ISSN 1831-9424

European Commission

RURAL OBSERVATORY

Renewable energy production and potential in EU rural areas

2024
EUR 31744 EN

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JRC135612

EUR 31744 EN

PDF ISBN 978-92-68-09638-3 ISSN 1831-9424 doi:10.2760/458970 KJ-NA-31-744-EN-N

Luxembourg: Publications Office of the European Union, 2024

Graphic design: Laura Spirito

How to cite this report: Perpiña Castillo, C., Hormigos Feliu, C., Dorati, C., Kakoulaki, G., Peeters, L., Quaranta, E., Taylor, N., Uihlein, A., Auteri, D. and Dijkstra, L., *Renewable energy production and potential in EU rural areas,* Publications Office of the European Union, Luxembourg, 2024, doi:10.2760/458970 (online), JRC135612.

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Renewable energy production and potential in **EU rural areas**

Perpiñá Castillo, C., Hormigos Feliu, C., Dorati, C., Kakoulaki, G., Peeters, L., Quaranta, E., Taylor, N., Uihlein, A., Auteri, D., Dijkstra, L.

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Abstract

The green energy transition and its boost to the deployment of renewable energy can offer a unique opportunity for rural areas to benefit from their natural resources. The present study aims to provide a quantitative assessment of the technical potential of renewable energy sources in the EU's rural areas, focusing on solar, wind and hydropower. This will help to provide relevant insights into how rural areas and communities can contribute to and benefit from the EU's green energy transition, without undermining natural areas, key biodiversity and bird areas, high-value natural farms and food production. Moreover, a comparative analysis between current renewable energy production and potential in rural areas identifies which sustainable development trajectories for the future deployment of renewables are the most suitable in each specific territory.

The report shows that solar photovoltaic systems in rural areas generate 136 TWh a year but have the potential to generate 60 times more (8 600 TWh/year). Rural areas produce 280 TWh a year through onshore wind but have the potential to produce four times more (1 200 TWh/year). Hydropower production in rural areas yields 280 TWh a year, but it could potentially be 25 % higher (350 TWh/year). This work also addresses the concept of energy communities, as an emerging framework intended to foster a just green transition for rural communities, where generated values and benefits can be retained locally, while also promoting democratic participation and citizen engagement.

Acknowledgements

The authors would like to thank the following persons for their contribution:

— colleagues at the European Commission's Directorate-General for Agriculture and Rural Development, in particular Alexia Rouby, Marina Royo de Blas, Silvia Nanni and Veronika Madner, for their support, fruitful exchanges and valuable comments they shared during the steering committee meetings and on the entire document;

— colleagues at the European Commission's Directorate-General for Regional and Urban Policy, in particular Joachim Maes, Magdalena Grzegorzewska, Jorge Duran Laguna, Sami Hout Ledo and Wallis Vandebrock-Goelen, for their support, constructive feedback and useful comments they shared during the steering committee meetings and on the entire document;

— colleagues at the European Commission's Directorate-General for Energy, for the revision of the document and useful comments on Chapter 6;

— colleagues at the Joint Research Centre (JRC), Energy Efficiency and Renewables Unit (C.2), in particular Sandor Szabo and Anatoli Chatzipanagi, for their fruitful comments and the exchanges they shared in several meetings, especially for Chapter 2;

— colleagues at the JRC, Energy Transition Insights for Policy Unit (C.7), in particular Paul Elsner, for being kind enough to share their thoughts and opinions on the entire document;

— colleagues at the JRC, Territorial Development Unit (B.3), namely Chris Jacobs-Crisioni for data preparation and useful suggestions on the land suitability analysis; Laura Spirito for the very fruitful collaboration and excellent work on the graphic design of the report; Carmelo Attardo for the development and implementation of the Rural Observatory, where outcomes from this analysis will be hosted; Matteo Berzi for his kind suggestions and comments; and Elisa Bazzani for the communication tasks on this work;

— Helena M. Ramos and Aonghus McNabola as external experts for sharing their knowledge and opinions in Chapter 4 on the number of operating hours of hydropower plants in water distribution networks;

— Philipp Wolfe for his valuable input regarding the purchase and usage of the Wiki-Solar database, and Sebastian Dunnett for his input on utilising open-source data on renewable energy supply installations;

— Michaël Pierrot for his collaboration during the process of purchasing the World Wind Farms database from The Wind Power EI, as well as providing data and recommendations for its usage;

— the JRC editor in chief and JRC reviewers of this report.

Executive summary

POLICY CONTEXT AND OBJECTIVES

The European Green Deal outlines the main policy initiatives for reaching net zero greenhouse gas (GHG) emissions by 2050, cutting emissions by at least 55 %, compared with 1990 levels, by 2030 (EC, 2019). Reducing GHG emissions requires higher shares of renewable energy sources (RESs) and greater energy efficiency. In March 2023, the European Parliament and the Council reached a provisional agreement to raise the **binding renewable energy target to at least 42.5 % in the EU energy mix by 2030** (EC, 2023a), getting the EU closer to completing the 'Fit for 55' legislation (EC, 2021a) to deliver the European Green Deal and the REPowerEU objectives (EC, 2022a).

The European Commission supports a just and sustainable transition, which entails ensuring that regions and communities are not left behind in the clean energy transformation. In addition, the Commission is committed to ensuring that **rural areas benefit from the new economic opportunities from renewable energy** (EC, 2021b). In the clean energy package, particularly the recast renewable energy directive, renewable energy communities (RECs) are identified as an essential component of the energy transition. To this end, the Rural Energy Community Advisory Hub is an EU initiative to accelerate and support the development of energy communities in rural areas.

The deployment of renewable energy in rural areas under the EU's legal framework for energy can also contribute to the rural action plan envisaged in the **Long-term Vision for the EU's Rural Areas** (EC, 2021b). Supporting especially the 'resilient rural areas' pillar of the rural vision, the plan states that EU funds can finance the renovation of buildings in rural areas and contribute to the European Green Deal's objectives by increasing energy efficiency and local renewable energy production. Renewable energy production is an opportunity for rural areas to combat energy poverty and boost local development, assuming that ecosystem services are appropriately valued, and business models retain value within rural communities.

Under this policy context and in support of the EU rural vision, this report is developed in cooperation with the European Commission's Directorate General (DG) for Agriculture and Rural Development and DG Regional and Urban Policy, in the framework of the Rural Observatory[1]. The study provides **an assessment of renewable energy in the EU's rural areas** focused on solar (as the fastest-growing source) and on onshore wind and hydropower energy sources (as the ones producing most renewable electricity today). It highlights the current contribution of rural areas to the EU's electricity production from these RESs and explores the technical potential production that is still untapped. Beyond energy contributions, the report also describes how rural areas can exploit economic, social and environmental opportunities arising from local RES production, and presents guidelines and best practices from renewable energy projects developed in rural areas.

KEY CONCLUSIONS AND POLICY IMPACTS

The report shows that **the EU has vast untapped potential for renewable energy** (i.e. additional electricity production compared with current levels) from solar, onshore wind and hydropower, totalling **12 500 TWh/year,** which can be achieved by preserving, at the same time, environmental and agricultural resources in the roll-out of new installations[2]. This untapped potential, plus current production, is more than five times the EU's total electricity consumption in 2021 (2 563 TWh) and is well above the EU's total energy consumption in 2021 (11 263 TWh) (Eurostat, 2021a).

Under source-specific sustainability criteria and technological conditions, **solar PV could reach an annual untapped potential production of 11 000 TWh, onshore wind of 1 400 TWh and hydropower of 133 TWh.** This places solar energy as the largest source of untapped potential, nearly 10 times the potential of onshore wind. This is a consequence of the higher capacity density of solar PV systems than wind turbine yields. Onshore wind has the potential to yield approximately 10 times as much power as is hidden in existing hydropower infrastructures[3].

1 The Rural Observatory (*https://observatory.rural-vision.europa.eu*) supports knowledge production, and aims to improve data collection and dissemination, related to EU rural areas. It offers relevant statistics, indicators and analyses based on data from multiple sources and at the most appropriate territorial granularity, covering the economic, social and environmental dimensions. The observatory contributes to a better understanding of rural areas, and it represents an important source of information for 'rural proofing', providing evidence for policy making in relation to rural areas development.

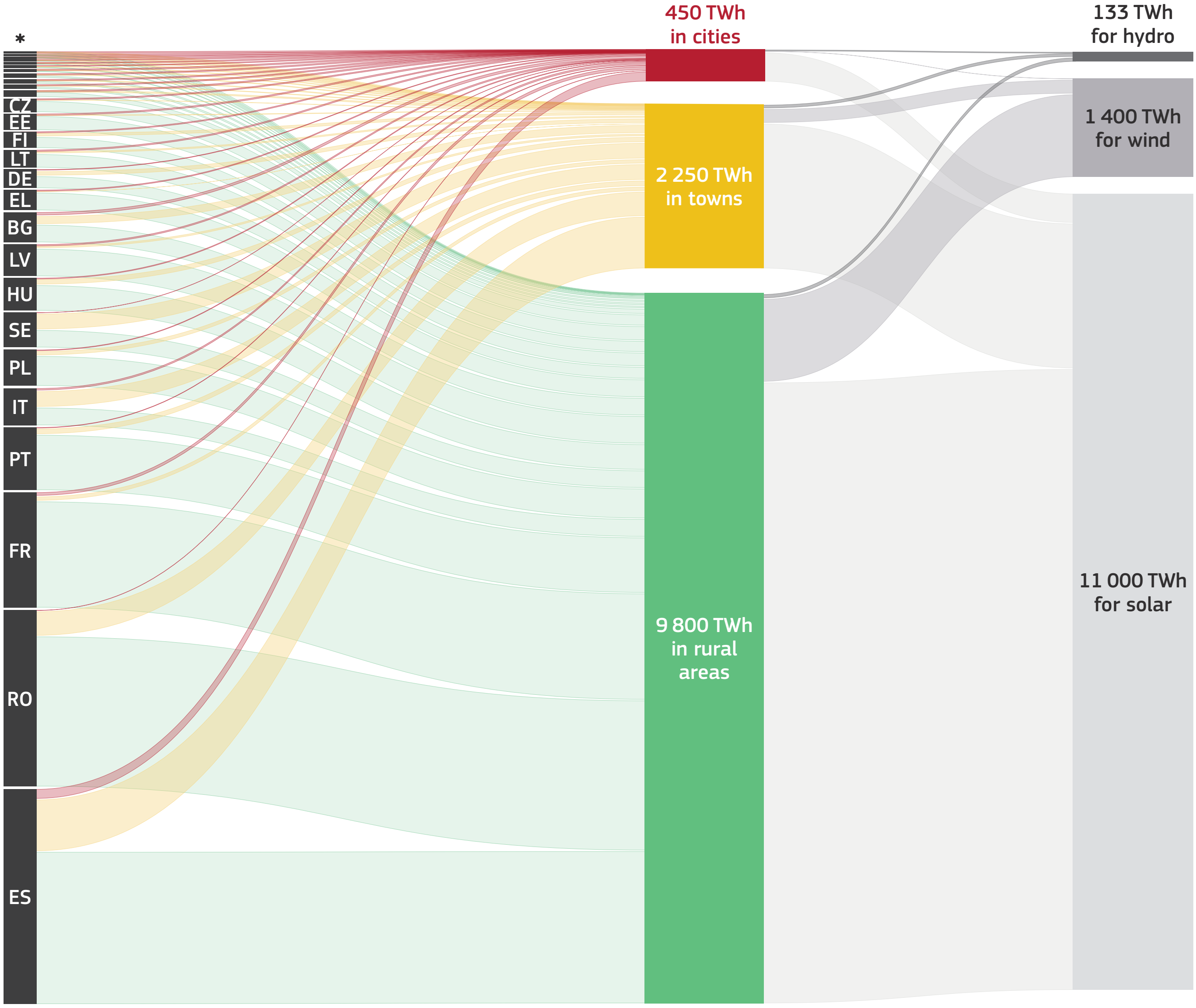
2 The EU's untapped potential should be regarded as a theoretical limit from the sum of the maximum potential of the three RESs. It is achieved by considering the option of overlapping suitable areas for ground-mounted photovoltaics and onshore wind, meaning that the real untapped potential is slightly lower (11 200 TWh/year) when only one of the two technologies is considered.

3 For estimating untapped hydropower potential, the current analysis adopts a highly conservative approach and only considers potential energy production from existing infrastructures. New hydropower developments, albeit possible, are not considered, as their energy production as well as their social and environmental feasibility is very site specific.

Figure 1. Contribution per Member State and per RES (hydropower, onshore wind and solar PV) to the EU's annual estimated untapped technical potential production in cities, towns and rural areas.

Source: Authors' own elaboration.

We estimate that **72 % of the electricity generated in the EU from solar PV, onshore wind and hydropower is produced in rural areas.** Despite their already significant contribution to the production of renewable energy, rural areas still retain much untapped potential (**78 % of the total EU's potential**), making them key players in contributing to reaching the goals related to climate change and the energy transition. **Figure 1** shows the estimated untapped potential renewable energy production per Member State and per RES by degree of urbanisation (i.e. cities, towns and suburbs, and rural areas).



* Other countries (after CZ): IE, DK, SK, HR, AT, NL, CY, BE, SI, LU and MT

To increase acceptance, maximise benefit from renewable energy and ensure a sustainable green transition, a balance between local sustainability, food and energy production is a prerequisite in the deployment of future renewable energy installations (Sacchelli et al., 2016; Perpiña Castillo et al., 2016; Dias et al., 2019). In this sense, a wide variety of factors regarding land use, environment, agriculture, topography, accessibility and climate conditions are considered in assessing suitable land to host renewable energy infrastructures. In particular,

protected nature sites and biodiversity areas, forestry and water bodies[4] **are excluded as suitable sites. The use of agricultural land for energy production is subject to strict limitations.** Furthermore, buffer zones around infrastructure and settlements are enforced to minimise disturbance and the local phenomenon known as 'not in my backyard' (NIMBY), a community's opposition to the possible impacts of a new renewable energy project.

This report estimates how much renewable energy could be produced in the EU by exploiting all its unused suitable land, as identified following the above criteria, for wind and ground-mounted solar power production. **The estimated amount of this suitable land, which must not be interpreted as a target, is 3.4 % of the total EU surface,** in line with other EU and global studies (Ruiz et al., 2019; Bódis et al., 2019a; Keramidas et al., 2022; Kakoulaki et al., 2023). It is expected that technological innovation and changes in the energy market will reduce the amount of suitable land needed to produce the same amount of renewable energy in the future.

As rural areas are highly diverse, their local specificities determine what is the most effective technology to achieve the highest technical potential at the local level. Rural municipalities in mountainous areas and with abundant water resources are suitable for hydropower production, while locations with high annual solar irradiation and large extents of suitable land should foster solar energy. Onshore wind is also a land-intensive installation that requires a minimum wind speed for appropriate functioning. Rural areas with insufficient wind or without suitable areas should promote rooftop PV systems, installed on either residential or commercial roofs. Assuming favourable local conditions, **rural areas are well positioned to host renewable energy projects, as almost 80 % of the suitable land available is located there.**

Local conditions should be also assessed when **establishing RECs in rural areas.** These communities are especially important in renewable energy production and supply, building renovation and promotion of energy efficiency. RECs entail the engagement of local authorities and citizens, along with the integration of key policies related to the common agricultural policy, rural development and farm modernisation. **Six case studies** are presented in this report to show the successful implementation of renewable energy projects in rural areas, driven by community engagement, collaboration and innovative financing models. These examples highlight the potential for RECs to achieve **energy security, economic and social benefits and environmental sustainability.**

4 Except for those suitable for floating PV installations.

MAIN FINDINGS

As of the first quarter of 2023, the estimated installed capacity in the EU was 200 GW for solar PV, 180 GW for onshore wind and 150 GW for hydropower. The annual amounts of **electricity produced by these three RESs** are, respectively, 250 TWh, 350 TWh and 375 TWh (including pumping), making **a total of 975 TWh**[(5)]. This is equivalent to roughly 38 % of the EU's total electricity consumption and 9 % of the EU's total energy consumption in 2021. The top five countries producing electricity from these RESs are Germany, Spain, France, Italy and Sweden, which together account for 68 % of the total EU production from these sources.

Rural areas currently generate the largest share of renewable electricity and hold the highest potential as well. **72 % of the electricity generated from these three RESs is produced in rural areas,** 22 % in towns and suburbs and 6 % in cities. Rural areas are also home to about **78 % of the EU's untapped RES potential** (85 % from ground-mounted PV systems, 12 % from onshore wind, 3 % from rooftop PV and 1 % from hydropower). The highest total amounts of untapped potential from the three RESs are found in Spain, Romania and France.

The estimated amount of suitable land needed to achieve the maximum technical potential of solar and wind, under the assumed criteria for sustainability and considering the system performance offered by today's technologies, is **2.3 % of the EU surface for ground-mounted PV systems,** and **2.8 % for onshore wind installations.** Most of this land (78 % for solar and 83 % for wind) is in rural areas. PV systems on rooftops do not need extra land to generate energy, and their annual technical potential (730 TWh) is achieved using **26 % of the EU's built-up areas** (0.17 % of its total surface).

Member States display strong variations in the availability of suitable land for new renewable energy installations, ranging from 0.1 % to almost 9 %. Considering both solar and wind, larger shares of suitable land are found in Latvia, Romania, Estonia, Lithuania, Cyprus and Portugal (above 5 % of each country's total area), whereas in Malta, Austria, Slovenia and Belgium these shares are residual (below 0.5 %). Shares differ greatly because of the implementation of land suitability analysis with strict agricultural, environmental and biodiversity constraints using the highest geographical granularity.

Based on our analysis of georeferenced solar plants data (roughly 22 000 points), in 2023 the EU's installed capacity of solar PV is estimated at 200 GW, generating 250 TWh/year of electricity. Most of the annual production, 204 TWh, is generated by ground-mounted systems (including industrial and commercial PV systems), and 46 TWh from small-scale rooftop PV systems (< 20 kW).

5 The current electricity production is estimated based on the installed capacity using georeferenced data on the three RESs from several data sources that cover the EU-27. The aim of this (downscaling) exercise is to estimate the current electricity production at the municipal level based on existing solar, wind and hydropower plants in operation registered until the first quarter of 2023. Outputs should therefore be considered estimates, which are dependent on the methodology and underlying data and may differ from other assessments and official sources (e.g. Eurostat) at the EU and Member State levels.

Rural areas provide 54 % of the EU's current solar PV production, with towns and suburbs contributing 36 % and cities 10 %. Germany is the largest producer of solar electricity in rural areas, followed by Spain, Italy, France and Poland.

The EU's estimated untapped potential production from ground-mounted PV and small-scale rooftop PV exceeds 11 000 TWh/year, equivalent to more than 40 times the PV production in 2023. 78 % of the EU's potential is found in rural areas, where the highest contribution (97 %) stems from ground-mounted PV and 3 % from small-scale rooftop PV systems. Rooftop PV is relevant in highly urbanised areas, especially in Malta, Belgium and the Netherlands.

Based on our analysis of georeferenced wind farms data (roughly 20 000 points) the EU's installed capacity for onshore wind power is estimated at 180 GW, generating **350 TWh/year of electricity.** More than 55 % of the total EU's onshore wind production is in Germany, Spain and France.

The EU's untapped potential installed capacity for onshore wind power is 530 GW, which could produce 1 400 TWh/year (i.e. four times the current production). Rural areas can play a key role in wind energy generation, accounting for 80 % of current production from onshore wind, and holding 84 % of the untapped potential for this technology. Onshore wind is the leading source of untapped RES potential in northern areas of Finland, of Sweden and of Ireland.

Based on our analysis of georeferenced hydropower data (roughly 3 335 points), in 2023 the EU's installed capacity of conventional and pumped-storage hydropower is estimated at 150 GW, generating **375 TWh/year of electricity** (including energy generated from pumping). Rural areas currently produce 75 % of the EU's hydropower electricity.

The EU's untapped potential capacity for hydropower from powering existing structures (namely hydropower reservoirs, water utilities networks and historical mills) is 88 GW, with a corresponding production of about 87 TWh/year, while an additional 46 TWh/year could be achieved from modernising the EU hydropower fleet (which entails no capacity increase in this assessment). The largest share, 61 % of the total EU's hydropower potential, could be produced by covering 10 % of the water surface of existing hydropower reservoirs with floating PV, while the modernisation of existing power plants accounts for 35 % of the potential. The remaining 4 % corresponds to the powering of historical watermills and water utilities, a potential 3.3 and 1.6 TWh/year, respectively.

Almost 51 % of the EU's estimated hydropower potential is in rural areas, where the highest contributions stem from modernisation strategies and floating PV. Sweden, France, Italy, Austria, Spain and Germany hold the highest hydropower potential, together accounting for 76 % of the total EU's potential production.

1 Introduction

1.1 RENEWABLE ENERGY IN THE EUROPEAN UNION AND IN RURAL AREAS

The global energy market disruption of 2022 has contributed greatly to the reshaping of EU strategies related to the energy sector, **accelerating the green transition towards renewable energy, with EU policies and financial instruments** placing green energy and diversification of energy supplies high on the agenda. The European Green Deal sets the stage for a major transformational change, aiming to turn Europe into the first climate-neutral continent by 2050. Under the 'Fit for 55' policy package, the EU is working on the revision of its climate-, energy- and transport-related policies to scale up and fast-forward the production of renewable energy. Renewables are a pillar of the clean energy transition, and the EU's 2030 energy target has been recently strengthened to reach 42.5 % of renewables in the energy mix, with the ambition to reach 45 % (EC, 2023a). The energy sector currently is responsible for over 75 % of the total greenhouse gas (GHG) emissions in the EU, so speeding up the production of energy from renewable energy sources (RESs) is vital to reach its **2030 renewable energy target, as well as to fulfil the 2030 target of at least a 55 % reduction in GHG emissions** (Regulation (EU) 2021/1119).

The 'Fit for 55' policy package envisages that, by 2030, more than half (59 %) of power generation will come from RESs (42 % from wind and solar, 17 % from other RESs). However, in response to the Russian invasion of Ukraine, in 2022 the European Commission presented the REPowerEU Plan (EC, 2022a), which increases EU targets for renewable energy generation to 1 236 GW of installed capacity by 2030. Alongside the REPowerEU, the EU also adopted the communication 'Safeguarding food security and reinforcing the resilience of food systems' (EC, 2022b), which calls on Member States to scale up the production of renewable energy without undermining food production and while supporting EU farmers and consumers.

Today wind and hydropower account for more than two-thirds of the total electricity generated from renewable sources, while the remainder comes from solar power (15 %), solid biofuels (7 %) and other RESs (8 %) (Eurostat, 2021c). Overall, the s**hare of energy from renewable sources consumed in the EU has substantially increased from 10 % in 2004 to 22 % in 2021,** with renewable electricity contributing with 9 %, renewable energy in transport with 2 % and renewable energy in heating and cooling with 11 % (Eurostat, 2021c). Despite this increase, evaluations of Member States' progress on the implementation of national targets have shown that substantial ambition and implementing efforts are still needed to deliver on the EU's 2030 objectives and to stay on course to achieve climate neutrality by 2050 (EC, 2023b).

