vorsatz D, Cabeza LF. Modeling global and regional potentials for building-integrated solar energy generation. Energ Buildings 2019;198:329–39. https://doi.org/10.1016/j.enbuild.2019.06.024.

[48] Molnár G, Ürge-Vorsatz D, Chatterjee S. Estimating the global technical potential of building-integrated solar energy production using a high-resolution geospatial model. J Clean Prod 2022;375:134133. https://doi.org/10.1016/j.jclepro.2022.134133.

[49] Urge-Vorsatz D, Petrichenko K, Antal M, Staniec M, Labelle M, Ozden E, et al. Best practice policies for low energy and carbon buildings. A scenario analysis. Research report prepared by the Center for Climate Change and Sustainable Policy (3CSEP) for the global buildings performance network. 2012.

[50] Güneralp B, Zhou Y, Ürge-Vorsatz D, Gupta M, Yu S, Patel PL, et al. Global scenarios of urban density and its impacts on building energy use through 2050. Proc Natl Acad Sci 2017;114:8945–50. https://doi.org/10.1073/pnas.1606035114.

[51] Chatterjee S, Kiss B, Ürge-Vorsatz D, Teske S. Decarbonisation pathways for buildings. Achiev. Paris Clim. Agreem. Goals. Cham: Springer International Publishing; 2022. p. 161–85. https://doi.org/10.1007/978-3-030-99177-7_7.

[52] Molnár G, Ürge-Vorsatz D, Chatterjee S. Estimating the global technical potential of building-integrated solar energy production using a high-resolution geospatial model. J Clean Prod 2022:375. https://doi.org/10.1016/j.jclepro.2022.134133.
[53] Zhang J, Su X, Shen M, Dai Z, Zhang L, He X, et al. Enlarging photovoltaic effect: combination of classic photoelectric and ferroelectric photovoltaic effects. Sci Rep 2013;3:1–6. https://doi.org/10.1038/srep02109.
[54] Eyring V, Bony S, Meehl GA, Senior CA, Stevens B, Stouffer RJ, et al. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci Model Dev 2016;9:1937–58. https://doi.org/10.5194/gmd-9-1937-2016.
[55] Schupfner M, Wieners K-H, Wachsmann F, Steger C, Bittner M, Jungclaus J, et al. DKRZ MPI-ESM1.2-HR model output prepared for CMIP6 ScenarioMIP. 2019. https://doi.org/10.22033/ESGF/CMIP6.2450.
[56] Bengtsson L, Arkin P, Berrisford P, Bougeault P, Folland CK, Gordon C, et al. The need for a dynamical climate reanalysis. Bull Am Meteorol Soc 2007;88:495–501. https://doi.org/10.1175/BAMS-88-4-495.
[57] Gelaro R, McCarty W, Suárez MJ, Todling R, Molod A, Takacs L, et al. The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). J Climate 2017;30:5419–54. https://doi.org/10.1175/JCLI-D-16-0758.1.
[58] Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci 2007;11:1633–44. https://doi.org/10.5194/hess-11-1633-2007.
[59] Buffat R, Grassi S, Raubal M. A scalable method for estimating rooftop solar irradiation potential over large regions. Appl Energy 2018;216:389–401. https://doi.org/10.1016/j.apenergy.2018.02.008.
[60] Horan W, Byrne S, Shawe R, Moles R, O'Regan B. A geospatial assessment of the rooftop decarbonisation potential of industrial and commercial zoned buildings: an example of Irish cities and regions. Sustain Energy Technol Assess 2020:38. https://doi.org/10.1016/j.seta.2020.100651.
[61] Brovelli MA, Zamboni G. A new method for the assessment of spatial accuracy and completeness of OpenStreetMap building footprints. ISPRS Int J Geo-Inf 2018:7. https://doi.org/10.3390/ijgi7080289.
[62] Microsoft. Global building footprint dataset. 2022.
[63] Jacobson MZ, Jadhav V. World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. Sol Energy 2018;169:55–66. https://doi.org/10.1016/j.solener.2018.04.030.
[64] Sudhakar K, Winderla M, Priya SS. Net-zero building designs in hot and humid climates: a state-of-art. Case Stud Therm Eng 2019:13. https://doi.org/10.1016/j.csite.2019.100400.
[65] Gevorgian A, Pezzutto S, Zambotti S, Croce S, Filippi Oberegger U, Lollini R, et al. European building stock analysis A country by country descriptive and comparative analysis of the energy performance of buildings. 2021.
[66] Mainzer K, Killinger S, McKenna R, Fichtner W. Assessment of rooftop photovoltaic potentials at the urban level using publicly available geodata and image recognition techniques. Sol Energy 2017;155:561–73. https://doi.org/10.1016/j.solener.2017.06.065.
[67] Schallenberg-Rodríguez J. Photovoltaic techno-economical potential on roofs in regions and islands: the case of the Canary Islands. Methodological review and methodology proposal. Renew Sustain Energy Rev 2013;20:219–39. https://doi.org/10.1016/j.rser.2012.11.078.
[68] Yang Y, Campana PE, Stridh B, Yan J. Potential analysis of roof-mounted solar photovoltaics in Sweden. Appl Energy 2020;279:115786. https://doi.org/10.1016/j.apenergy.2020.115786.
[69] Romero Rodríguez L, Duminil E, Sánchez Ramos J, Eicker U. 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. https://doi.org/10.1016/j.solener.2017.02.043.
[70] Jordan DC, Kurtz SR. Photovoltaic degradation rates-an analytical review. Prog Photovolt Res Appl 2013;21:12–29. https://doi.org/10.1002/pip.1182.
[71] SunPower. Maxeon 6 AC solar panel. 2022.
[72] Joshi S, Mittal S, Holloway P, Shukla PR, Gallachóir Ó, B, Glynn J.. High resolution global spatiotemporal assessment of rooftop solar photovoltaics potential for renewable electricity generation. Nat Commun 2021;12:5738. https://doi.org/10.1038/s41467-021-25720-2.
[73] Hoogwijk MM. On the global and regional potential of renewable energy sources. Utrecht University; 2004.
[74] Mainzer K, Fath K, Mckenna R, Stengel J, Fichtner W, Schultmann F. A high-resolution determination of the technical potential for residential-roof-mounted photovoltaic systems in Germany. Sol Energy 2014;105:715–31. https://doi.org/10.1016/j.solener.2014.04.015.
[75] Mazzer M, Moser D. How solar energy could power Italy without using more land. Nat Italy 2021. https://doi.org/10.1038/d43978-021-00048-z.
[76] European Commission. Eurostat database, European Commission: Energy consumption in households by type of end-use. 2022.
[77] Kougias I, Taylor N, Kakoulaki G, Jäger-Waldau A. The role of photovoltaics for the European green deal and the recovery plan. Renew Sustain Energy Rev 2021:144. https://doi.org/10.1016/j.rser.2021.111017.
[78] Merabet A, Al-Durra A, El-Saadany EF. Energy management system for optimal cost and storage utilization of renewable hybrid energy microgrid. Energ Conver Manage 2022;252:115116. https://doi.org/10.1016/j.enconman.2021.115116.
[79] Abdelghany MB, Al-Durra A, Gao F. A coordinated optimal operation of a grid-connected wind-solar microgrid incorporating hybrid energy storage management systems. IEEE Trans Sustain Energy 2023:1–13. https://doi.org/10.1109/TSTE.2023.3263540.