Between 2021 and 2022, significant increases of electricity generation from RESs are recorded in solar PV (29 %) and wind (9 %), while hydropower and other RESs decreased (18 % and 4 %, respectively) (Eurostat, 2021b) (**Figure 2**). **In 2022, 39 % of electricity was generated from renewables.** A total of 57 GW of new renewable energy capacity was installed, essentially solar PV and wind turbines. In both sectors, this is about 50 % more than in 2021. This increase also helped to balance out low production of hydropower in 2022 (12 % of total power production), which recovered towards average levels in 2023 thanks to rainfalls and higher reservoir levels. In May 2023, wind and solar energy surpassed fossil fuels for the first time in EU electricity generation (EC, 2023b).

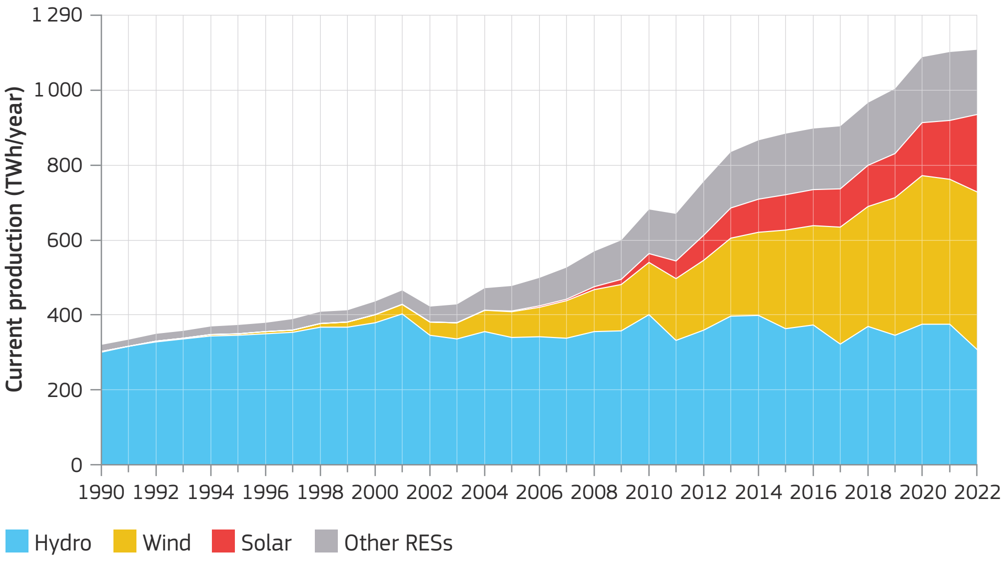


Figure 2. Development of renewable energy production in the EU-27. Other RESs include biofuels, geothermal, heat, tides and renewable waste.

Source: Authors' own elaboration based on Eurostat (2021b, 2021d).

Against this backdrop, **rural areas (Box 1) are recognised as major players in the process of advancing towards the climate change and energy transition goals,** primarily thanks to their abundance of natural resources (e.g. water, land). Energy decentralisation, CO_2 offsetting, reduced energy dependency and lower energy prices, together with business opportunities for the renewable energy sector, are some of the main positive outcomes of RES development that are beneficial for society as whole (RECAH, 2023a). Nonetheless, for rural areas to truly benefit from RES expansion, it is crucial to adopt an endogenous development model based on a bottom-up approach to the use of local resources, safeguarding the balance between renewable energy exploitation and other possible competing uses and visions (e.g. of land, food production, water, wood), and creating value not only for the renewable energy companies or entrepreneurs, but also and foremost for the specific rural context (Poggi et al., 2018; Baldock et al., 2021).

BOX 1. Degree of urbanisation

The degree of urbanisation classifies the entire territory of a country along an urban–rural continuum. It combines population size and population density thresholds to capture three mutually exclusive classes: **cities, towns** and **suburbs,** and **rural areas.** The classification is based on the identification of:

- urban centres (contiguous grid cells of 1 km² with a population density of at least 1 500 inhabitants per km² and, collectively, at least 50 000 inhabitants);
- urban clusters (contiguous grid cells of 1 km² with a population density of at least 300 inhabitants per km² and, collectively, at least 5 000 inhabitants);
- Rural grid cells (all grid cells of 1 km² not falling under the previous categories);

Once all grid cells have been classified, the next step concerns the classification of each municipality by overlaying these results onto local administrative units, as follows:

- **cities** = at least 50 % of the population lives in one or more urban centres;
- **towns and suburbs** = less than 50 % of the population lives in an urban centre, but at least 50 % of the population lives in an urban cluster;
- **rural areas** (thinly populated areas) = more than 50 % of the population lives in rural grid cells.

Source: Eurostat (2018), accessible from: *https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography/degurba*

The development of renewable energy in **rural areas can also bring socioeconomic and environmental opportunities with associated jobs and benefits for rural communities.** They have great potential as the principal source of natural resources and ecosystem services, which are essential to advancing towards the green transition. Currently, the potential for rural communities to respond to climate challenges is centred largely on the land-based sector, particularly on agriculture and forestry (Markantoni et al., 2015), where nature-based solutions, sustainable forest management, changes in farming systems and appropriate management of protected habitats, water resources, carbon-rich soil and wetlands can provide both environmental and economic benefits. Besides this, rural areas can contribute to the management of natural resources and mitigation of the effects of climate change, especially through renewable energy production.

With the recent boost of renewable energy development, **sustainability is becoming a key consideration, including impacts on the natural and cultural landscape** (Poggi et al., 2018). Concerning renewable energy production, spatial planning will be essential in ensuring that future sites are effectively positioned and properly integrated into municipal planning. Future installations of renewable energy infrastructure may have negative impacts on landscape character, agricultural production, land-use change, local identity and biodiversity (Van der Sluis et al., 2019; Guerin, 2019; Hernandez et al., 2014). Given these possible environmental impacts, the Commission has put forward guidelines for Member States to ensure the sustainable selection of renewable energy sites for solar and wind installations (EC, 2022a JRC, 2023). The proposals include giving priority to artificial and built-up surfaces, such as rooftops, transport infrastructure areas, parking areas, waste sites, industrial sites, mines and artificial inland water bodies, such as lakes or reservoirs, and to degraded land not usable for agriculture. Moreover, it recommends the exclusion of Natura 2000 sites, nature parks and reserves, bird migratory routes and other areas identified based on sensitivity maps.

Rural communities are well placed, therefore, to develop and implement innovative renewable energy projects and become actors in the green economy. Fair access to energy and the benefits of generating energy from RESs should be ensured for all citizens, especially in rural areas, where many of their resources (land, water, etc.) are plentiful and can generate local economic and social benefits (ENRD, 2020). In 2022, the European Commission launched the **Rural Energy Community Advisory Hub** (RECAH) initiative to set up energy communities in rural areas of the EU (RECAH, 2023a). Rural energy communities engage with stakeholders and actors who live and are active in their socioeconomic context (e.g. citizens, farmers, agriculture businesses, local authorities) to produce renewable energy and participate in energy-related activities. Given their rural specificities, these communities face challenges and barriers, and are often confronted with physical or technical constraints and interconnectivity limits (RECAH, 2023a).

1.2 AIM AND SCOPE OF THE WORK

This work examines to what extent rural areas can contribute to the energy transition through the production of electricity from renewable energy technologies, namely solar PV, onshore wind and hydropower. It also explores how and under what favouring/enabling conditions rural areas and communities can benefit from an increase in RES production on their territory, while safeguarding their land resources, agri-food and biodiversity systems.

A pan-European assessment is conducted to estimate the technical potential of the aforementioned RESs at high-spatial resolution, along with estimates of their current (first quarter of 2023) installed capacity and production levels, at the local level and by degree of urbanisation (**Box 1**). By comparing the technical potential and current installed capacity and production, this study identifies the amount of **untapped renewable energy potential,** defined as the difference between the source entire potential and its current production of electricity, and which technology offers the greatest opportunities depending on the local characteristics of each place. The results of this study can offer valuable insights for policymakers and stakeholders seeking to promote renewable energy and sustainable development, particularly in rural areas.

The selection of solar, wind and hydropower for this study is based on the fact that large-scale PV farms and onshore wind farms are the most representative, efficient and cost-effective forms of renewable energy production today. Moreover, these technologies require wide spaces, which are predominantly found in rural areas, making it essential to ensure the **conservation of natural and agricultural resources when assessing land's suitability** for the deployment of new installations. Rooftop PV's potential is also explored, as its deployment is extremely flexible and scalable, without requiring additional use of land. The additional potential of hydropower, through the modernisation of existing plants, the exploitation of small hydropower technology, and by coupling floating photovoltaic (FPV) systems with hydropower reservoirs, is also investigated.

Other RESs such as biofuels (e.g. biogas, biomass), offshore wind, geothermal or renewable waste are beyond the scope of this analysis. Agri-PV, a new emerging design for compatible use of PV panels in agricultural areas, is also not part of this study, but findings from recent related studies (Chatzipanagi et al., 2022 and 2023) are included where relevant.

Finally, a dedicated chapter is focused on **energy communities,** since they provide unique opportunities for rural areas to retain the value of their natural resources and benefit from the green energy transition through the production of renewable energy. Throughout the analysis of various case studies of renewable energy communities (RECs), this work proposes guidelines and best practices to support local communities aiming to set up their projects in successful ways.

1.3 STRUCTURE OF THE REPORT

This report is structured as follows.

1 **Chapter 1** introduces the **main climate and energy EU policies** to contextualise the role of renewable energy in rural areas and the reasons for the analysis.

2 **Chapter 2** analyses **solar energy** in terms of current electricity production and technical potential for both ground-mounted and rooftop PV systems. Emphasising the large contribution that the EU's rural areas can make to new solar installations, the untapped solar technical potential is evaluated at the municipality level, considering environmental and agricultural constraints.

3 **Chapter 3** focuses on **onshore wind.** It describes the current production and technical potential of onshore wind energy at the local level. Paying attention to the role of rural areas in the roll-out of new installations, it explores their untapped wind potential while attending to the preservation of natural and agricultural resources.

4 **Chapter 4** explores the potential and current production of **hydropower** and considers the most relevant and sustainable hydropower strategies in rural areas. It includes modernisation of the existing plants, powering of water utilities, restoration of historical watermills and floating PV in hydropower reservoirs.

5 **Chapter 5** presents an **overall analysis combining the three RESs,** particularly in rural areas. It explores different RES trajectories at the municipality level to quantify the total untapped RES potential based on territorial and technical specificities.

6 **Chapter 6** provides an **overview of the concept of RECs and a perspective on them in practice.** It briefly describes the main activities, drivers and challenges, and the social, economic and environmental benefits of establishing a REC. Based on several case studies and on relevant literature review, a preliminary guide to best practices is included for the development and success of RECs.

7 Finally, **Chapter 7** summarises the **main findings** of the work to support the development of renewable energy, especially solar and wind, to advance towards a fair and sustainable energy transition.

2 Solar energy

2.1 SOLAR ENERGY IN THE EUROPEAN UNION: STATUS AND OUTLOOK

The EU Solar Energy Strategy outlines necessary actions to accelerate the deployment of solar technologies and foresees **over 320 GW of installed solar PV capacity by 2025,** twice the 2021 level, and almost 600 GW of total capacity by 2030 (EC, 2022d). As part of the strategy, the European Solar Rooftops Initiative aims to accelerate the underutilised potential of rooftops to produce clean energy without the demand of extra land, and to increase the energy efficiency of buildings. The strategy also envisages agri-PV systems, that is, the use of agricultural land for both PV power generation and agricultural production simultaneously. The technical potential capacity of agri-PV has been recently estimated at 1 TW, using only 1 % of the utilised agricultural area (Chatzipanagi et al., 2023).

BOX 2. Solar PV – the sun at work

In the last decade, the cost of solar panels has dropped dramatically, making solar one of the cheapest forms of electricity to date. Solar technologies can deliver energy in different forms, such as heat, cooling and electricity, and power a variety of other energy-related applications such as hydrogen generation and water desalination. Solar technologies convert sunlight into electrical energy, either directly through PV panels or indirectly through mirrors that concentrate solar power. PV systems range from the small to medium scale, when installed on rooftops of residential, industrial or commercial buildings (distributed PV systems), to large, centralised ground-mounted solar parks (utility-scale PV). Emerging technologies are also coupling large PV systems with agriculture (agri-PV systems) and on reservoirs (Floating PV systems).

Solar PV technology is a green, affordable and rapid solution for reducing the EU's dependence on fossil fuels. A record amount of new solar PV capacity (41 GW) was installed in 2022, 60 % more than in 2021 (26 GW) (EC, 2023b). This positive trend is expected to continue in the coming years. In 2021, the total net electricity generation in the EU was 2 785 TWh, and **solar energy contributed approximately 160 TWh, i.e. 6 % of the EU's total electricity production** (Eurostat, 2021e).

The green energy transition is an opportunity for rural areas to benefit economically, socially and environmentally from the production of renewable energy. Rural areas account for 83 % of the land in the EU, covered mainly by forest and agriculture (EC, 2021b). Rural areas can leverage their potential by establishing appropriate business models and by adopting enabling legislation and recommendations for faster and sustainable deployment of solar PV systems. To fast-track the installation of utility-scale solar systems, it is recommended to prioritise areas with low environmental impact, and without undermining food production systems.

In this context, this chapter presents our estimation of the **technical potential** (i.e. maximum achievable installed capacity and electricity production) **of small-scale rooftop and ground-mounted solar PV systems** (including commercial and industrial systems), taking into consideration environmental, technical and socioeconomic factors. These factors are the basis on which to identify suitable areas for new PV installations, ensuring sustainability. The energy production for 2023 is also estimated from point location data about existing installations collected from various sources. The analysis emphasises how rural areas contribute to and may benefit from the green energy transition, by assessing the **untapped potential for solar PV at the municipality level,** providing the main findings and conclusions under the lens of the degree of urbanisation, with a focus on rural areas.

2.2 CURRENT EUROPEAN UNION PRODUCTION OF SOLAR ENERGY

In 2023, **the estimated electricity production of solar PV systems is 250 TWh in the EU-27,** with an estimated installed capacity of almost 200 GW[6] (see **Annex 1** for disaggregated results). These estimates are derived from point location data of existing PV solar installations. Two main sources have been used to build our EU solar database (detailing 21 728 solar plants): 'Harmonised global datasets of wind and solar farm locations and power' (Dunnett et al., 2020) and 'Lists of utility-scale solar projects – Wiki-Solar' (WolfeWare Ltd, 2023).

In our analysis, small-scale plants (< 20 kW)[7] are associated with **rooftop PV systems,** while medium-scale (commercial and industrial solar plants, 20 kW – 1 MW) and large utility-scale solar plants (> 1 MW) are aggregated

6 Discrepancies are found with what Eurostat reports in 2022 mainly because the current production is estimated based on the installed capacity from the two data sources described. The aim of this exercise is to estimate the electricity production at the municipal level based on the almost 22 000 solar farms in operation registered until 2023. It is worth mentioning that the distinction between rooftop and ground-mounted systems is not reported by Eurostat.

7 The three groups of installed capacity (< 20 kW; 20 kW – 1 MW; > 1 MW) were used as defined at the Member State level by Eurostat. Official sources were crucial to cross-check our national results aggregated from solar plant locations in each municipality.

as **ground-mounted PV systems**[8] (**Figure 3**). Data from the 'Fit for 55' EU scenario were used to apply the compound annual growth rate for the installed capacity to the harmonised global datasets between 2020 and 2023. This approach allows us to geographically locate each solar plant and to estimate the current installed capacity and electricity production at the municipality level in 2023 as follows.

— The estimated **installed capacity (GW)** for each municipality is based on two calculations.

  1. The total panel area (m^2) covered by small-scale rooftop and medium-size PV systems (industrial and commercial) in a certain municipality in relation to the total panel area of the country uses data (point location) from the harmonised global dataset from OpenStreetMap (Dunnett et al., 2020). This approach locally distributes the installed capacity as expressed in equations (**A1.1**) and (**A1.2**) (**Annex 1**), also taking into consideration the national installed capacity from the combination of the two data sources mentioned and the compound annual growth rate between 2020 and 2023 of the installed capacity from the 'Fit for 55' package at the Member State level (EC, 2021a).
  2. For large-size solar plants, we rely on data from the utility-scale solar project (Wiki-Solar) that contains the capacity (MW alternating current) for each existing solar PV installation until the beginning of 2023. In this case, equation (**A1.3**) (**Annex 1**) shows the total installed capacity, by adding up all the solar PV systems that are in each municipality.

— Based on the previously estimated installed capacity, the **current electricity production (GWh/year)** is derived and computed as (1) small-scale rooftop PV systems and (2) ground-mounted (including industrial and commercial) PV systems at the municipality level and by degree of urbanisation. The estimated current production takes into consideration the capacity density of installed panels (kWh/kW_p) using a 1 km raster layer as expressed in equations (**A1.4**), (**A1.5**) and (**A1.6**) (**Annex 1**).

8 For the purpose of readability and simplicity small-scale rooftop PV systems (< 20 kW) will be referred as 'rooftop PV systems' and ground-mounted PV systems including industrial and commercial solar systems will be referred as 'ground-mounted PV systems' throughout the whole document.

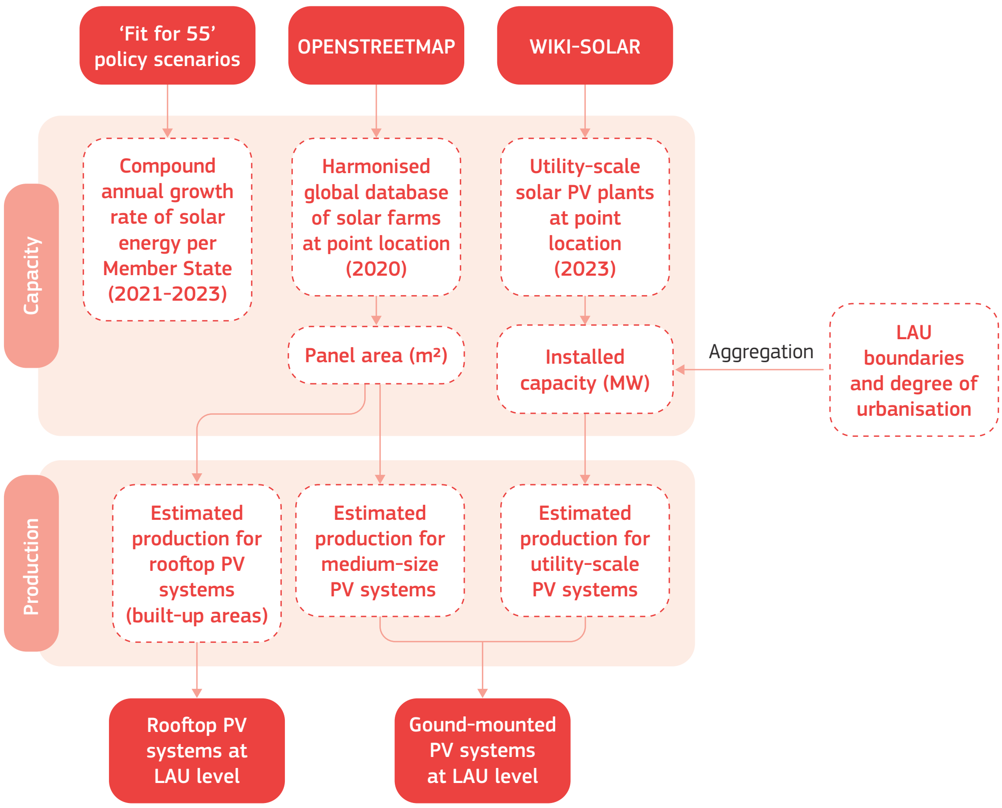


Figure 3. Scheme of the workflow for the estimations of installed capacities and electricity production of solar PV installations in 2023.

Note: (1) small-scale rooftop PV systems and (2) ground-mounted PV systems, including commercial and industrial solar systems. LAU, local administrative unit.

Source: Authors' own elaboration.

According to our estimates, most of the production, 204 TWh (82 %), is generated by ground-mounted systems, while 46 TWh (18 %) is generated by rooftop PV systems. **Rural areas produce 54 % of the current EU electricity production by solar PV systems,** followed by 36 % in towns and suburbs and 10 % in cities (**Figure 4** and **Annex1**).

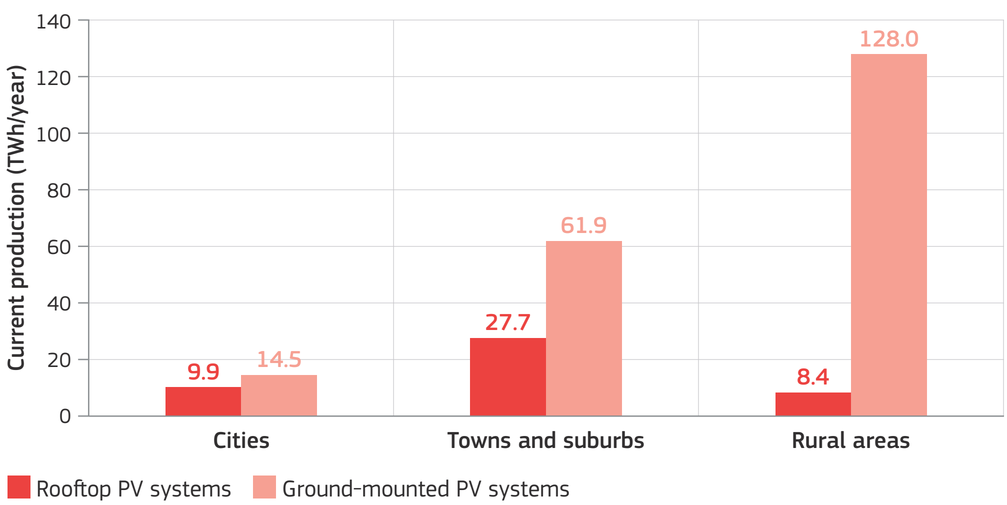


Figure 4. Estimated annual electricity production (TWh) from small-scale rooftop and ground-mounted PV systems, including industrial and commercial solar systems, by degree of urbanisation, 2023.

Source: Authors' own elaboration from Wiki-solar (WolfeWare Ltd, 2023), Open Street Map (Dunnett et al., 2020) and the 'Fit for 55' package (EC, 2021a).

Germany is the leading solar electricity producer from both rooftop and ground-mounted PV systems, with more than 65 TWh/year (**Figure 5**). Spain, Italy, France and Poland also rank high. With more than 7 TWh/year, Germany and Italy are the main producers of solar energy from rooftop PV systems, followed by Belgium and Austria (nearly 4 TWh/year) (see **Annex 1** for more details).

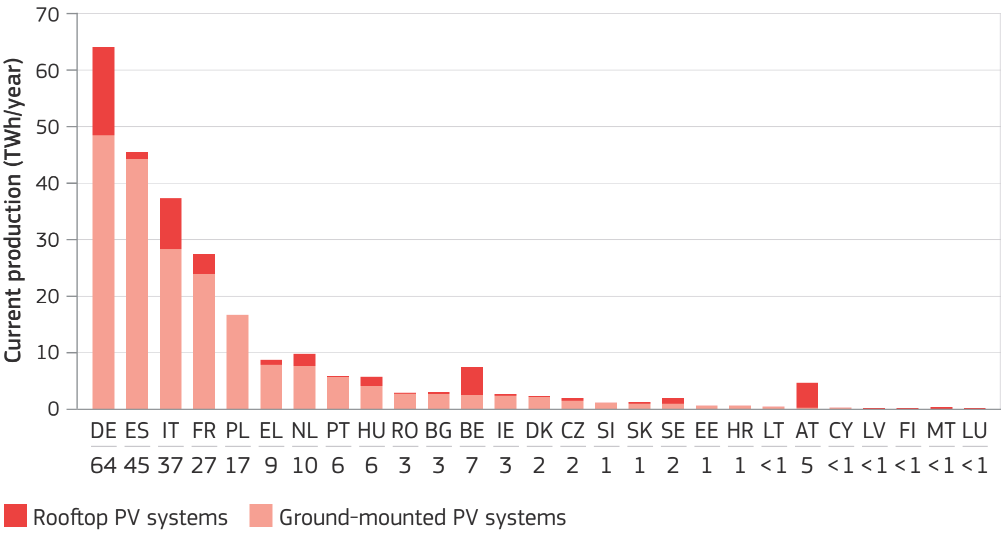


Figure 5. Estimated annual electricity production (TWh) from small-scale rooftop and ground-mounted PV systems, including industrial and commercial solar systems, 2023.

Source: Authors' own elaboration from Wiki-solar (WolfeWare Ltd, 2023), Open Street Map (Dunnett et al., 2020) and the 'Fit for 55' package (EC, 2021a).

When the electricity production of solar PV systems is measured per unit area (**Figure 6**), the Netherlands and Germany are currently the leading countries, producing more than 100 MWh/km² per year in all the three classes (cities, towns and suburbs, rural areas). By contrast, Lithuania, Luxembourg, Latvia and Finland produce less than 10 MWh/km² in all the three degrees of urbanisation.

In Austria and Malta, solar electricity production in cities and in towns is remarkable. On average, cities have the highest electricity production per unit area (estimated at 150 MWh/km²), followed by towns and suburbs (110 MWh/km²) and rural areas (45 MWh/km²). This is probably due to a combination of rooftop systems and small-scale solar plants (< 1 MW) installed in cities and in towns and suburbs, as well as to their smaller surface area. This results in higher production per unit area than in rural areas, which are characterised by larger extents of land.

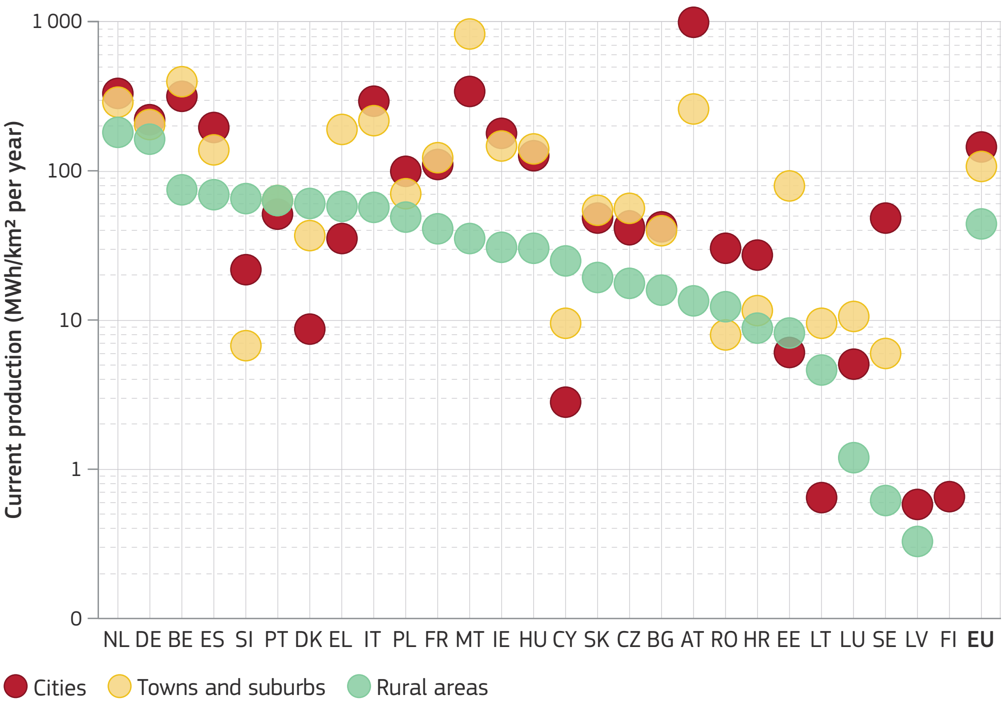
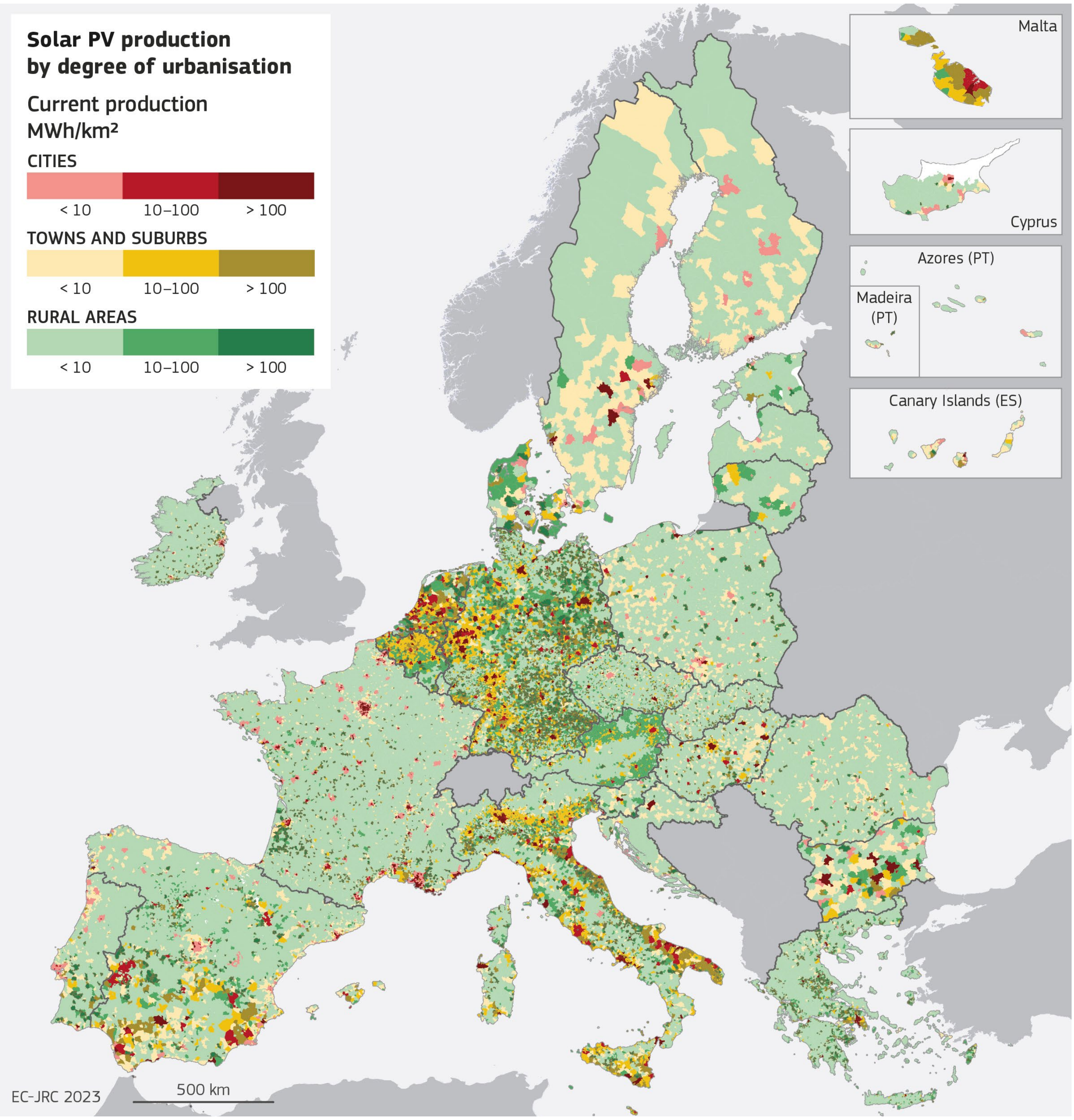


Figure 6. Estimated electricity production in 2023 (MWh/km² per year) of solar PV systems in EU Member States and by degree of urbanisation.

Note: Graphical visualisation in logarithmic scale.

Source: Author's own elaboration from Wiki-solar (WolfeWare Ltd, 2023), Open Street Map (Dunnett et al., 2020) and the 'Fit for 55' package (EC, 2021a).



Municipality patterns of solar PV production per unit area (measured as MWh/km² per year) by degree of urbanisation are mapped in **Figure 7.** Although rural areas present the lowest production per unit area, they host the largest plants in Germany, Spain, France, Portugal and Poland, with 189 municipalities having more than 100 MW of installed capacity each. Spatial patterns distinguish at least two clusters of high local production: (1) central Europe, including Germany, Belgium and the Netherlands, where most municipalities in the categories 10–100 MWh/ km² and > 100 MWh/km² per year; (2) Greece, Spain, France, Italy, Poland and Portugal, where the highest production is in scattered municipalities (> 100 MWh/km² per year).

Figure 7. Estimated annual electricity production of solar PV systems at the municipality level (MWh/km²) by degree of urbanisation in the EU-27.

Source: Authors' own elaboration from Wiki-solar (WolfeWare Ltd, 2023), Open Street Map (Dunnett et al., 2020) and the 'Fit for 55' package (EC, 2021a).

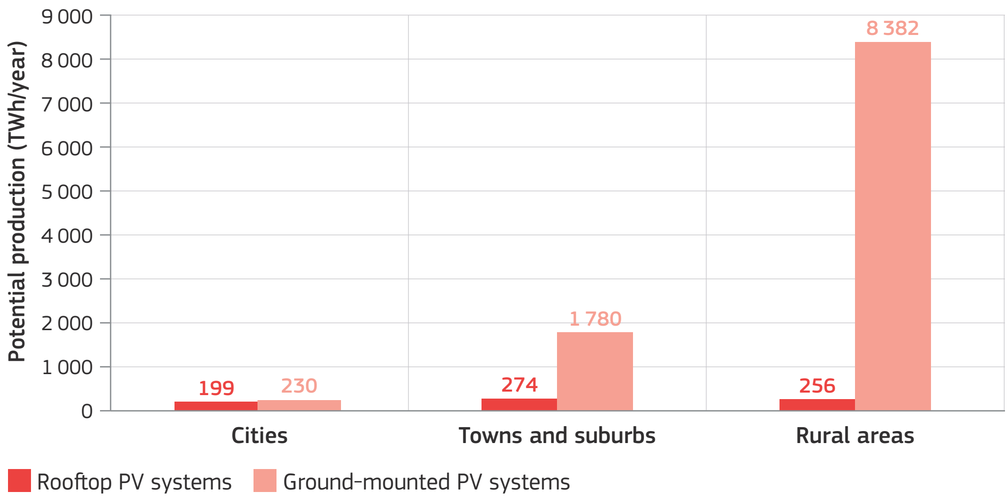
2.3 SOLAR ENERGY TECHNICAL POTENTIAL

In the EU, **the maximum estimated technical potential of solar PV amounts to 10 TW** of installed capacity, providing an **annual electricity potential production of 11 100 TWh.** These estimates are obtained by adding up rooftop (**Section 2.3.1**) and ground-mounted PV systems (**Section 2.3.2**) potentials, as obtained from our methodological approach. Ground-mounted PV systems are the technology contributing the most to the EU's total potential (93 %). This maximum potential may be achieved from the full exploitation of the **suitable land** (see glossary) available for new PV installations under certain technical and sustainability conditions, which is equal to **2.4 % of the total area of the EU.**

Rural areas account for about 78 % of the EU's total solar technical potential. More than 97 % of this potential corresponds to ground-mounted PV systems, while less than 3 % stems from rooftop PV systems. Reaching this maximum potential in rural areas would require 78 500 km² of suitable land, i.e. 2.3 % of the total surface of rural areas. Towns and suburbs follow, with roughly 18 000 km² of suitable land, whereas 3 600 km² would be needed in cities. In absolute terms, similar figures are found across the urban–rural continuum for rooftop PV potential (**Figure 8**).

Figure 8. Solar PV technical potential of rooftop and ground-mounted PV systems by degree of urbanisation.

Source: Authors' own elaboration.



Looking at national figures, the top 5 countries with the highest potential of solar PV electricity generation are Spain, Romania, France, Portugal and Italy (**Figure 9**). Altogether, these five countries account for more than 7 800 TWh/year, which represents 70 % of the total EU potential. On the other hand, countries such as Cyprus, Austria, The Netherlands, Slovenia, Belgium, Luxemburg and Malta contribute less than 0.3 %.

France, Germany, Italy and Spain, followed by urbanised countries like The Netherlands, Belgium and Malta, have the highest potential to produce electricity from rooftop solar PV, thanks to their large building stock (see **Annex 1** for more details).

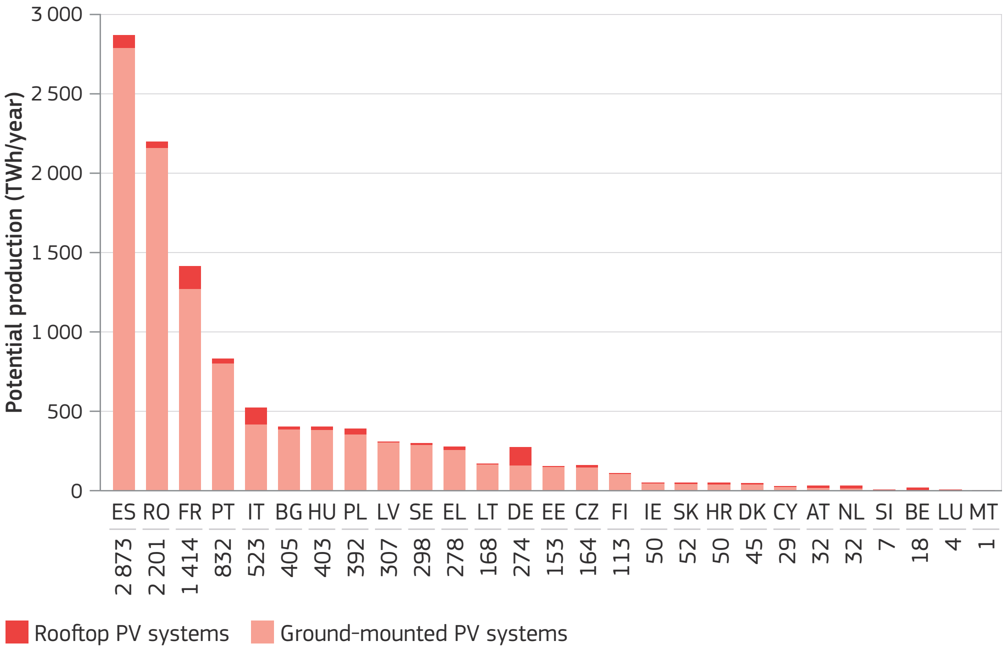


Figure 9. Rooftop and ground-mounted PV technical potential (TWh per year) at the Member State level.

Source: Authors' own elaboration.

Annual solar potential production by unit area is shown in **Figure 10**, aggregated at the Member State level and by degree of urbanisation. Rural areas present, on annual average, the highest potential production per unit area (2 700 MWh/km²), with 2 500 MWh/km² in cities and 2 400 MWh/km² in towns and suburbs. Cyprus, Malta, Greece, Luxembourg and Austria have the highest potential per unit area in cities, while in rural areas Portugal and Romania have an extraordinary potential per unit area. Big variations exist within countries, with the smallest differences between the three classes in Poland, Denmark, the Netherlands, Sweden and Finland.

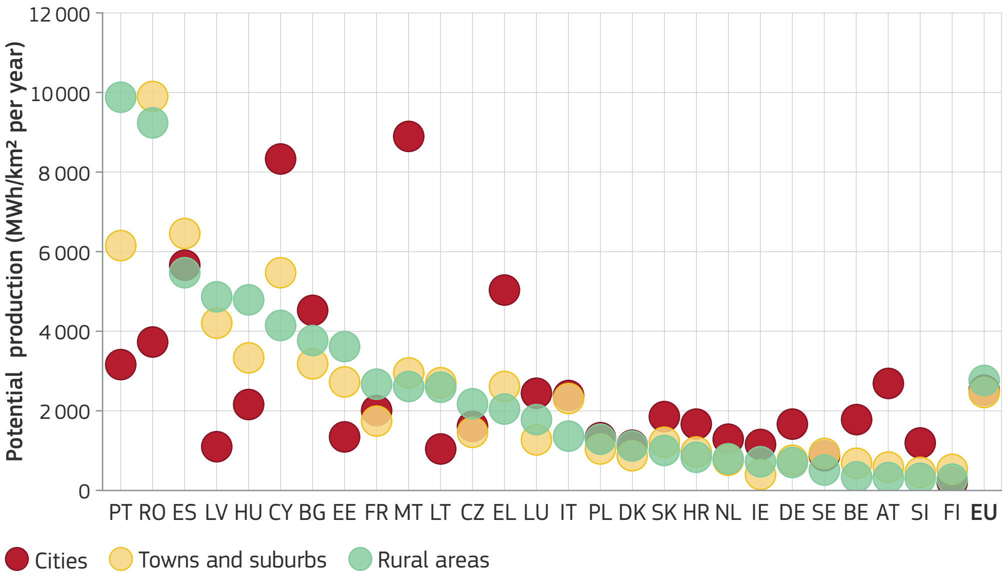


Figure 10. Solar PV technical potential production per km² in the EU's municipalities (MWh/km² per year) by degree of urbanisation at the Member State level.

Source: Authors' own elaboration.

At the local level, the analysis focuses on the patterns of solar PV technical potential production per square kilometre (MWh/km² per year) in the EU's municipalities and by degree of urbanisation (**Figure 11**). Municipalities within rural areas of Portugal, Spain, France, the Baltic countries, Romania, Hungary,

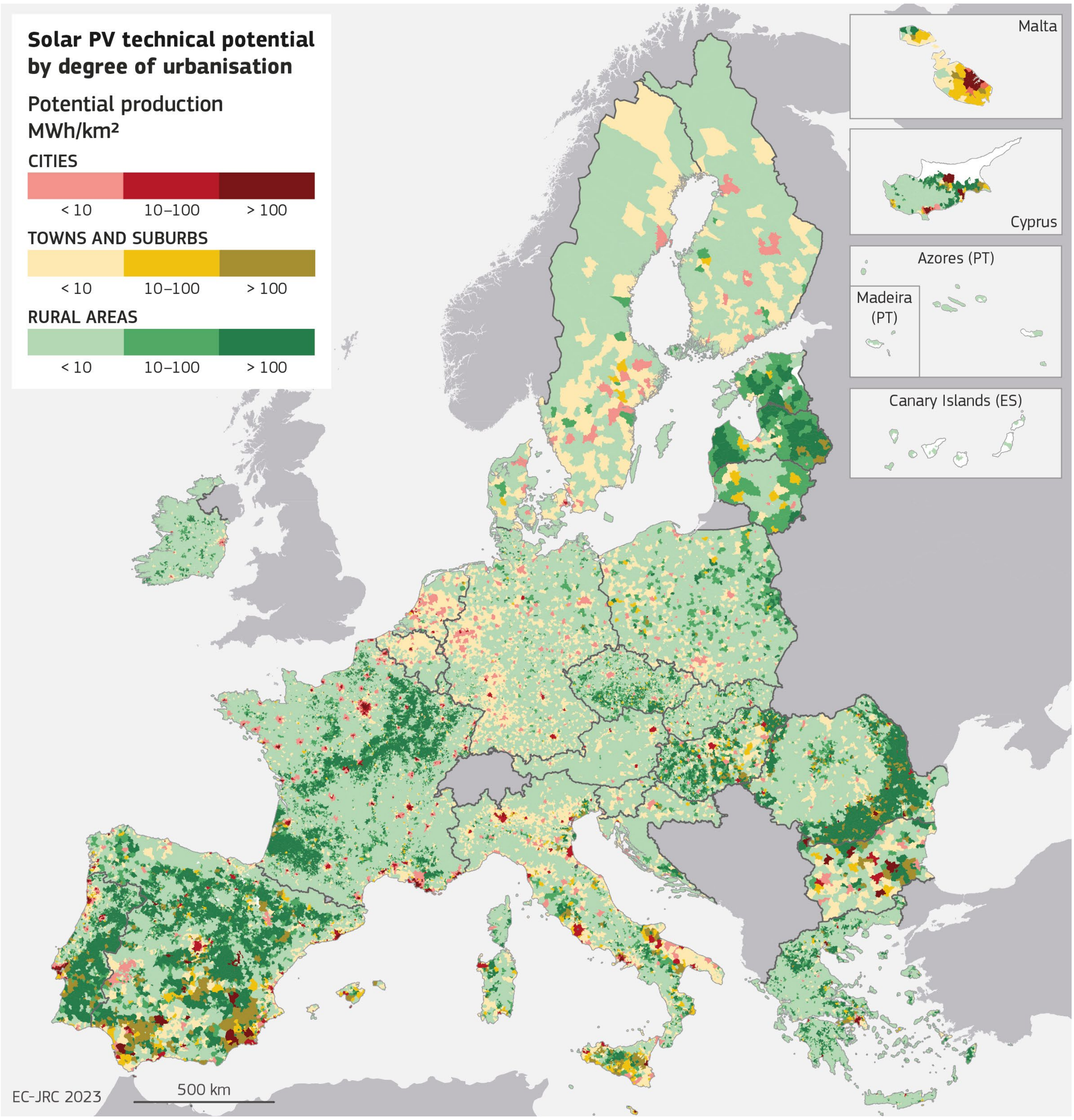


Figure 11. Annual solar PV technical potential production per municipality area (MWh/km²) and by degree of urbanisation in the EU-27.

Source: Authors' own elaboration.

Czechia and Cyprus have the highest PV potentials per square kilometre (MWh/km² per year). This high potential is found in almost 20 000 municipalities (23 % of the EU's rural areas), and it can reach up to 90 000 MWh/km² per year in some municipalities.

The highest solar PV potential in cities is found in capitals (Paris, Madrid, Rome, Sofia, Valletta, etc.) and main urban areas, where the rooftop potential is dominant. Towns and suburbs in the south of Spain, Portugal and Italy (including Sicily) are particularly relevant, while scattered patterns are observed in Bulgaria, the Baltic countries and Malta.

2.3.1 ROOFTOP PHOTOVOLTAIC TECHNICAL POTENTIAL

The rooftop[9] PV technical potential could reach 730 TWh/year, which represents 6.5 % of the total EU solar PV technical potential and, by itself, 28 % of the total EU's electricity consumption of 2021. This potential is estimated based on the built-up surface needed for rooftop PV systems, which represents 0.17 % (or 7 100 km²) of the total EU surface, but **considering only 26 % of the existing EU's built-up areas** (Bódis et al., 2019b). The remaining 74 % of built-up areas includes rooftops with unfavourable conditions such as poor orientation and/or inclination, air-conditioning units and chimneys, shading from other constructions, or walkways for maintenance. Our analysis takes into consideration open-source statistical and satellite data to estimate the technical potential for rooftop PV electricity production with a spatial resolution of 100 m (**Figure 12**), following the methodology described by Bódis et al (2019b).

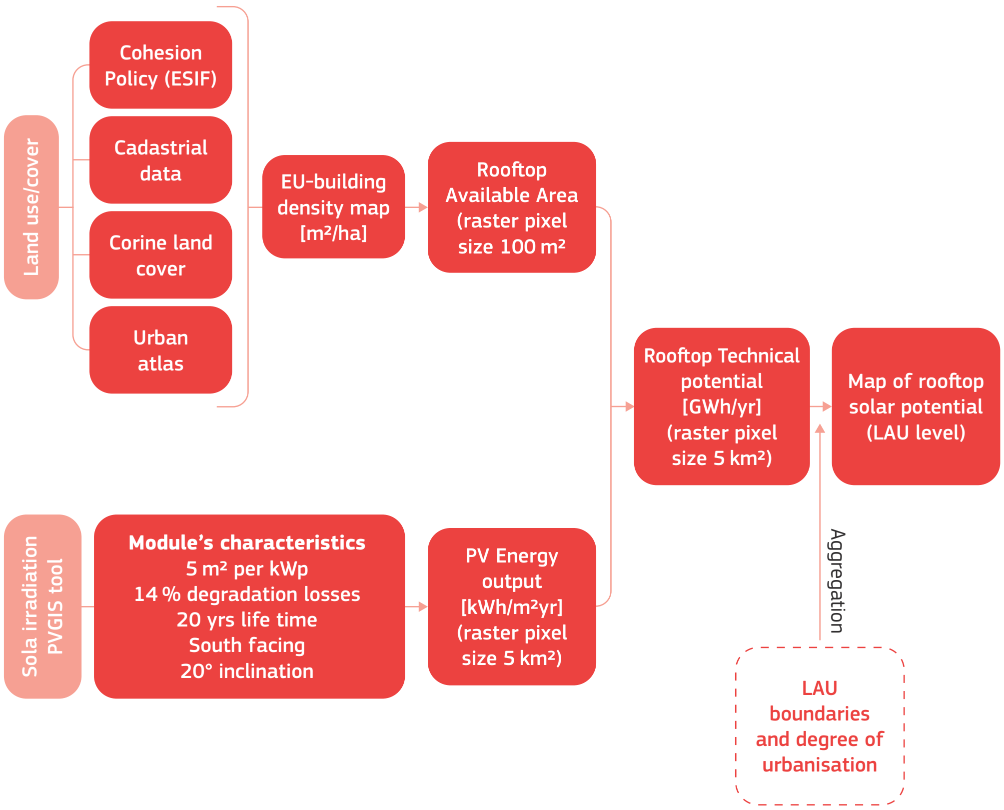


Figure 12. Scheme of the workflow for the estimation of the rooftop PV technical potential.

Note: ESM, European Settlement Map; LAU, local administrative unit; PVGIS, Photovoltaic Geographical Information System.

Source: Authors' own elaboration based on Bódis et al. (2019a).

From our results, the technical potential of rooftop PV is largest in towns and suburbs (38 %), followed by rural areas (35 %) and cities (27 %) (see **Annex 1** for more details). In rural areas, 3 % (256 TWh/year) of the total solar potential production (8 600 TWh/year) is generated by rooftop PV systems.

France, Germany, Italy and Spain could all reach rooftop PV production of more than 50 TWh/year, with France leading the ranking with almost 150 TWh/year. In absolute numbers, the highest potential is found in main capitals (Paris, Madrid,

9 In our analysis, rooftop PV systems are considered to be small-scale installations in urban areas with a capacity of less than 20 kW.

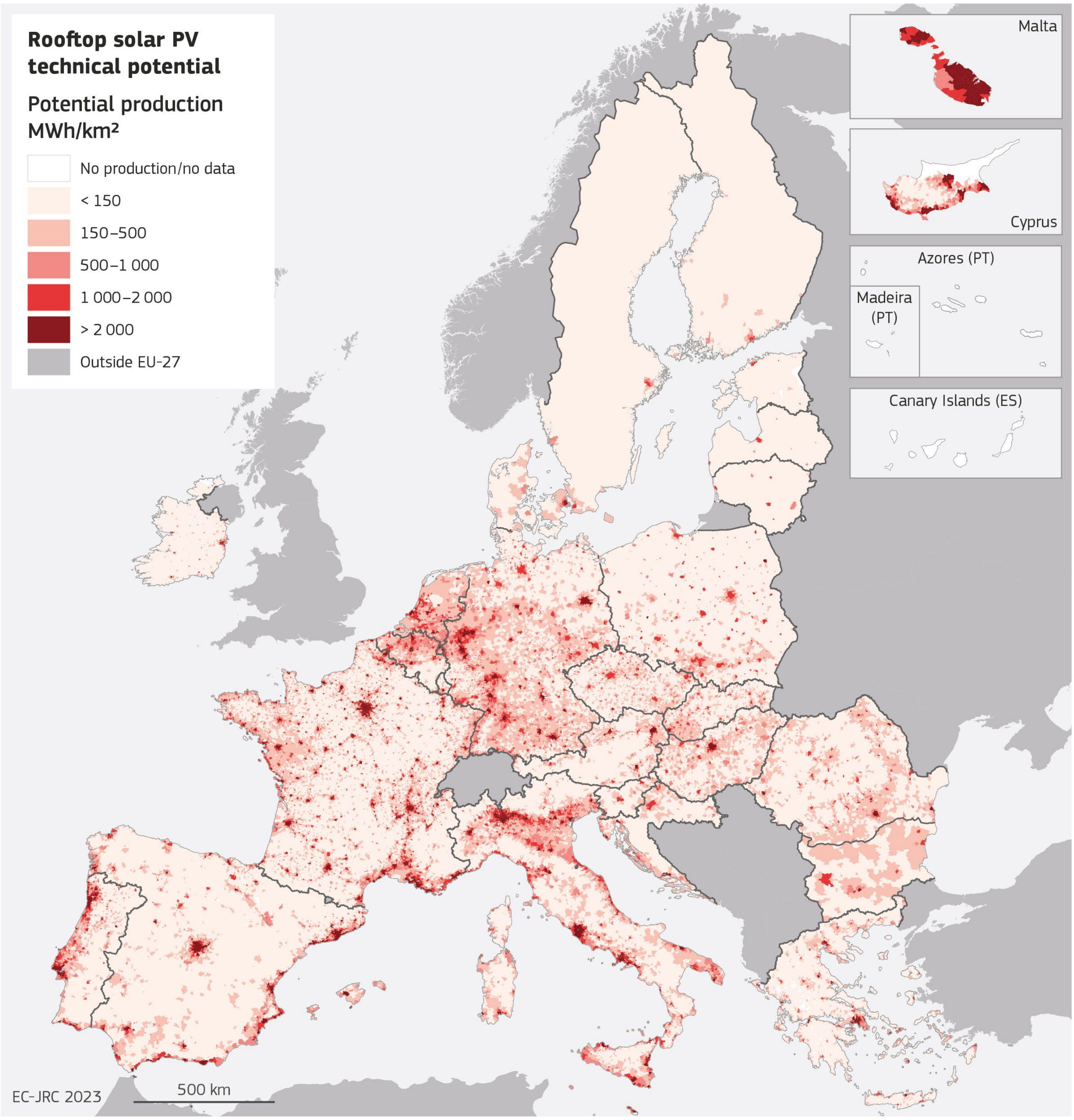


Figure 13. Annual rooftop PV potential electricity production per municipality area (MWh/km²) in the EU-27.

Source: Authors' own elaboration based on data from Bódis et al. (2019b).

Rome, Sofia, Valletta, etc.) and their surroundings, and along coastal areas, following the spatial patterns of built-up areas.

The rooftop technical potential by municipality (measured in MWh/km² per year) is represented in **Figure 13.** The average EU rooftop potential production by municipality is 314 MWh/km² per year, with cities showing the highest potential (2 200 MWh/km²), followed by towns and suburbs (810 MWh/km²) and rural areas (133 MWh/km²). Some rural municipalities (in total 135), particularly in Greece, France, Italy and Cyprus, show annual potential rooftop production above 2 000 MWh/km², together accounting for almost 2 TWh/year. More than 1 700 cities are above the same threshold.

2.3.2 GROUND-MOUNTED PHOTOVOLTAIC TECHNICAL POTENTIAL

An assessment of solar and land resources is crucial to identify suitable locations for ground-mounted PV system deployment and estimate their energy potential. These resources vary with geographic location, climate and landscape, and the suitability of the conditions needs to be evaluated for sustainable and effective solar PV deployment, ensuring **the protection of natural areas and food production systems, as well as the conservation of high nature value (HNV) farmlands.** The selection of suitability factors and sustainability criteria is essential to identify and map the suitable land available for new PV systems (Doljack et al., 2017; Sacchelli et al., 2016; Perpiña Castillo et al., 2016; Tercan et al., 2021; Bódis et al., 2019a; Dias et al., 2019).

To achieve this objective, high-resolution spatial layers for each criterion and associated thresholds are combined to identify unsuitable locations at EU scale (**Figure 14**). Buffer zones around residential and industrial areas (700 m) and infrastructures (500 m) are marked as unsuitable areas, as well as areas further than 5 km away from roads, for accessibility reasons. Forests, water bodies, protected areas and biodiversity areas are excluded as suitable sites. Topographic restrictions are also considered (e.g. areas with slopes steeper than 10° and north-facing areas are unsuitable) (see **Annex 2** for details).

Particular attention is given to agriculture, by **avoiding the use of highly productive agricultural land for energy production.** Almost 45 % of the land in rural areas is used for agriculture, and a badly planned deployment of ground-mounted PV systems might cause negative impacts on biodiversity, land-use and land-cover change, soil, water resources and human health (Sacchelli et al., 2016; Dias et al., 2019; Hernandez et al., 2014). An appropriate balance between electricity generation and agricultural production can be achieved by excluding the following from suitable land: (1) HNV farmlands (EEA, 2022); (2) permanent crops (vineyards, fruit trees, olive trees, etc.) and rice fields (LUISA base map); (3) other arable land, mixed crop systems and pastures[10].

Other arable land, mixed-crop systems and pastures are included under certain conditions. They are considered suitable land only when they show low productivity[11], are at high risk of agricultural abandonment (Perpiña Castillo et al., 2020) and are affected by severe erosion (ESDAC, 2016). Under certain favourable conditions, solar PV infrastructure can promote revegetation and protect soil structure, especially alleviating soil erosion (Choi et al., 2020; Verheijen et al., 2023; Liu et al., 2019). The remaining **land-use/cover classes, namely scrub and/or herbaceous vegetation associations** (natural grasslands, moors and heathland, sclerophyllous vegetation and transitional woodland-shrub) **are considered suitable land available for new installations** when the other criteria are met.

10 Suitability maps are derived from the LUISA (Land Use-based Integrated Sustainability Assessment) Territorial Modelling Platform at 100 m spatial resolution (Pigaiani et al., 2021; *https://joint-research-centre.ec.europa.eu/luisa_en*; *https://data.jrc.ec.europa.eu/collection/luisa*).

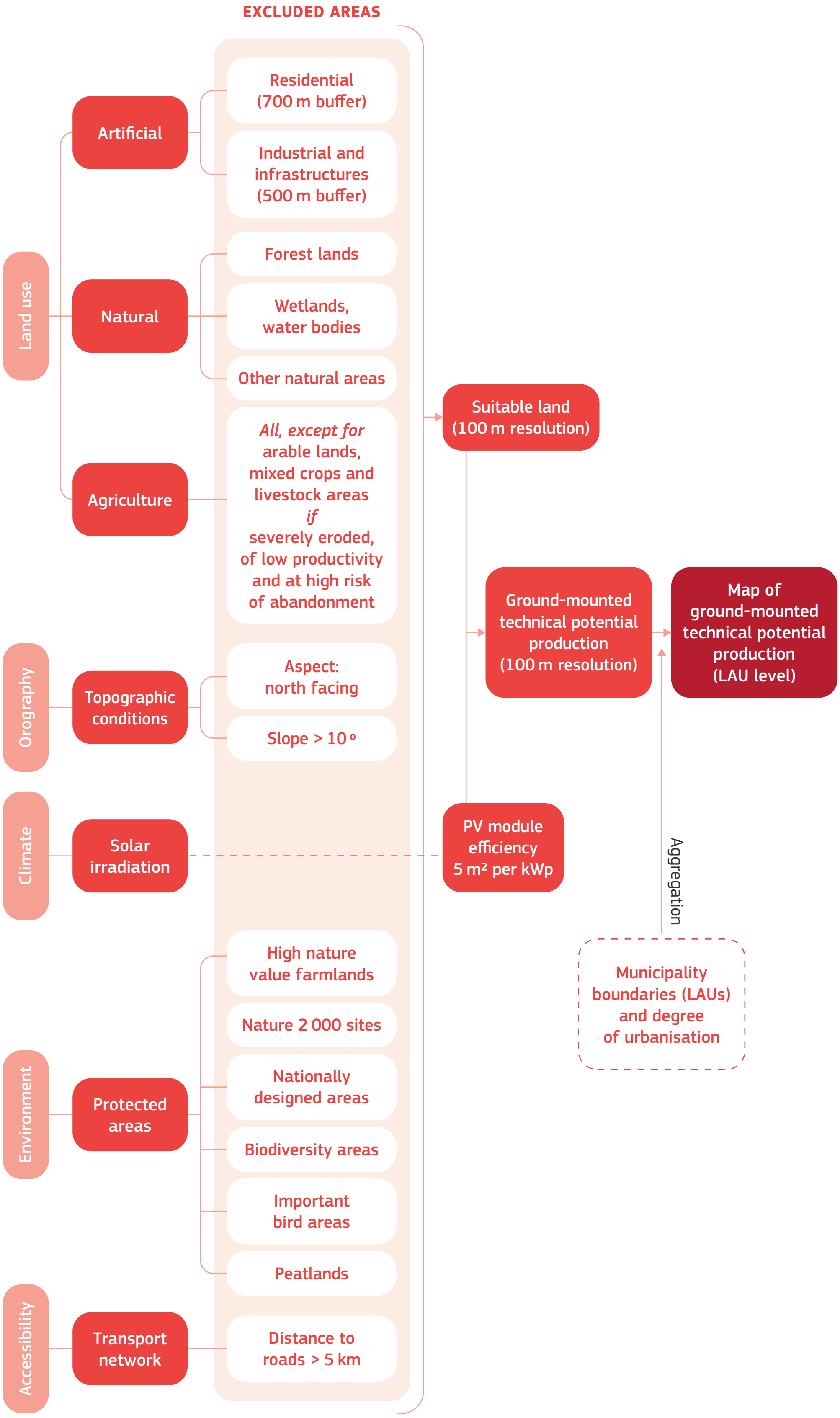
11 Agricultural land of low productivity is therefore defined as those agricultural plots falling in the lowest quintile (below 20 %).

A detailed description and references for selected criteria and thresholds can be found in **Table A2.1** and **Table A2.2** (**Annex 2**), while information on the datasets used is detailed in **Annex 5.**

Figure 14. Scheme of the workflow for the estimation of the technical potential of ground-mounted PV.

Note: The description, main references and maps of the restrictions and suitability factors can be found in Annexes 2 and 5. LAU, local administrative unit.

Source: Authors' own elaboration.



After applying all exclusions and constraint factors (**Figure 14**), **the maximum suitable land for a sustainable deployment of solar PV ground-mounted systems amounts to 92 800 km², which is equal to 2.2 % of the EU's total land area.** Agricultural areas of low productivity combined with high risk of abandonment and severe erosion make up 80 % of this suitable land, which amounts to 4 % of the EU's agricultural land.

Latvia has the largest share (8.5 %) of suitable land available for new PV installations, followed by Romania (7.6 %), Estonia (6.2 %), Cyprus (6.1 %), Portugal (5 %), Lithuania (4.4 %), Hungary (3.9 %), Spain (3.2 %) and Bulgaria (2.6 %), which are all above the EU average. Together, these countries account for 61 % of the EU's available suitable land. **Most of this land (78 %) is in rural areas,** while 18 % is in towns and suburbs and only 4 % in cities (see **Annex 1** for more details).

Once how much suitable land is available has been established, the maximum annual potential production of ground-mounted PV systems can be estimated from the installed capacity at the pixel level (100 m spatial resolution). Considering a capacity density of installed panels[12] ρ_s = 93 MW_p/km² and grid-level capacity factors (CFs) derived from the average annual solar irradiation (PVGIS, 2022), the annual potential production (*PV pot prod*) of ground-mounted PV in an area a_i is given by equation (1):

$$PV\ pot\ prod\ [MWh] = \rho_s \left[\frac{\mathrm{MWp}}{\mathrm{km}^2}\right] \cdot CF_i \left[\frac{\mathrm{MWh}}{\mathrm{MW_p}}\right] \cdot a_i\ [\mathrm{km}^2] \qquad \text{(Eq. 1)}$$

where the potential installed capacity of each grid cell of area a=0.01 km² (1 ha) amounts to 0.93 kW_p.

Based on the criteria and technical characteristics described, in the EU the maximum potential installed capacity for ground-mounted solar PV systems amounts to 8 600 GW. The potential capacity for ground-mounted systems is more than six times that of rooftop PV.

Based on the potential installed capacity described above, we estimate that, in the EU, **the potential production from solar PV ground-mounted systems is 10 400 TWh/year.** This amounts to 93 % of the EU's solar PV potential, with the remaining 7 % stemming from potential rooftop installations. **81 % of the EU's ground-mounted potential is found in rural areas.** Towns and suburbs hold 17 % and cities the remaining 2 %.

12 The used capacity density amounts to an area of 5.5 m² being needed to install a capacity of 1 kWp, or 18.2 % panel efficiency (Kakoulaki et al, 2021). Assuming 1 m × 1.65 m modules with an inter-row spacing of three times their height and an inclination of 20°, the effective capacity density is reduced to 93 MWp/km².

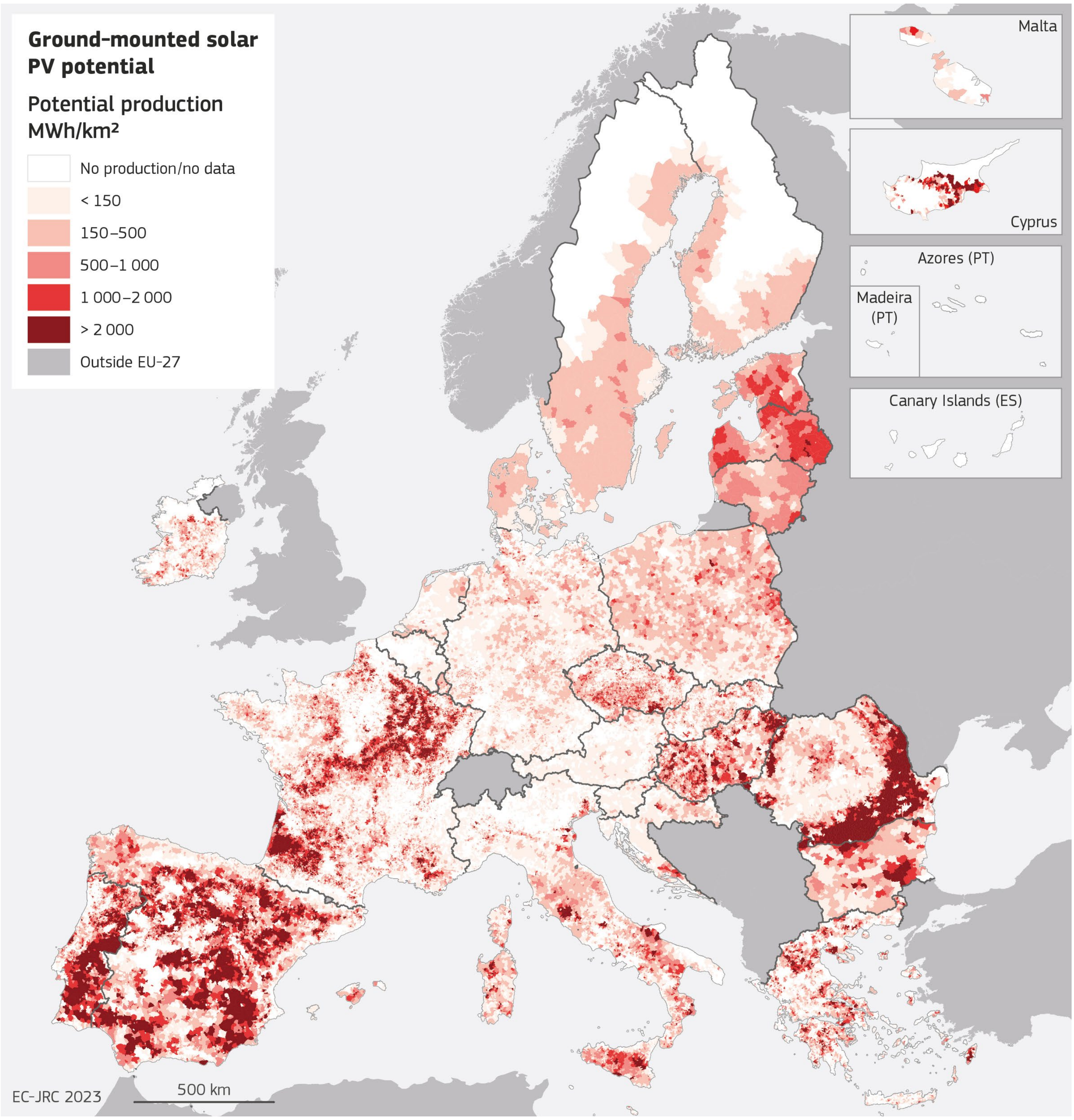


Figure 15. Annual ground-mounted solar PV potential electricity production per municipality area in the EU-27 (MWh/km²).

Source: Authors' own elaboration.

By degree of urbanisation, on average, rural areas could produce up to 2 700 MWh/km² per year, while towns and suburbs could reach 1 000 MWh/ km² and cities 325 MWh/km². A total of 6 062 municipalities shows a very high potential per km² (above 10 GWh/km² per year), 94 % of which are rural areas (**Figure 15**). Ground-mounted PV potential per square kilometre is highest in Spain, Portugal, France, Romania, Bulgaria, Estonia, Lithuania, Hungary, Greece and Italy.

2.4 UNTAPPED POTENTIAL OF SOLAR ENERGY

In this analysis, we refer to 'untapped potential' as the difference between the technical potential (maximum achievable potential production) and current production. In the EU, **the untapped potential of solar energy amounts to 11 000 TWh/year.** Most of the EU municipalities (95 %) have untapped solar potential, with the highest values found in Spain, Romania and France, all exceeding 1 000 TWh/year (**Figure 16**). **78 % of the EU's untapped solar potential production is found in rural areas,** 18 % in towns and suburbs and 4 % in cities.

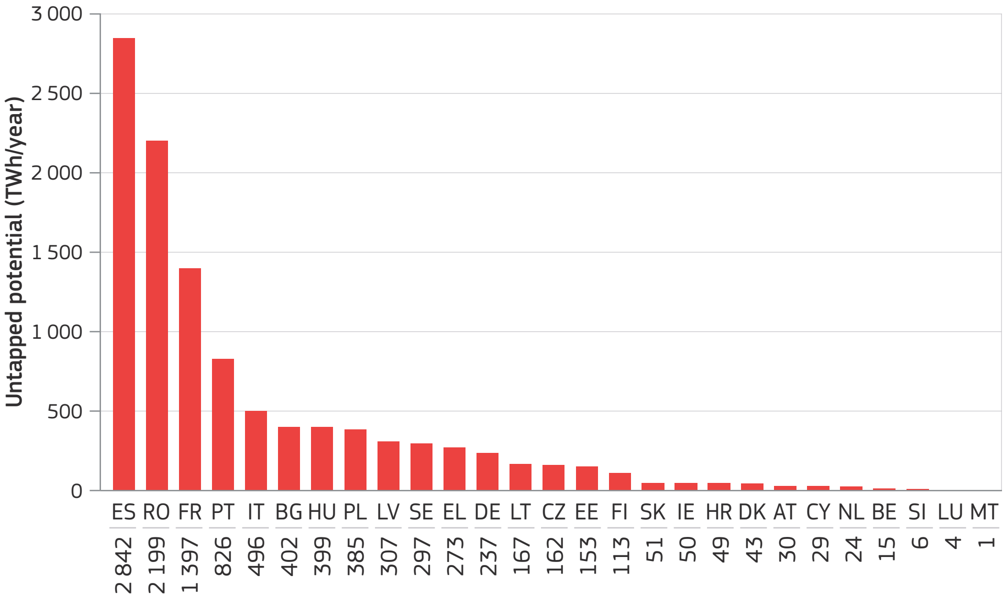


Figure 16. Untapped solar PV potential production (difference between potential and current production) for EU Member States (TWh/year).

Source: Authors' own elaboration.

2.5 % of the EU's municipalities (2 514) are already fully exploiting their local resources for solar electricity generation, particularly in Germany, the Netherlands, Italy and Greece, and to a lesser extent in Spain, France, Ireland and Belgium. These municipalities with low untapped potential are mostly classified under the category 'Low technical potential but high production' in **Figure 17.** Despite low solar technical potential compared with the EU average (lower than 2 500 MWh/km² per year), these municipalities have the highest current electricity production (greater than 65 MWh/km² per year), meaning they have performed well in terms of solar PV deployments in the past.

The category including most municipalities with substantial untapped solar potential is 'High technical potential but low current production'. Almost 21 % of all EU municipalities fall under this category, with the highest shares found in Baltic countries (Latvia (68 %), Estonia (48 %), Lithuania (45 %), Hungary (45 %), Romania (42 %), Spain and Portugal (40 %) (**Figure 18**).

In some cases, the lack of untapped potential is due to our methodology being quite restrictive in terms of environmental criteria (e.g. exclusion of natural protected areas, HNV farmlands, etc.) and to the fact that we favour the use of productive agricultural land for food rather than energy production.

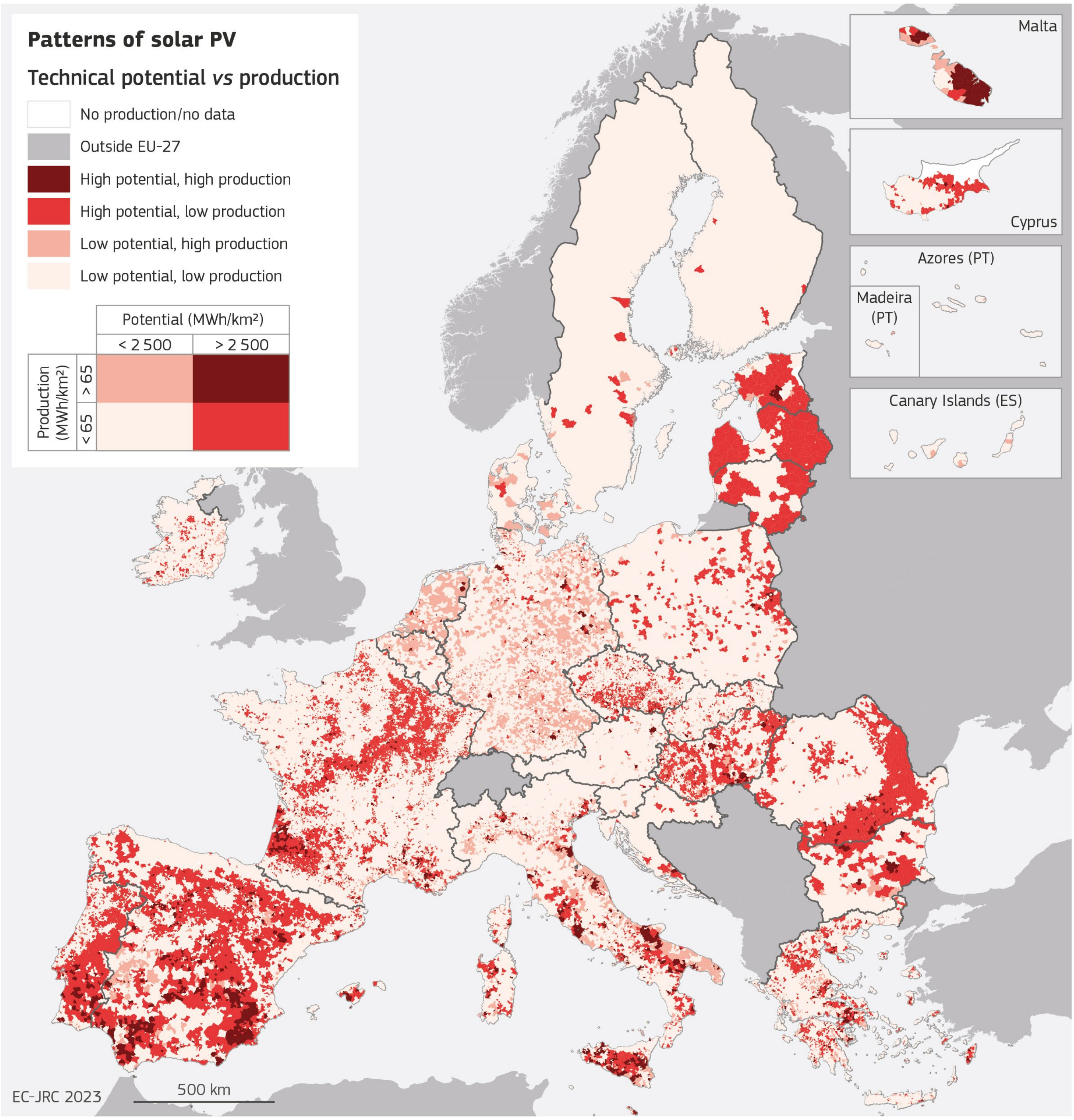


Figure 17. Patterns of current and potential production of solar PV systems to identify untapped potential in the EU's municipalities.

Note: Mean values of the technical potential (2 500 MWh/km²) and current production (65 MWh/km² per year) are used as thresholds to define each category.

Source: Authors' own elaboration.

2.5 CONCLUSIONS

This chapter presents an assessment of the current and potential installed capacity and electricity production of solar PV systems at the local level, emphasising the contribution of the EU's rural areas. The current estimated installed solar capacity is in line with the EU's policy-driven energy path, reaching 200 GW by the first quarter of 2023. This is mainly driven by Germany (60 GW), Spain (27 GW) and Italy (25 GW), which altogether account for 76 % of the total EU's installed solar PV capacity. The solar plants with the highest installed capacities (more than 100 MW) are found in rural areas in Germany, Spain, France, Portugal and Poland.

In 2023, the **estimated annual electricity production of solar PV systems amounts to 250 TWh in the EU.** Most of the production, 204 TWh (82 %), is generated by ground-mounted systems (including industrial and commercial systems), while 46 TWh (18 %) is generated by small-scale rooftop PVs. **Rural areas account for 54 % (136 TWh/year) of the total EU electricity production from solar PV systems,** followed by towns and suburbs (36 %, 90 TWh) and cities (10 %, 24 TWh). Germany is the largest electricity producer in rural areas, with almost 40 TWh/year, followed by Spain, France, Poland, Italy and Greece.

Suitable land for the deployment of new ground-mounted PV installations has been identified according to strict environmental and sustainability criteria prioritising food production and the conservation of natural and protected areas. Agricultural land has been excluded, unless it is at high risk of abandonment, of low productivity and severely eroded. To complement this, buffers around infrastructure and settlements have also been applied. The maximum suitable land that is available under the envisaged constraints amounts to **2.4 % of the total EU surface,** almost 93 000 km². **Most of this land, 78 %, is in rural areas,** while 18 % is in towns and suburbs, and 4 % in cities.

Using all suitable land, the **solar PV technical potential in the EU (i.e. the maximum achievable potential production) is more than 11 100 TWh/year,** 93 % from ground-mounted PV systems and 7 % from rooftop PVs. Considering the EU electricity consumption of 2021 (2 563 TWh), solar PV alone could potentially provide more than four times the total EU's consumption, while it currently accounts for almost 10 %.

The installation of **PV systems on rooftops** does not require additional land. By **using 26 % of the EU's built-up areas,** which represents 0.17 % of its total surface, it is possible to achieve a technical potential production of electricity of 730 TWh/year. By degree of urbanisation, the rooftop PV technical potential is similar in rural areas (36 %), towns and suburbs (37 %) and cities (27 %). The highest rooftop PV potential is found in main capitals (Paris, Madrid, Rome, Sofia, Valletta, etc.).

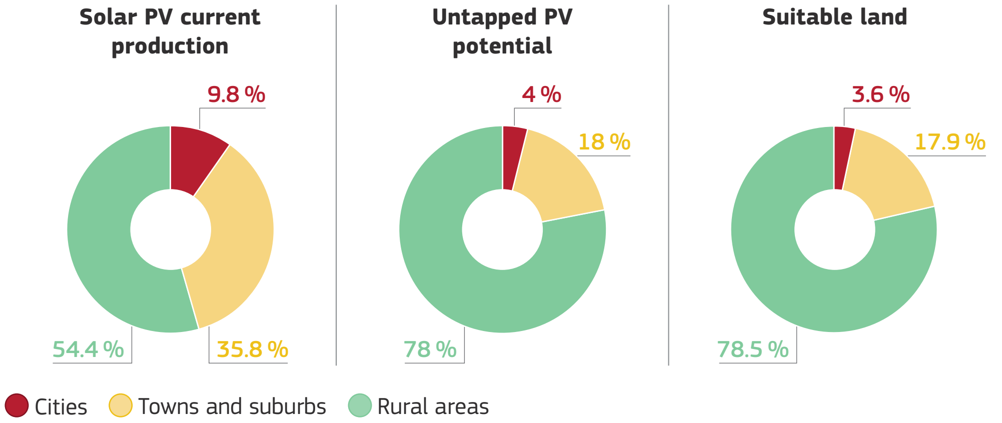


Figure 18. EU current production, untapped potential and suitable land for solar PV installations by degree of urbanisation.

Source: Authors' own elaboration.

Rural areas account for 8 600 TWh/year, which represents 78 % of the total EU's solar technical potential production. More than 97 % of this potential corresponds to ground-mounted PV systems. In almost all Member States (except for Malta), rural areas have the highest solar potential. Rural areas also offer, on average, the highest annual potential production per unit area (2 700 MWh/km²), compared with 2 500 MWh/km² in cities and 2 400 MWh/km² in towns and suburbs.

In the EU, t**he untapped potential amounts to 10 900 TWh/year, 78 % of which is available in rural areas.** Exploiting this potential would allow rural areas to contribute to the Green Deal objectives while retaining most of the social and economic benefits of RESs. The highest values of untapped solar potential are found in Spain, Romania, France and Portugal. 2.5 % of the EU's municipalities are already fully exploiting their local resources for solar electricity generation (particularly in Germany, the Netherlands, Italy and Greece). This signals that, over time, these municipalities have steadily promoted the deployment and stepped up the performance of PV solar technologies.

The main figures are summarised in **Table 1.**

Table 1. Main figures of the EU estimated production, installed capacity and suitable land available for solar PV systems.

Note: Total figures are rounded for better interpretation (Annex 1 provides totals and national figures).

Source: Authors' own calculations.

	CURRENT		POTENTIAL		SUITABLE LAND	
PV solar system	**Capacity (GW)**	**Production (TWh/year)**	**Capacity (GW)**	**Production (TWh/year)**	**Area (km²)**	**% of the EU**
Rooftop PV	40	46	1 400	730	7 150	0.17
Ground-mounted PV	160	204	8 600	10 400	92 800	2.24
Total	**200**	**250**	**10 000**	**11 100**	**100 000**	**2.41**

3 Wind energy

3.1 WIND ENERGY IN THE EUROPEAN UNION: STATUS AND OUTLOOK

Following the objectives of the REPowerEU plan presented by the European Commission in May 2022, the EU's 2030 energy target has been recently strengthened to reach 42.5 % of renewables in the energy mix, with the ambition to reach 45 % (EC, 2022a, 2023a). This strengthens the targets of the 'Fit for 55' legislation of the European Green Deal, which set the goal at 40 % of renewables by 2030. Wind energy, with both onshore and offshore technologies, is set to play a key role in reaching these targets: in the REPowerEU plan, the capacity of wind energy is proposed to increase to 510 GW by 2030.

In 2021, **the EU had 188 GW of installed capacity of wind energy, 92 % in onshore wind farms and 8 % offshore** (Eurostat, 2021f). These capacities made it possible to produce 406 TWh of electricity with wind energy in 2021, the equivalent of 16 % of the EU's total electricity consumption in that year (Eurostat, 2021c). More recent reports show that in 2022 the EU-27's installed wind capacity reached 204 GW, of which 188 GW was onshore and 16 GW offshore, delivering 487 TWh of renewable electricity (Wind Europe, 2023).

In the EU, wind energy saw important developments during the 2000s, especially in the case of onshore wind. Onshore capacities grew from a few gigawatts in 2000 to more than 70 GW in 2010, as seen in **Figure 19,** and continued to increase steadily in the following decades. In 2022, the EU installed 16 GW of capacity in new wind installations, 92 % of it onshore (Wind Europe, 2023). However, even though wind power capacities have grown rapidly in recent decades, reaching the REPowerEU target of 510 GW requires a boost in growth: wind capacity should increase by 30 GW per year until 2030. If the increase in capacity is undertaken mainly through new onshore wind installations, this would require almost tripling current installed capacities in less than a decade.

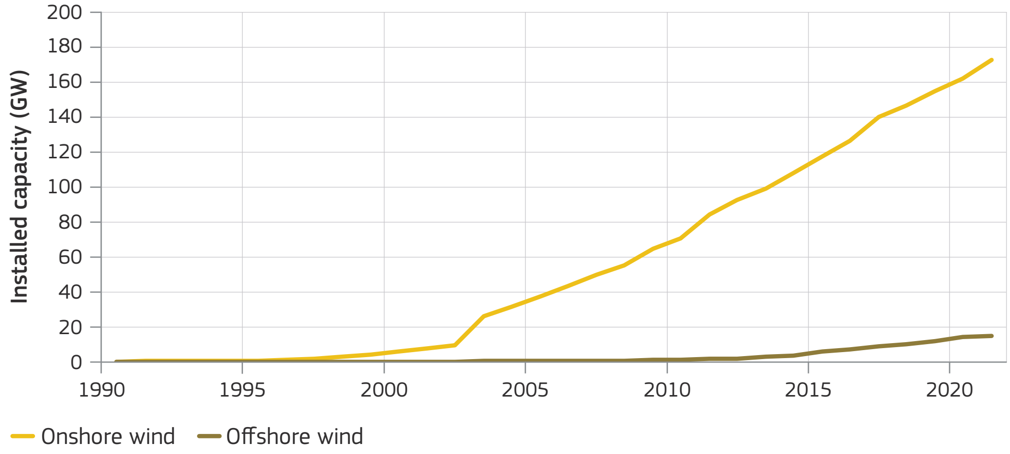


Figure 19. Development of wind installed capacity in the EU-27.

Source: Authors' own elaboration based on Eurostat (2021f).

In this section, we assess the current and potential production of electricity from onshore wind energy at the local level in the EU, as its deployment is especially relevant to rural municipalities. Today, rural areas are responsible for 80 % of onshore wind production and, according to our estimates, hold 84 % of the potential, which makes them key actors in the energy transition, and opens up opportunities to benefit from it.

In its Long-Term Vision for Rural Areas, the European Commission already identified support to rural municipalities in the energy transition and fighting climate change as a flagship initiative towards more resilient rural areas. Our goal in this analysis is to **identify paths for sustainable development of onshore wind capacities, giving special attention to the role of rural areas** in the process. We propose sustainable land-planning practices in the roll-out of new installations, ensuring that the natural and agricultural resources of rural areas are preserved.

BOX 3. Wind power – energy is in the air

Wind is a clean, free and abundant renewable energy source. Wind power can be used to produce electricity by harnessing the kinetic energy of the moving air by means of wind turbines. In modern wind turbines, kinetic energy is first converted into rotational energy by the rotor blades, and then into electrical energy by a generator. Recent developments in the design of onshore and offshore wind turbines have yielded an increase in generating capacity, increasing rotor diameter and hub height, thus enabling new wind farms to harness the power of higher and more consistent wind speeds and allowing turbines to be potentially sited also in forest areas, reaching above the canopy.

Wind turbines can be located on land (onshore wind), where wind speeds are highly influenced by the local geomorphology, or on waterbodies, usually at sea (offshore wind), where wind speeds are generally higher. Wind power stations can be deployed in the form of small distributed systems, with one or a few turbines, although that option is less common, or clustered in large utility-scale wind farms.

3.2 CURRENT EUROPEAN UNION PRODUCTION OF ONSHORE WIND ENERGY

In 2021, onshore wind energy in the EU reached an installed capacity of 173 GW and annual electricity production of 339 TWh, which amounted to about 13 % of the EU's electricity consumption in that year (Eurostat, 2021a, 2021b). To estimate the current status of onshore wind energy in each municipality of the EU, we employ the World Wind Farms database, which provides up-to-date information on the location and capacities of wind farms in the EU (Wind Power, 2023). The database reports 180 GW of installed capacity for onshore wind in the EU, including active installations up to April 2023.

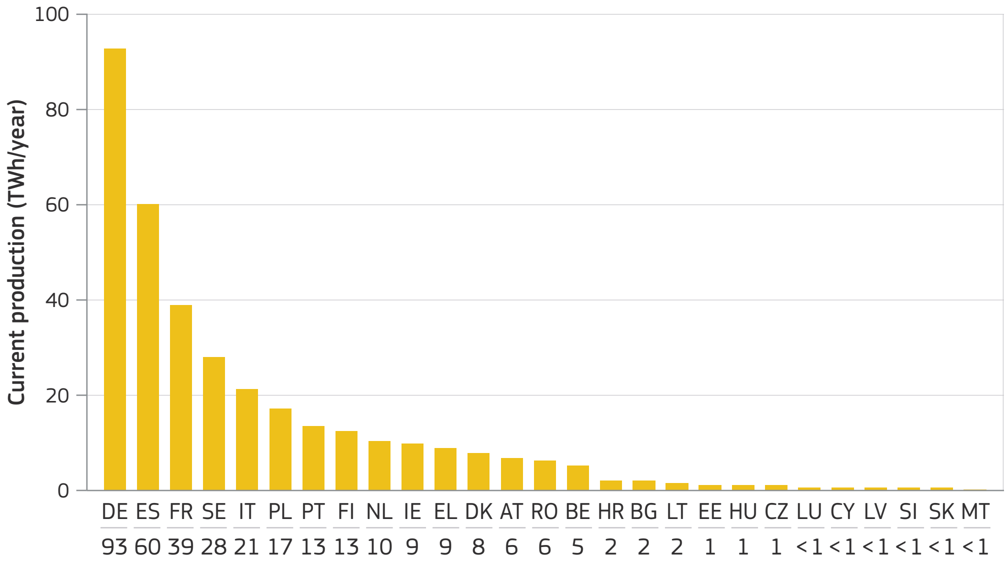
The annual electricity production of each onshore wind farm is estimated from its installed capacity, provided by World Wind Farms, and grid-level capacity factors from the Global Wind Atlas (DTU, 2023). Power losses are estimated at the country level by comparing national CFs derived from Eurostat data with the average capacity factor of the wind farms in each country (see **Annex 3** for details). The annual production of each wind farm (denoted by Wind prod) is then given by equation (2):

$$Wind\ prod\ [\mathrm{MWh}] = cap\ [\mathrm{MW}] \cdot \mathrm{CF} \cdot \mathrm{LF} \cdot 365 \cdot 24 \qquad \text{(Eq. 2)}$$

where LF are the estimated loss factors. For the EU, our estimates give annual onshore wind electricity production of 350 TWh in 2023. As seen in **Figure 20,** the Member States currently delivering the highest production are Germany (93 TWh/year), Spain (60 TWh/year) and France (39 TWh/year), which together account for more than 55 % of the EU's onshore wind production. On the other hand, the Member States with the highest production relative to their surface area are the Netherlands, Germany, Denmark and Belgium, producing more than 150 MWh/year per km². These patterns can be seen in **Figure 21,** where the estimated electricity production from onshore wind in the EU's municipalities is shown relative to their size.

Figure 20. Estimation of annual electricity production from onshore wind for the EU Member States.

Source: Authors' own elaboration from World Wind Farms database (Wind Power, 2023) and Global Wind Atlas capacity factors (DTU, 2023).



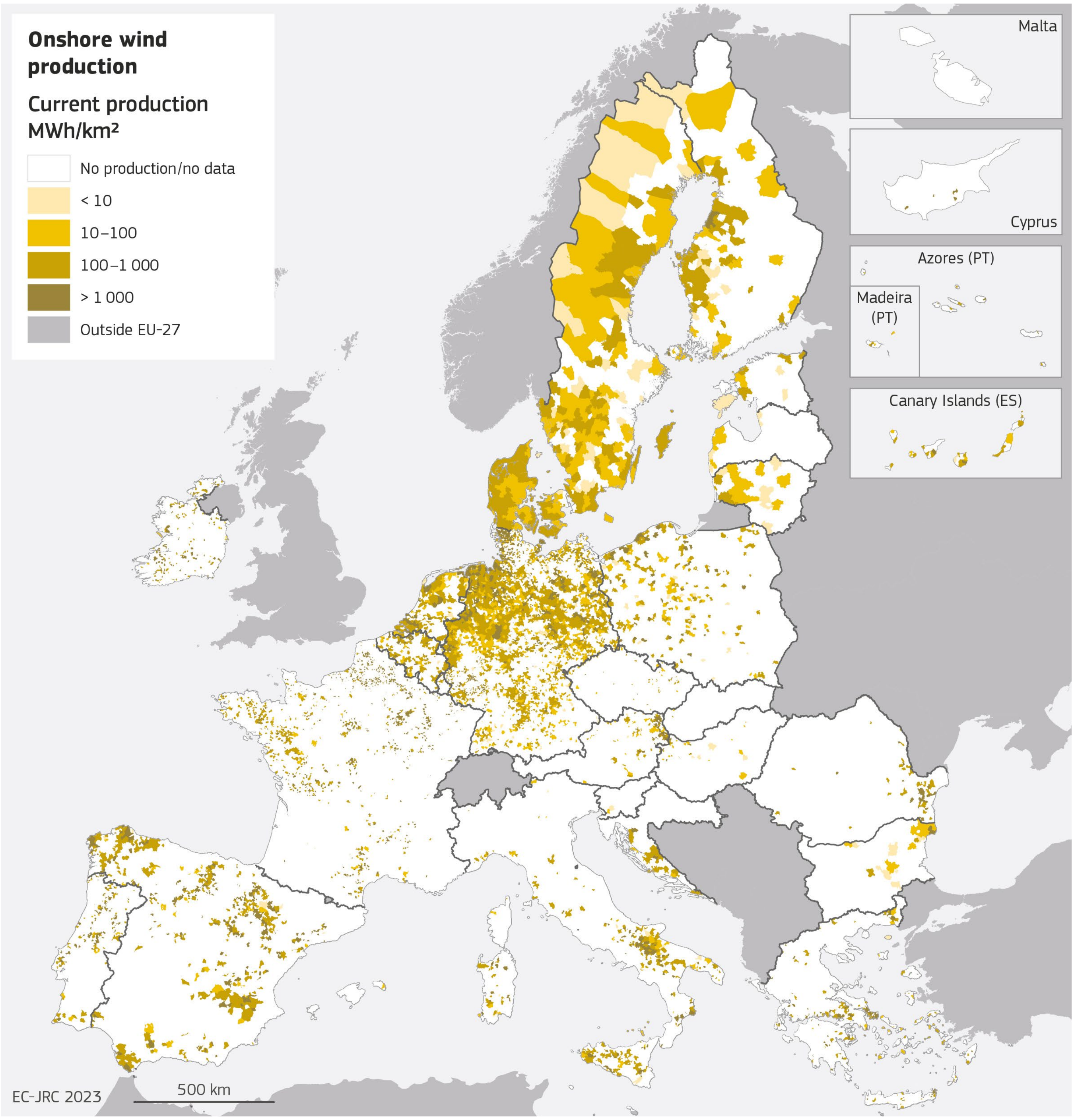


Figure 21. Estimated annual production of onshore wind electricity in the EU's municipalities, 2023.

Note: Production is shown per unit municipality area.

Source: Authors' own elaboration from World Wind Farms database (Wind Power, 2023) and Global Wind Atlas capacity factors (DTU, 2023).

Rural municipalities play a key role in the generation of onshore wind energy in the EU. Our analysis shows that they **are responsible for 80 % of the current production of the EU's onshore wind energy** (280 TWh/year), followed by towns and suburbs (60 TWh/year or 17 %) and cities (10 TWh/year or 2.5 %). Municipality patterns by degree of urbanisation can be observed in **Figure 22.** In the EU, almost 1 400 municipalities (1.4 % of all municipalities) are delivering a very high production per unit area (above 1 000 MWh/km² per year), of which 83 % are rural areas, 15 % are towns and suburbs and 1.8 % are cities. These high-production municipalities are located predominantly in Germany (55 %), Spain (17 %) and Austria (3.6 %).

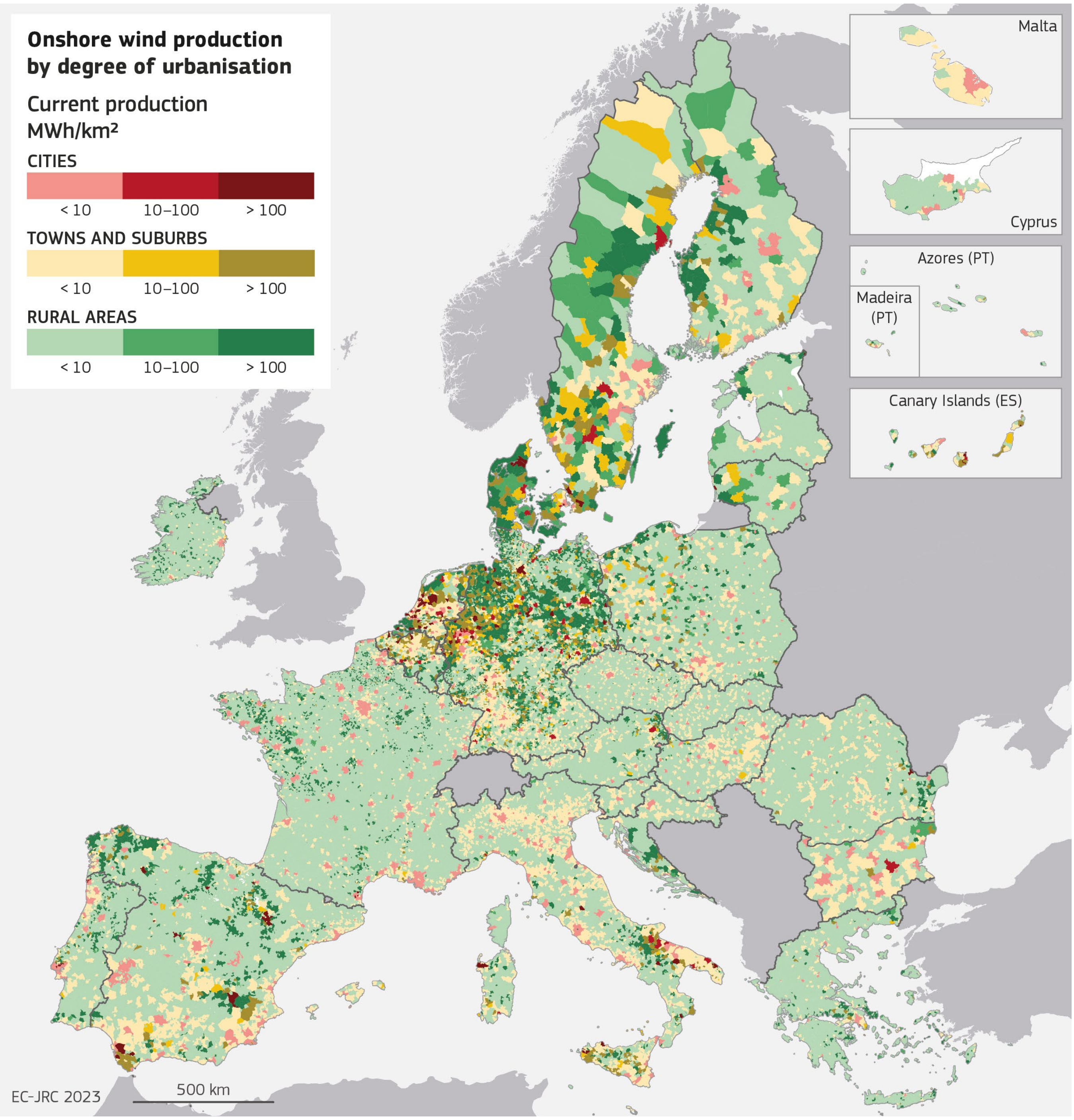


Figure 22. Estimated annual production of onshore wind electricity in the EU's municipalities by municipality area and by degree of urbanisation.

Source: Authors' own elaboration from World Wind Farms database (Wind Power, 2023) and Global Wind Atlas capacity factors (DTU, 2023).

On average, rural areas deliver the highest production per unit area (110 MWh/km²/year), followed by towns and suburbs (54 MWh/km²/year) and cities (23 MWh/km²/year). As shown in **Figure 23,** in 20 out of 27 Member States rural areas show a higher production per unit area than towns and suburbs or cities. Rural areas in Denmark and Germany are currently leading in production relative to their size, delivering more than 300 MWh/km²/year of electricity with onshore wind.

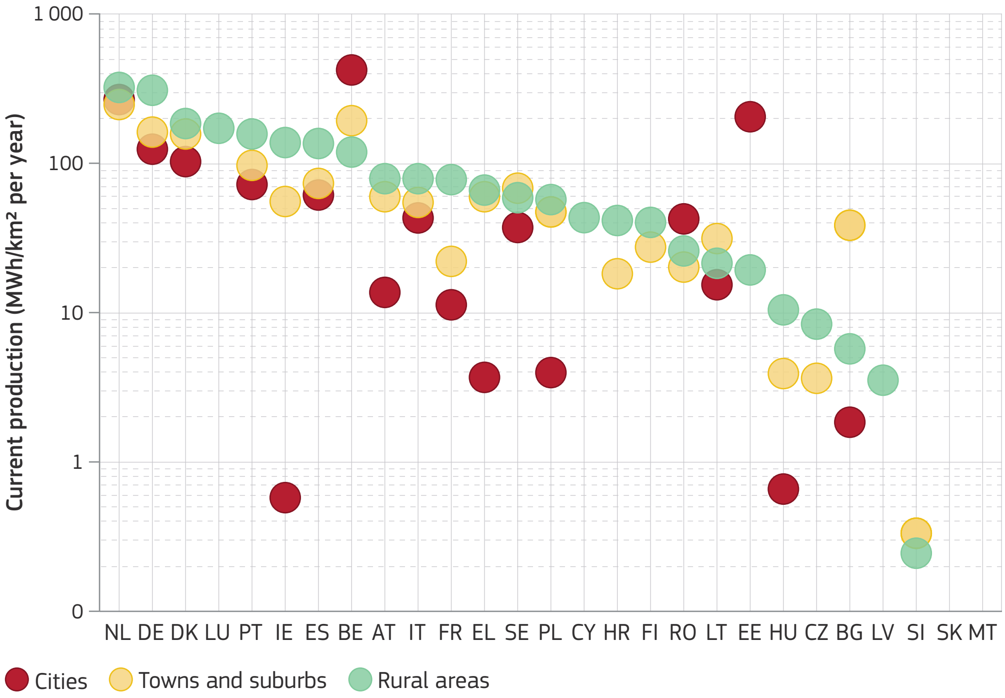


Figure 23. Estimated annual onshore wind electricity production by degree of urbanisation, 2023.

Note 1: Graphical visualisation in logarithmic scale.

Note 2: Yearly production in MWh is shown per unit area.

Note 3: Current production in Slovakia and Malta is estimated to be below 0.1 MWh/km² per year.

Source: Authors' own elaboration from World Wind Farms database (Wind Power, 2023) and Global Wind Atlas capacity factors (DTU, 2023).

3.3 ONSHORE WIND TECHNICAL POTENTIAL

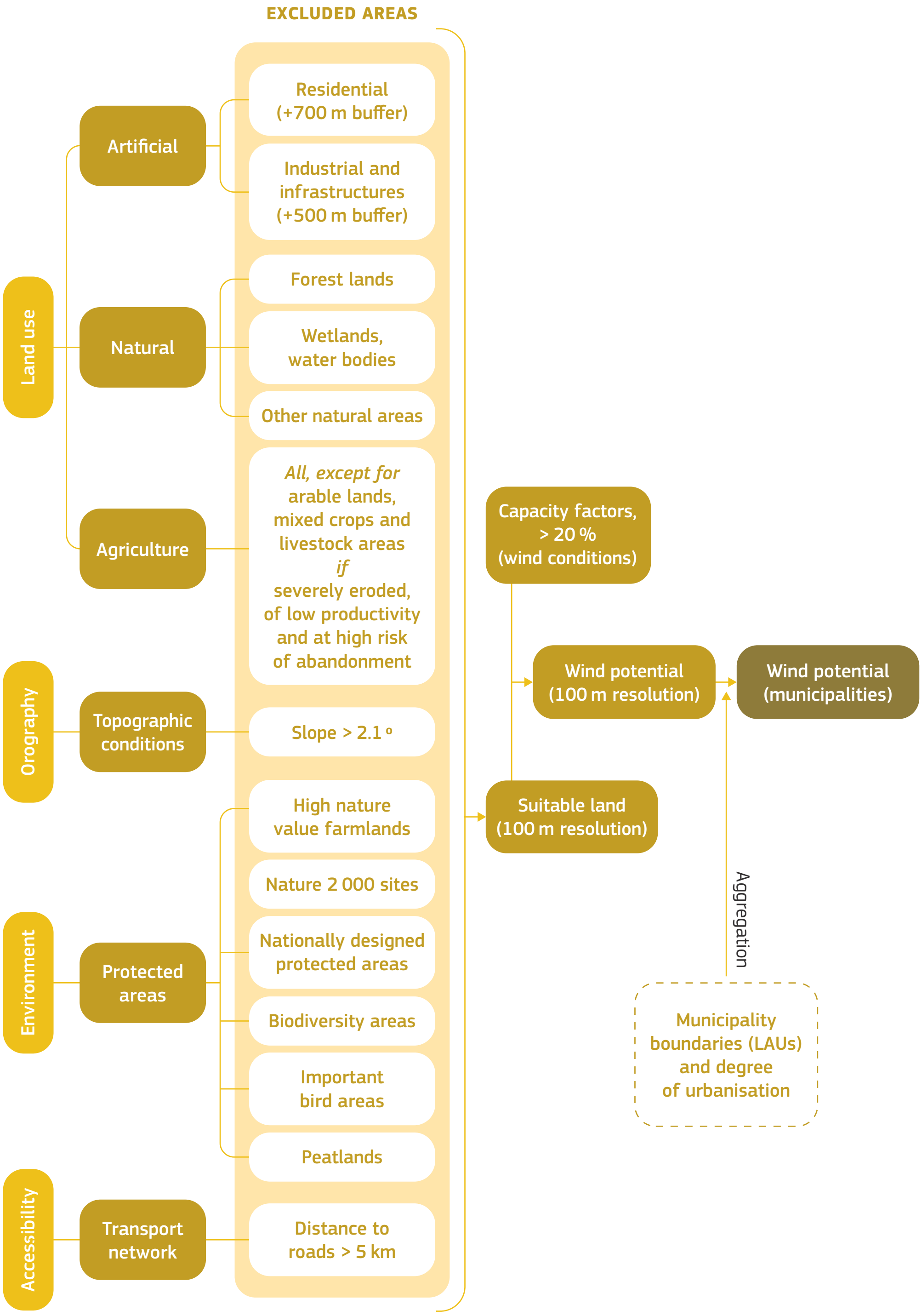
In order to determine suitable sites for new wind installations, a variety of factors are considered, as summarised in **Figure 24.** The land use, environmental and accessibility restrictions employed are the same as those considered when identifying sites for new ground-mounted PV installations (see **Table A2.1** in **Annex 2**): artificial areas are excluded, including buffer zones around residential areas (700 m) and industrial and infrastructure areas (500 m), and a minimum distance to roads of 5 km is required. Forests, water bodies and protected areas are also excluded, as well as agricultural areas, except for those arable lands, mixed crops and livestock areas that are at high risk of abandonment, severely eroded and of low productivity ((Perpiña Castillo et al., 2020; ESDAC, 2016). The remaining land use/cover classes, namely scrub and/or herbaceous vegetation associations (natural grasslands, moors and heathland, sclerophyllous vegetation and transitional woodland-shrub) are considered suitable land available for new installations where land use, environmental and accessibility criteria are met.

For the installation of new wind turbines, setback distances in residential areas are subject to country-specific regulations. In the EU, setback distances fall within the 120–2 000 m range, depending on the size of the turbine. For this work, we have chosen an EU-wide setback distance of 700 m from settlements, which ensures that noise levels fall below 40 dB in residential areas, even in the case of large turbines (Dalla Longa et al., 2018). Regarding orography restrictions, an upper limit on the slope of the terrain is set at 2.1 °. This threshold selects fairly flat land surfaces, excluding mountainous areas as potential sites for wind turbines. Finally, we also exclude those areas where capacity factors from

Figure 24. Methodology outline for the computation of onshore wind energy potential in the EU's municipalities.

Note: The description, main references, and maps of the restrictions and suitability factors can be found in Annexes 2 and 5.

Source: Authors' own elaboration.



the Global Wind Atlas (DTU, 2023) are lower than 20 %, identifying them as unsuitable because of unfavourable wind conditions. Further details regarding wind-specific restrictions can be found in **Annex 2** (see **Table A2.3**), while information on the datasets used is detailed in **Annex 5.**

Taking all land-use restrictions into consideration, a map of land availability is created for the EU at 100 m resolution. We find that the **maximum suitable land available for new onshore wind installations could amount to 2.8 % of the EU's surface,** or 110 000 km². Agricultural areas with a high risk of abandonment, severe erosion and low productivity make up 77 % of this suitable land available, which amounts to 5 % of the EU's agricultural land. The Member States with the largest available areas are Romania (21 000 km²), France (15 000 km²), Sweden (13 000 km²) and Spain (12 000 km²), which together account for 54 % of the EU's suitable land. On the other hand, the highest shares of suitable land are found in Latvia (12 % of the country's surface), Estonia (9.5 %), Romania (9.1 %) and Hungary (6.4 %), as can be seen in **Figure 25.** By degree of urbanisation, we find that **83 % of the EU's available suitable land is in rural areas,** while 16 % is in towns and suburbs and 2.5 % in cities.

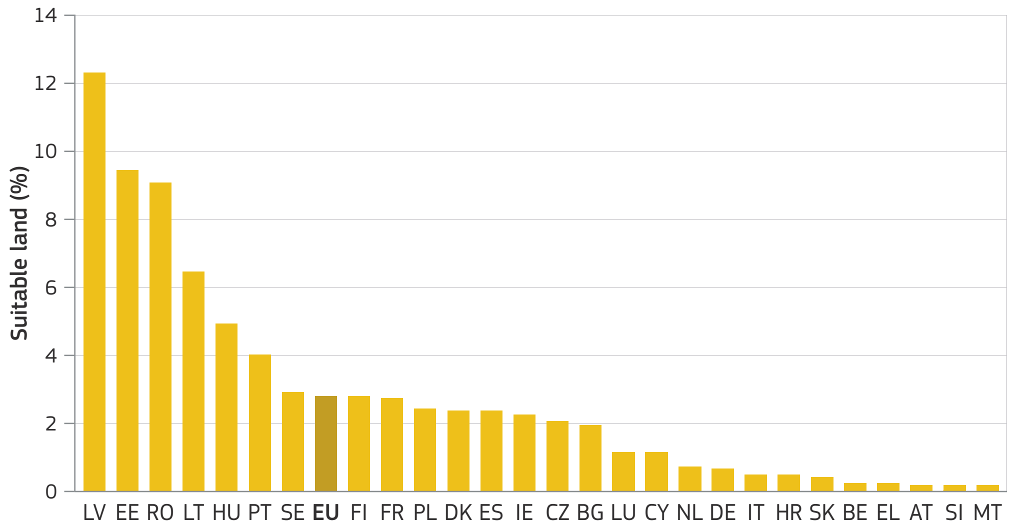


Figure 25. Share of suitable land for new onshore wind installations in EU Member States.

Source: Authors' own elaboration.

Having determined the suitable land available, we compute the potential onshore wind capacity that could be installed in it, assuming a power density of $\rho^w = 5\frac{\text{MW}}{\text{km}^2}$ (Dalla Longa et al., 2018). For each grid cell of 100 m selected as available for new installations, this yields a potential installed capacity of 50 kW. To compute the potential capacity at the pixel level, we employ capacity factors from the Global Wind Atlas (see **Annex 3** for details on capacity factors). These reflect wind conditions and allow us to derive the annual production at any location given the installed capacity. Moreover, we assume a 15 % power loss due to external factors (environmental fluctuations, turbine downtime and maintenance, electrical losses, etc.) (Dalla Longa et al., 2018). Then, for each grid cell of area a = 0.01 km², the annual potential production (denoted by Wind pot prod) is given by equation (3):

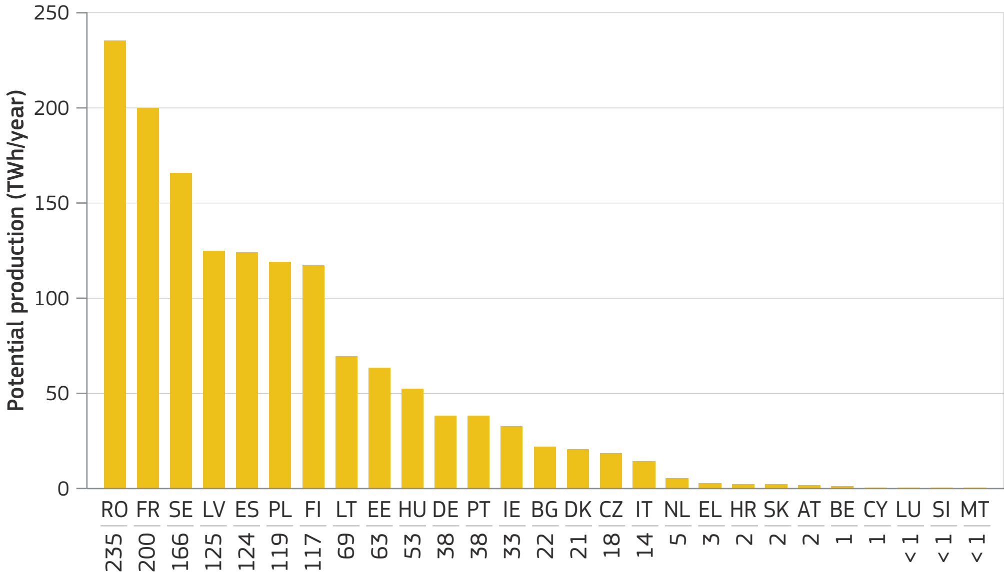
$$Wind\ pot\ prod\ [MWh] = \rho^w \left[\frac{MW}{km^2}\right] \cdot CF \cdot L \cdot a\ [km^2] \cdot 365 \cdot 24 \qquad \text{(Eq. 3)}$$

where L = 1 – 0.15 accounts for power losses.

Adding up the potential production from all the suitable available land, we estimate that **potential onshore wind installations in the EU could amount to 570 GW of installed capacity,** providing **annual electricity production of 1 500 TWh,** which constitutes **57 % of the EU's electricity consumption** in 2021. At the country level, the highest potential is found in Romania (240 TWh/year), France (200 TWh/year) and Sweden (170 TWh/year), followed by Latvia, Spain, Poland and Finland, each of which could potentially produce more than 100 TWh/year, as shown in **Figure 26.**

Figure 26. Estimated potential production of electricity with onshore wind in EU Member States.

Source: Authors' own elaboration.



At the municipality level, onshore wind potentials per unit area can be seen in **Figure 27.** In general, high potential for onshore wind is found in areas with ample suitable land and favourable wind conditions. As terrains with steep slopes are not suitable for wind installations, municipalities located in mountainous regions such as the Pyrenees, the Alps, the Apennines and the Carpathian Mountains show low potential. Areas surrounding mountainous regions typically present unfavourable wind conditions, as can be observed in the distribution of capacity factors shown in **Figure 28,** and therefore also show low potential for onshore wind. Wind conditions are most advantageous in the northern coastal regions of Europe, especially in Ireland, Denmark, the Netherlands and Germany.

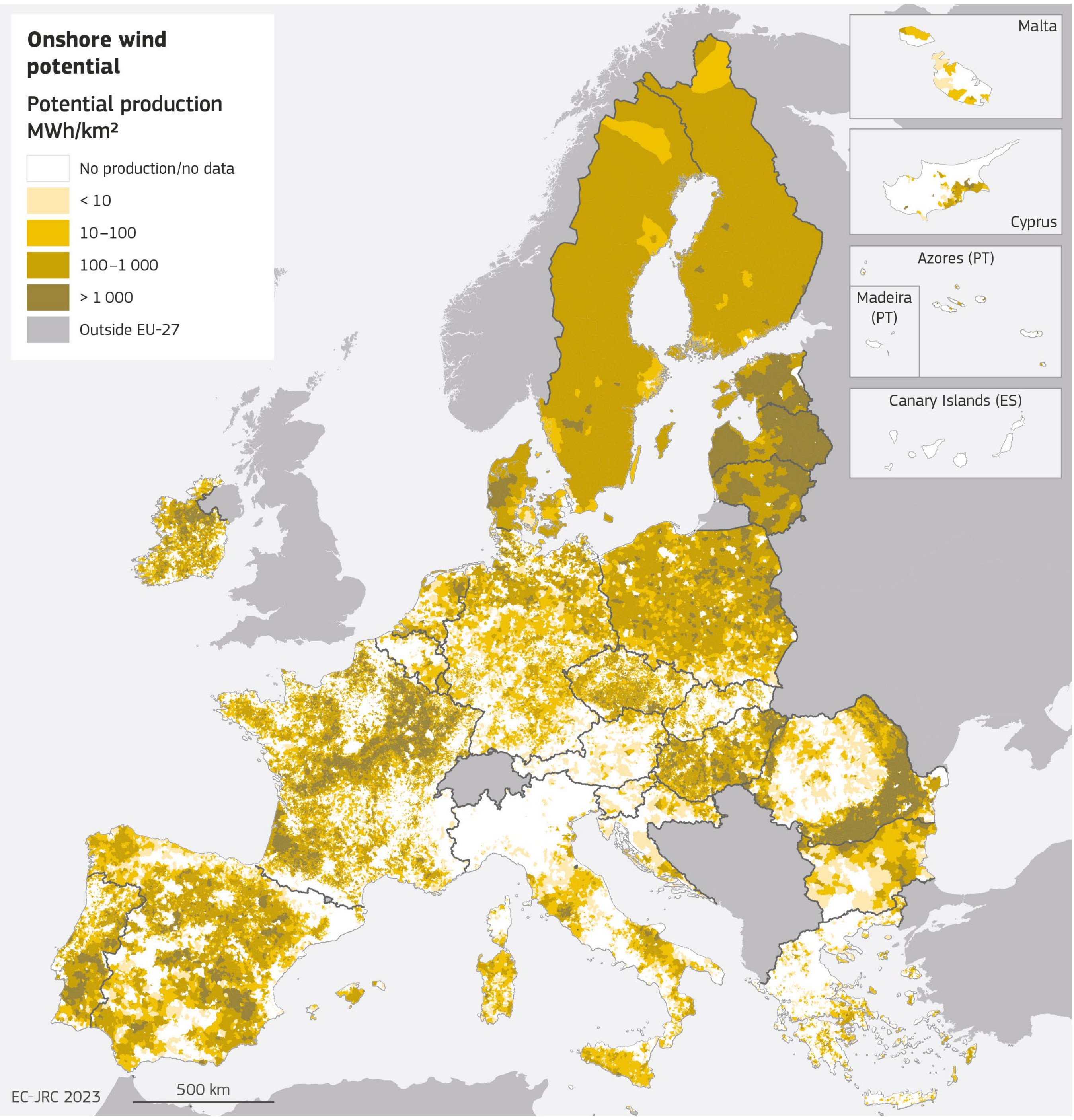


Figure 27. Estimated annual potential production of onshore wind electricity per unit area in the EU's municipalities.

Source: Authors' own elaboration.

By degree of urbanisation, we find that **rural municipalities account for 84 % of the EU's onshore wind potential,** followed by towns and suburbs (15 %) and cities (1.4 %). In all Member States except for Italy and Malta, rural areas are responsible for the highest share of potential onshore wind production in the country. In **Figure 29,** patterns of potential production by unit area and by degree of urbanisation are shown for the EU's municipalities. We find that rural areas show, on average, the highest potential production per unit area (300 MWh/km² per year), followed by towns and suburbs (96 MWh/km² per year) and cities (34 MWh/km² per year). As seen in **Figure 30,** rural areas show the highest average potential production per unit area in Latvia, Estonia

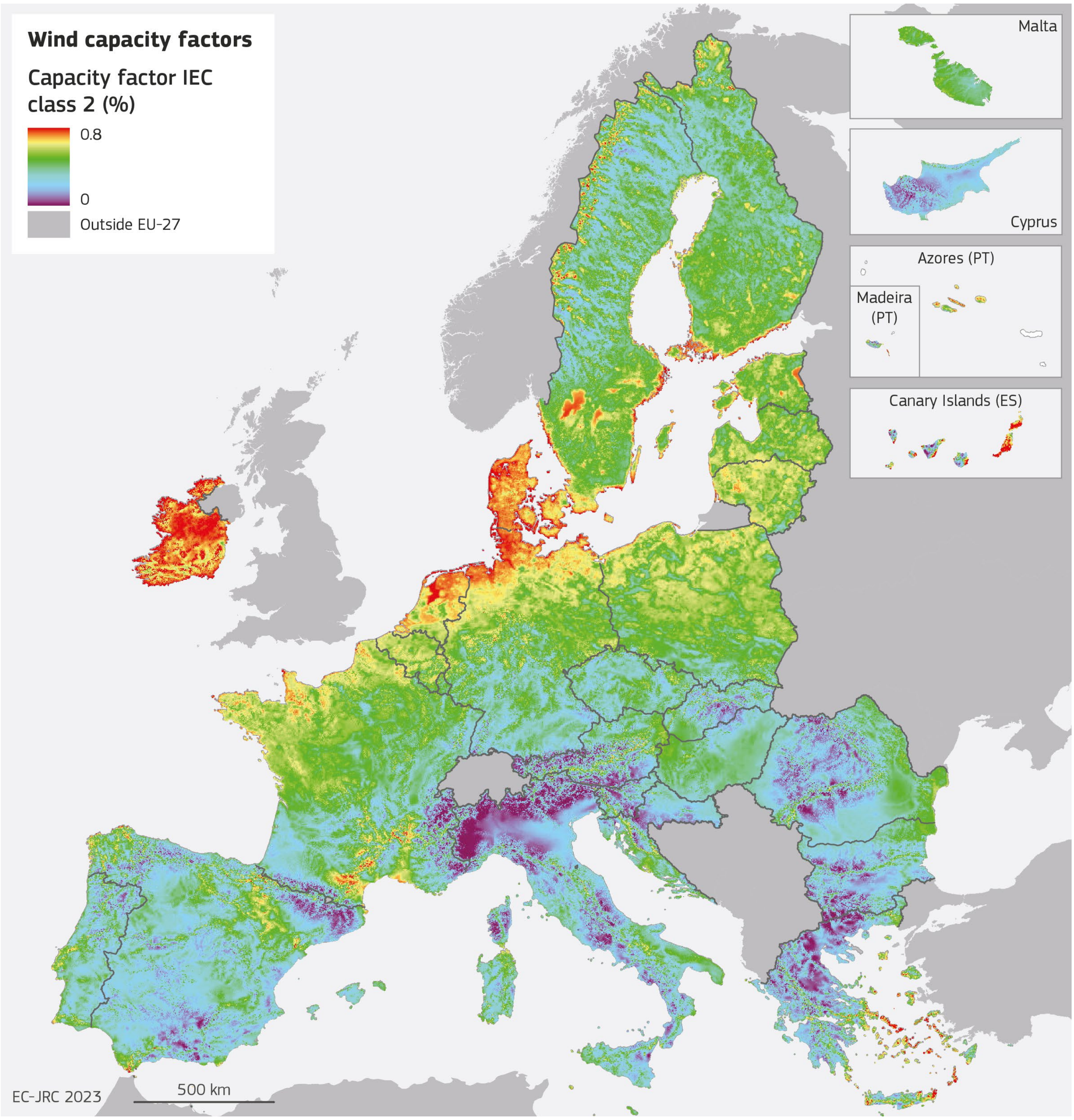
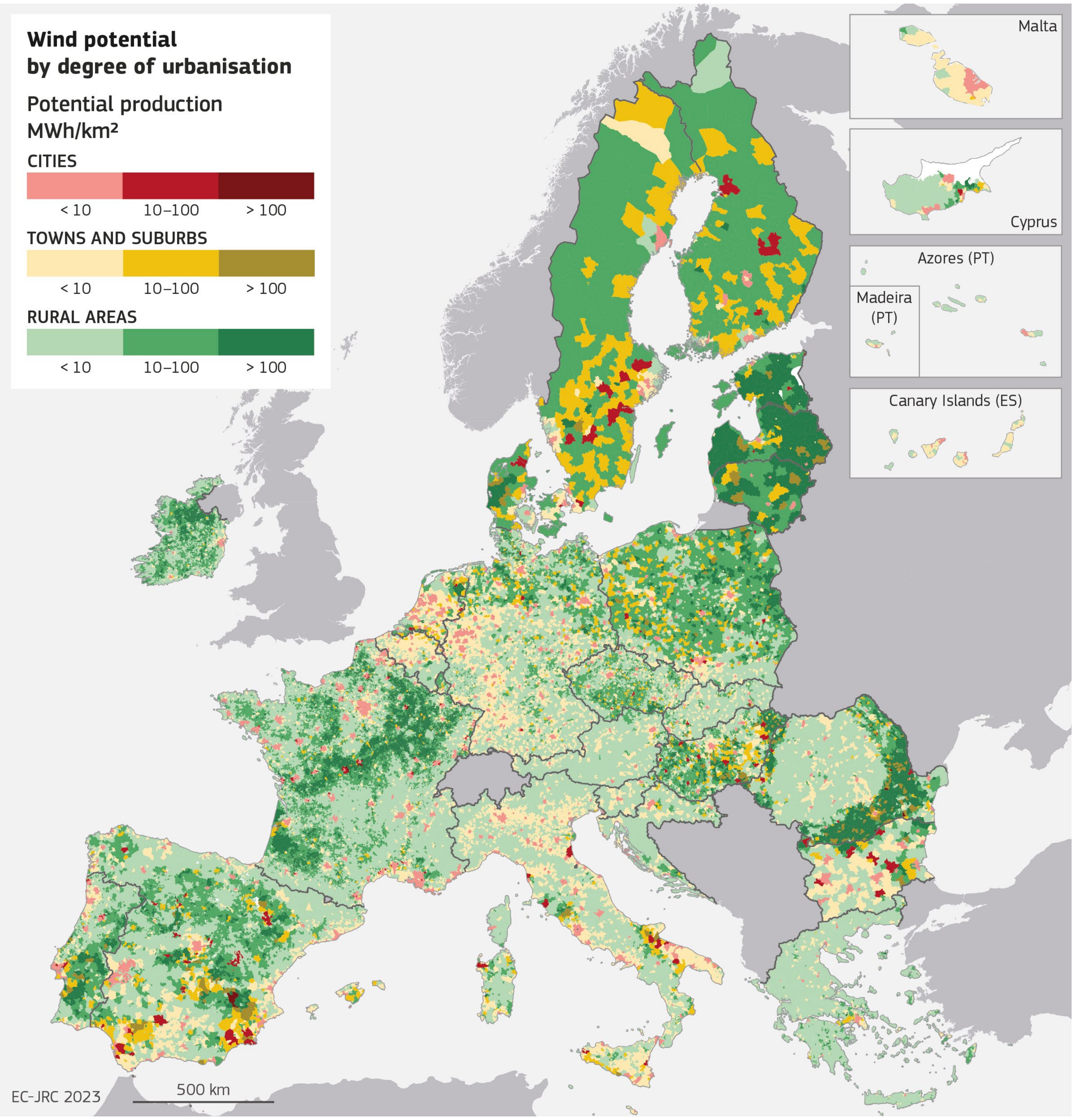


Figure 28. Wind capacity factors, International Electrotechnical Commission (IEC) class 2.

Source: Authors' own elaboration based on Global Wind Atlas (DTU, 2023).

and Lithuania, reaching more than 1 GWh/km² per year, followed by rural areas in Romania, Hungary and Denmark, which could produce more than 500 MWh/km² per year. Moreover, 96 % of the municipalities with a very high potential per square kilometre (more than 1 GWh/km² per year) are rural areas, while 3.7 % are towns and suburbs and fewer than 0.4 % are cities. These high-potential areas, which constitute 7.5 % of the EU's municipalities, are especially important in Latvia, Estonia and Lithuania, where more than 40 % of the countries' municipalities show a very high potential per unit area.



Other key regions for potential onshore wind are found in Romania, especially in municipalities close to the southern and eastern borders with Bulgaria and Moldova. Areas around the Hungary–Romania border are also among those with the highest potential, at both sides of the border. In both countries, more than 15 % of the municipalities could potentially produce above 1 GWh/km² per year. This percentage is above 10 % in France, with many high-potential municipalities located in central regions, and in Ireland, where high-potential areas are found mostly in the north of the country. In Poland, Denmark, Czechia, Portugal and Spain the percentage of municipalities with very high potential production per unit area is above 5 %, following more scattered patterns.

Figure 29. Estimated onshore wind potential production per km² in the EU's municipalities by degree of urbanisation.

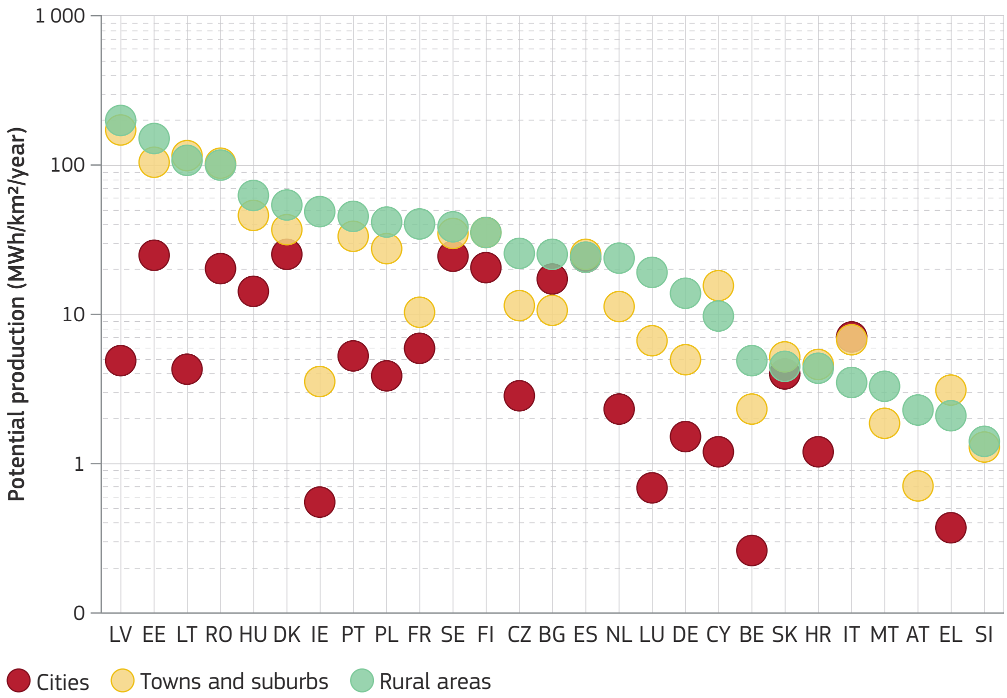
Source: Authors' own elaboration.

Figure 30. Estimate annual onshore wind potential production by degree of urbanisation by EU Member State.

Note 1: Yearly production in MWh is shown per unit area.

Note 2: Graphical visualisation in logarithmic scale.

Source: Author's own elaboration.



3.4 UNTAPPED POTENTIAL OF ONSHORE WIND ENERGY

To determine ways forward for the development of onshore wind energy in the EU's municipalities, in this section we evaluate the difference between their current and potential electricity production with this technology. For each municipality, we define its untapped potential as the difference between its potential and current production of electricity. According to our analysis, **the untapped potential for onshore wind in the EU reaches 1 400 TWh/year, for which 530 GW of additional installed capacity is needed**. Combining current production with untapped potential we find that, in the EU, electricity production with onshore wind could reach 1 700 TWh/year (from 710 GW of total installed capacity), which is equivalent to 67 % of the electricity consumed in the EU in 2021. As shown in **Figure 31,** the Member States with the highest untapped potential are Romania (233 TWh/year) and France (188 TWh/year), followed by Sweden, Latvia, Poland, Spain and Finland, all showing untapped potential in the 100–150 TWh/year range.

The evaluation of the untapped potential is carried out at the municipality level, subtracting the estimated current production from their technical potential. In some cases, current production exceeds our assessment of potential production. For these municipalities, we assume that wind resources are close to being exhausted and therefore have no untapped potential. This is the case for almost 5 400 municipalities, located predominantly in Germany (46 %), France (18 %), Spain (9 %) and Italy (5 %). These correspond to the dark red areas in **Figure 32,** where patterns of potential and current production across the EU's municipalities

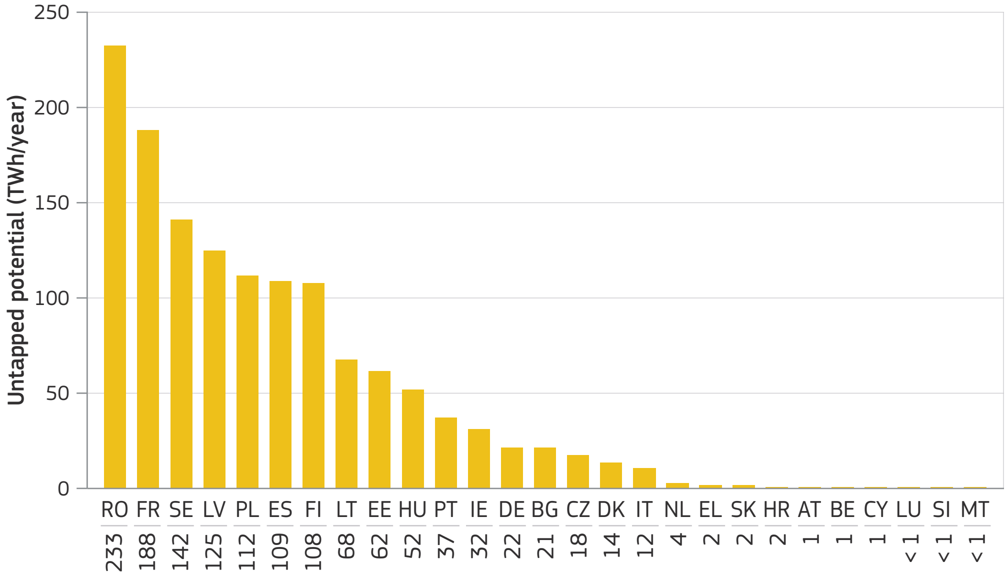


Figure 31. Untapped onshore wind potential production of electricity (difference between current and potential production) for the EU Member States.

Source: Authors' own elaboration.

are depicted. The fact that the potential in some municipalities is lower than their estimated current production is due to our methodology for assessing the sustainable development of onshore wind energy: The evaluation of potential production includes major constraints on land availability, such as the exclusion of a wide variety of protected areas and significant limitations on the usage of agricultural land (see **Section 3.3** for details), which might not have been considered when selecting wind farm sites in the past.

At the country level, the technical potential of onshore wind is lower than our estimate for current production in the cases of Germany, Greece, the Netherlands, Austria and Belgium. In general, these countries have undergone an intensive development of onshore wind installations. A prominent case is Germany, where production of onshore wind has been growing steadily since the mid 1990s. Our estimates for this country yield a production of 93 TWh/year in 2023, while potential production is assessed to be 38 TWh/year. This illustrates how the estimates from our high spatial resolution assessment of wind potentials are sensitive to the methodology used and its restrictions on land use, which can be considered conservative. The untapped potential of Member States, shown in in **Figure 31,** is computed by adding up the untapped potential of their municipalities, with contributions coming only from municipalities with higher technical potential than estimated current production.

By degree of urbanisation, we find that 84 % of the EU's untapped potential for onshore wind is found in rural areas, followed by towns and suburbs (15 %) and cities (1.4 %). Incidentally, the distribution of the untapped potential by degree of urbanisation is identical to that of the technical potential (see **Section 3.3**). Areas with high potential and low production can be identified as those that could benefit most from new onshore wind installations. They correspond to light green areas in **Figure 32,** and amount to 26 % of the EU's municipalities. High-potential, low-production areas constitute a large share of the country's municipalities in Latvia (91 % of its municipalities), Lithuania (83 %), Estonia (76 %) and Finland (75 %), covering large areas of the countries, and are also more than half of

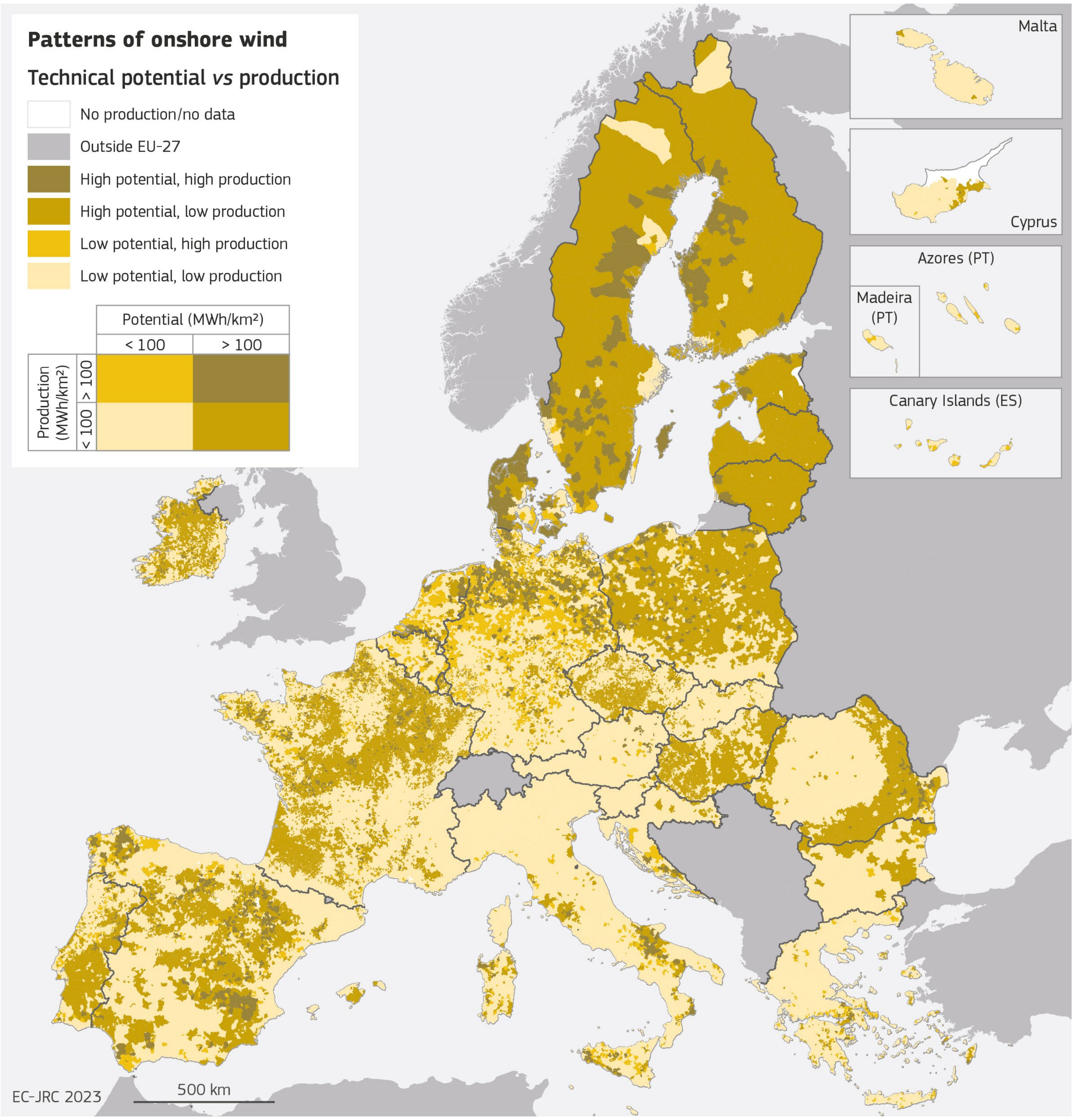


Figure 32. Patterns of current and potential annual production of onshore wind energy in the EU's municipalities.

Note: A threshold of 100 MWh/km² has been used to identify areas of high/low potential and production of electricity with onshore wind.

Source: Authors' own elaboration.

the municipalities of Sweden, Hungary and Poland. In France and Spain, where untapped potential is also high at the national level, high-potential, low-production areas amount to around 30 % of the municipalities, following scattered patterns. In Romania, the Member State with the highest untapped potential for onshore wind, the distribution of municipalities with high untapped potential follows a distinct pattern, with high-potential areas located close to the country's borders.

3.5 CONCLUSIONS

Onshore wind in the EU has seen a steady and significant increase since the 2000s, reaching 180 GW of installed capacity in 2023, according to our estimates. It constitutes one of the main sources of renewable energy, **currently producing 350 TWh per year,** the equivalent of 13 % of the electricity consumed by the EU in 2021. At present, the Member States currently delivering the highest production are Germany (93 TWh/year), Spain (60 TWh/year) and France (39 TWh/year), which together account for more than 55 % of the EU's onshore wind production. In the near future, major new deployments of onshore wind installations will be necessary to reach the 2030 target of 510 GW set by the REPowerEU plan.

In our assessment of the onshore wind potential of the EU's municipalities, a wide variety of factors regarding land use, environment, agriculture, orography, accessibility and wind conditions have been considered (see **Figure 24** and **Annex 2**), with the aim of ensuring that **sustainability and conservation of local resources are central priorities in the roll-out of new installations.** Most prominently, protected areas have been thoroughly excluded, and arable land has been deemed suitable for new wind installations only if it is already at high risk of abandonment, has low productivity and is severely eroded. Furthermore, buffers around infrastructure and settlements (of any size) have been enforced. Under these considerations, **we estimate that 2.8 % of the EU's area could be used for new onshore wind installations.** Altogether, we find that **EU municipalities hold an untapped potential** of 530 GW of installed capacity, **which could potentially produce 1 400 TWh/year.** Therefore, we conclude that the 2030 target for wind energy in the EU (510 GW) can be reached while ensuring sustainable land-use practices in the roll-out of new installations. Combining the untapped potential with current production, the EU could reach electricity production of 1 700 TWh/year with 710 GW of installed capacity of onshore wind, accounting for 67 % of its electricity consumption. The main results for onshore wind are summarised in **Table 2.**

EU-27 ONSHORE WIND

Current status	Untapped potential
180 GW current onshore wind capacity	530 GW potential onshore wind capacity
13 % onshore wind in EU-27 electricity consumption	53 % onshore wind in EU-27 electricity consumption

Table 2. Current status and untapped potential of onshore wind in the EU-27.

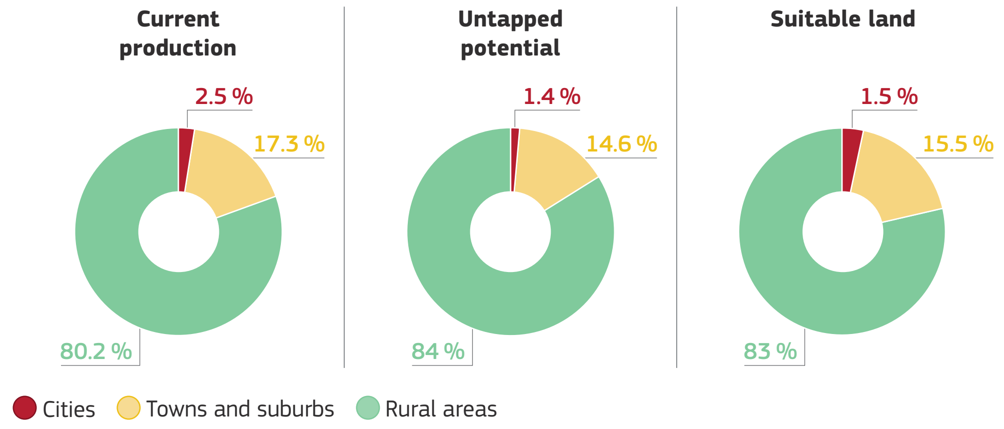
Source: Authors' own elaboration.

Municipalities with low current production and high potential are especially suited to accommodate new installations. These constitute a large share of the country's municipalities in Latvia (91 % of its municipalities) Lithuania (83 %), Estonia (76 %) and Finland (75 %), covering large areas of the countries, and are also more than half of the municipalities of Sweden, Hungary and Poland (see **Figure 32**). Per Member State, the highest untapped potential is found in Romania (233 TWh/year) and France (188 TWh/year), followed by Sweden, Latvia, Poland, Spain and Finland, all showing untapped potential in the 100–150 TWh/year range.

When studying the EU's municipalities by degree of urbanisation, we find that rural areas play a key role in the production of renewable energy through onshore wind, both today and in the future: **rural municipalities currently produce 80 % of the EU's onshore wind energy and hold 84 % of the untapped potential** for this technology. Moreover, 83 % of the suitable land available for new installations is in rural areas (**Figure 33**).

Figure 33. Onshore wind current production of electricity, untapped potential, and suitable area available for new installations in the EU's municipalities by degree of urbanisation.

Source: Authors' own elaboration.



4 Hydropower

4.1 HYDROPOWER IN THE EUROPEAN UNION: STATUS AND OUTLOOK

Hydropower is the oldest renewable energy technology, the use of which dates back thousands of years. It is still the largest source of low-carbon electricity worldwide, accounting for about 1 397 GW of global installed capacity in 2022 and annual energy generation of about 4 410 TWh (IHA, 2022), which has been steadily increasing over the last few decades. The **installed hydropower capacity in the EU is approximately 150 GW.** In the last decade, the **EU's annual energy generation from hydropower** has been oscillating between 322 and 398 TWh/year, depending on the hydrological and climate conditions, with an average of **363 TWh/year,** corresponding to **14.6 % of the EU's total electricity consumption** and about one-third (33 %) of the EU's annual renewable electricity generation (Quaranta et al., 2022b).

The International Energy Agency (IEA) has forecast that at least 850 GW of installed hydropower capacity are needed globally to meet the ambitious climate goals of net zero emissions by 2050 (IEA, 2021). According to the latest World Energy Transitions Outlook from the International Renewable Energy Agency (IRENA), hydropower will play a key role in keeping the rise of global temperatures below 1.5 °C (the so-called net zero target), providing **low-carbon energy, but also crucial capabilities such as energy storage and system flexibility** required to further integrate volatile RESs (IRENA, 2023). While various global energy outlooks envisage considerable potential for hydropower expansion in many areas of the world, such as emerging and developing countries (IEA, 2021; IRENA, 2022; IHA, 2023), in the European Union hydropower technology has reached a high level of maturity and the potential for large power plants has been largely exhausted. Nonetheless, it is estimated that significant potential for green and sustainable hydropower remains, mainly from powering existing facilities and from the modernisation and refurbishment of the EU fleet (Quaranta et al., 2021a, 2022a).

Even though hydropower is a renewable energy technology associated with several side benefits (e.g. multiple uses of reservoirs, such as water management and flood control; flexibility of hydropower operations; great export capacity of hydropower companies), new hydropower barriers in freshwater systems can generate adverse impacts on the ecosystems. Therefore, EU nature legislation (mainly the water framework directive and the birds and habitats directives) and environmental policy documents recommend first upgrading existing hydropower plants (brownfield developments) and exploiting untapped potential by integrating hydropower in existing hydraulic structures (power utilities, non-powered dams, weirs, etc.) before proceeding with new hydropower projects (EC, 2018).

Key priorities and challenges for the future of hydropower in the EU are outlined in the EU Clean Energy Transition Partnership and primarily address increases in flexibility and storage capabilities, digitalisation and lifetime of the current fleet, climate risks, sustainable standards, and hydropower market and services to address the changing role of hydropower (CETP, 2020; Quaranta et al., 2023).

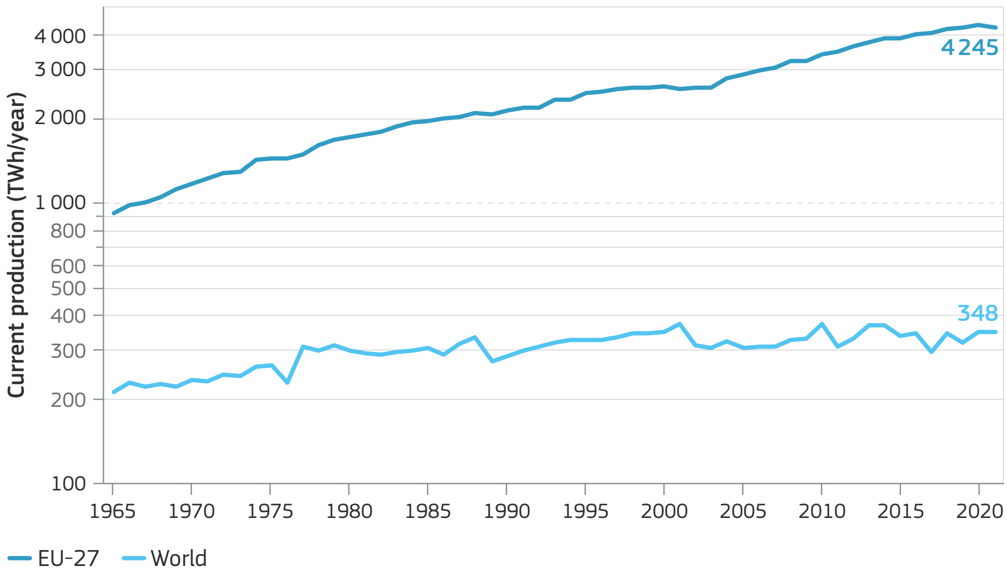


Figure 34. Trends in renewable hydropower production (excluding energy generated from pumping) in the world and EU-27 (TWh/year).

Note: Graphical visualisation using logarithmic scale.

Source: Authors' own elaboration based on Eurostat (2021f).

4.2 CURRENT EUROPEAN UNION PRODUCTION OF HYDROPOWER

Hydropower is already highly developed in the EU, leaving limited scope for greenfield projects (i.e. building on new sites); either morphologically suitable locations are already exploited or new large plants are not environmentally viable in most EU Member States. The spatial distribution of the current installed hydropower capacity differs greatly across the EU and is mostly located in the Alpine and other mountainous and hilly regions that ensure favourable topography, but with significant variations depending on the hydrological and morphological conditions, and the country-specific energy traditions, market structure and level of development.

While national figures on hydropower in the EU are well known, in the context of this analysis an **estimation and characterisation of the current EU capacity and energy generation at a detailed geographical level** (municipality) has been carried out, as it allows us to recognise the contributions of different regions to overall renewable energy production. Moreover, it is a prerequisite for computing the potential efficiency gains achievable from different modernisation strategies.

BOX 4. Hydropower – water for energy, storage and flexibility

Hydropower is a method of generating electricity that uses water (potential and kinetic energy) to produce electricity. It is one of the oldest sources of renewable energy, having already been used in pre-industrial times, for instance in watermills. Nowadays hydropower plants are generally classified into three types: pure or conventional hydropower, which includes the **reservoir** type and the **run-of-river** type; and **pumped-storage** hydropower, including closed-loop and open-loop systems. Pumped storage is becoming more and more important, as it can play a critical role as a **source of flexible and reliable power storage** in future power systems, **enabling higher penetration of variable renewable energy sources,** such as wind and solar. The principle of pumped-storage hydropower plants is based on pumping water from a lower to an upper reservoir at times of low demand (and low prices) and when there is a surplus of electricity delivered to the grid from other RESs, and releasing water at times of high demand (and high prices) to generate electricity. In terms of installed power capacity, the EU hydropower fleet is composed of 47 % plants of the reservoir type, 22 % of the run-of-river type and 31 % of the pumped-storage type.

For the purposes of this assessment, the Joint Research Centre (JRC) hydropower database (JRC, 2019) was used as the main source of information for characterising the EU hydropower fleet. To address known gaps and flaws, this dataset has been combined with the updated JRC Open Power Plants Database (Hidalgo Gonzalez et al., 2019) and the Global Hydropower Database (Wan, 2019), reaching a total of 3 335 geo-localised plants in the EU (see **Figure 35**). The consolidated database shows a cumulative installed capacity of nearly 103 GW for pure hydropower, in comparison with the 105 GW declared in Eurostat, and a total installed capacity for pumped-storage hydropower of 46 GW, consistent with the figure reported in Eurostat for 2021. Overall, the EU's total installed capacity in the harmonised database accounts for 98 % of the capacity reported by Eurostat for 2021 (Eurostat, 2021g). It must also be noted that around **25 000 hydropower plants are in operation in the EU-27,** but most of them are very small hydropower plants and some of them are power plants in existing infrastructures (e.g. in closed pipes), which are difficult to track and are not included in the database. However, the plants not included provide a negligible contribution to the EU-27's hydropower generation.

Some incompleteness in the input database had to be addressed. Missing information concerning the energy generation of specific power plants was estimated using the average capacity factor (CF) of power plants belonging to the same river for the run-of-river plant type (see definition in **Box 4**). When this strategy was not applicable, the average CF of the Member State for that plant type was used. The national average CF, for each plant type *t* and country *c,* is defined in equation (4):

$$CF_{tc} = E_{tc} \,/\, (P_{tc} \cdot h) \qquad \text{(Eq. 4)}$$

where E_{tc} is the annual energy generation (MWh), P_{tc} is the installed power capacity per type and country (MW) and h is the number of operating hours in 1 year (8 760).

The total **estimated hydropower annual energy generation** for the entire EU database is **376 TWh,** in line with the 375 TWh reported by Eurostat in 2021 (including generation from pumped hydropower plants). The breakdown of national figures for both estimated capacity and production also shows a high level of agreement with data reported by Eurostat and IRENA (Eurostat, 2021b, 2021f; IRENA 2022) (see **Table A4.2** in **Annex 4**).

Our assessment reveals how hydropower productivity varies across EU Member States and territories. The forerunners of hydropower energy are notably countries with higher availability of mountainous regions and water resources such as Sweden, France, Italy, Austria, Spain, and Germany, which together account for 76 % of the total hydropower production in EU. On the other hand, when looking at production by degree of urbanisation, it is clearly **in rural areas** that the most suitable conditions and availability of resources (water, morphology and land) are found. As seen in **Figure 35,** rural areas account for 80 % of the installed capacity and **75 % of the total production (about 280 TWh/year),** while towns and suburbs host 15 %, and cities 4.7 %, of the total capacity and produce 18.3 % and 6.6 %, respectively, of the total energy generation. In all Member States except for Latvia and Bulgaria, rural areas provide the highest share of hydropower energy production, as shown in **Figure 36.**

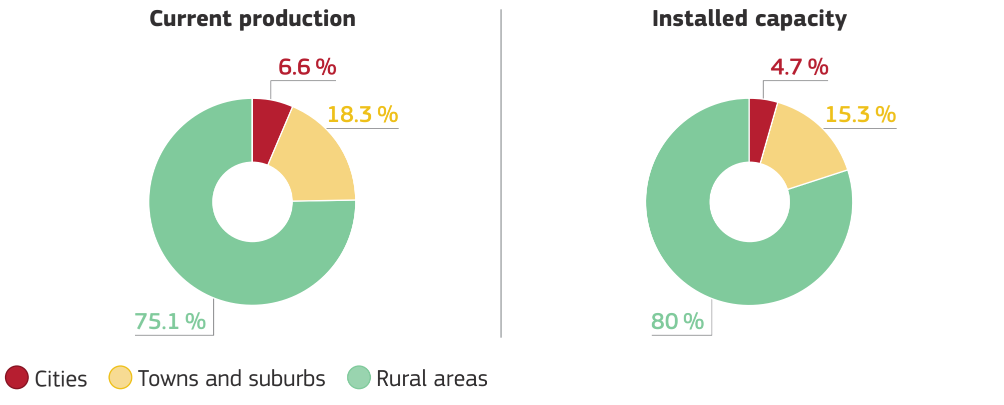


Figure 35. Shares of estimated hydropower production and installed capacity in the EU-27 by degree of urbanisation.

Source: Authors' own elaboration based on JRC (2019); Hidalgo Gonzalez et al. (2019); Wan (2019).

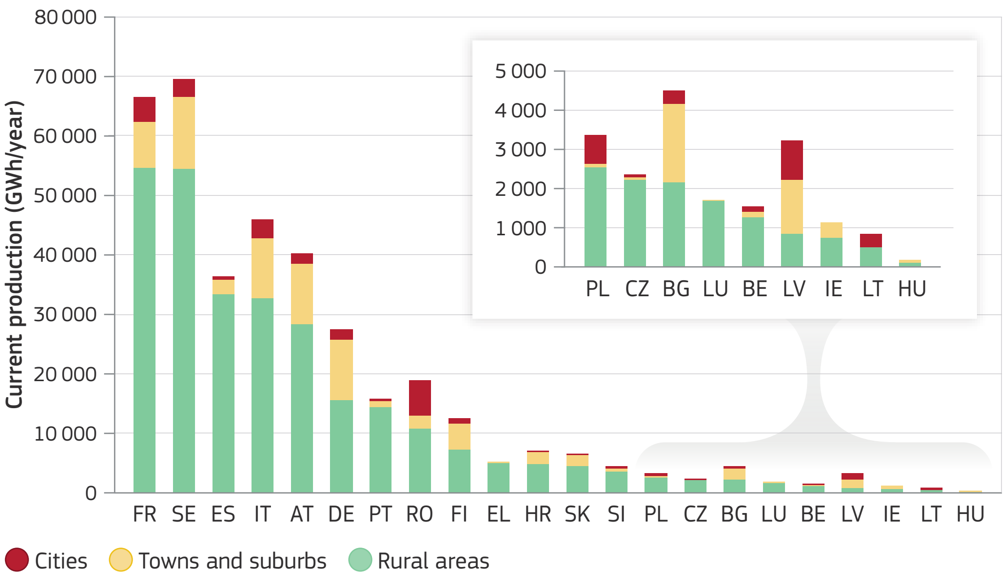


Figure 36. Estimated current hydropower energy production by degree of urbanisation in EU Member States (GWh/year).

Note: Only coutries with reported hydropower production are displayed.

Source: Authors' own elaboration based on JRC (2019); Hidalgo Gonzalez et al. (2019); Wan (2019).

4.3 HYDROPOWER SUSTAINABLE UNTAPPED POTENTIAL

As new hydropower plant projects in the EU are complex and highly controversial because of environmental constraints, our estimate of hidden hydropower potential excludes new developments. Several assessments and scientific studies have been carried out to assess the residual sustainable opportunities for hydropower and related trends in the EU (Quaranta et al., 2022a, 2023). Here, we investigate three **sustainable strategies to increase hydropower potential in the EU.** They do not entail additional impacts on the environment, they leverage existing structures and can provide multiple benefits beside energy generation, particularly in rural areas.

The following strategies are investigated:

— **modernisation** of the existing European hydropower fleet,

— coupling of **FPV** with hydropower reservoirs,

— **small hydropower (SHP) technology integration** in existing hydraulic structures such as **water utilities** (wastewater treatment plants and water distribution networks), and the restoration of **historical watermills.**

The modernisation strategy aims to expand energy generation by better exploiting (or restoring to its original value) the available power capacity of a hydropower plant (i.e. without increasing the current capacity, except for recovering wasted energy). Existing hydropower plants could also be refurbished by increasing the installed power capacity, but these options were not considered in this study, as they generally imply an increase in water withdrawal or head increase (e.g. dam heightening), which may generate adverse impacts on the ecosystem. However, it must be noted that in northern and Alpine regions, where more water availability is expected in the future as a result of climate change, an increase in water withdrawal will not represent a problem, but rather be a key strategy for increasing hydropower generation (Terrier et al., 2011). By contrast, all the remaining strategies involve new installations (turbines or PV) and thus an increase in the installed power capacity. Because of their hybrid nature, here we include FPV systems as part of Europe's hydropower potential, as they can be interpreted as form of hydropower plant revamping, with FPV being excluded from the solar PV potential described in **Chapter 2.**

Other approaches exist that can contribute to further exploiting hydropower in the EU and are particularly relevant to rural areas. These are, however, beyond the scope of this work, mainly for lack of sufficient reliable data to carry out a pan-European assessment. More specifically they include the powering of existing non-powered dams (Patsialis et al., 2016), the powering of pressurised irrigation networks (Pérez-Sánchez, 2016; García Morillo et al., 2018; Mitrovic et al., 2021) and the conversion of conventional hydropower schemes or twin reservoirs into pumped hydropower schemes (Fitzgerald et al., 2012; Gimeno-Gutiérrez et al., 2015).

The following sections briefly describe the rationale, the methodology and the main outputs of each strategy, while spatial patterns of the technical untapped potential of hydropower are presented below and further discussed in **Section 4.3.4.** Overall, we estimate a cumulative untapped potential production of 133 TWh/year in the EU-27, including contributions from FPV in hydropower reservoirs. By degree of urbanisation (see definition in **Box 2**), we found that about 50 % of the EU's total untapped potential production for hydropower is located in rural areas, followed by towns and suburbs (45 %) and cities (5 %), while, if we look at the potential from modernisation of the existing plants and from new installations separately, we find that rural areas account for 75 % and 37 %, respectively.

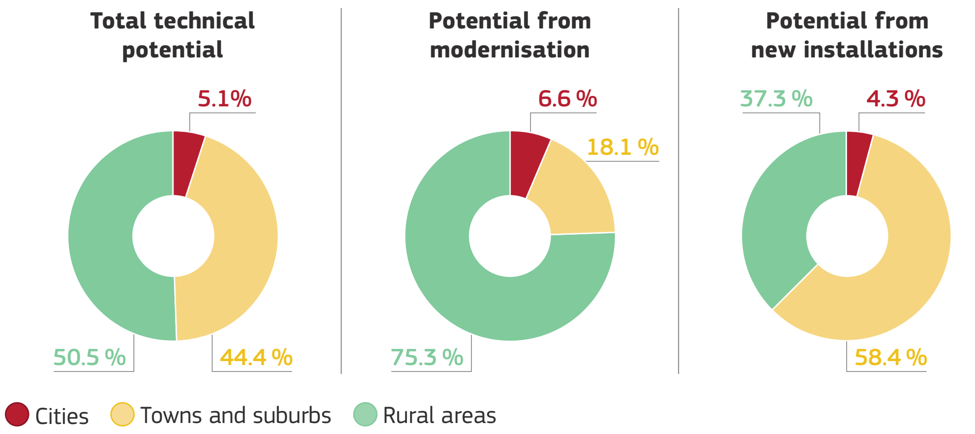


Figure 37. Shares of untapped hydropower potential by degree of urbanisation. New installations include reservoir FPV, water utilities and repowering of historic water wheels.

Source: Authors' own elaboration.

4.3.1 MODERNISATION OF THE EXISTING HYDROPOWER FLEET

Hydropower plants typically have an operating life of more than a hundred years if maintained regularly. However, most of the EU hydropower fleet was commissioned in 1970–1980, and it currently has an average age of 42 years, taking into consideration estimates of 18–20 % plants having already undergone some kind of modernisation (Quaranta et al., 2021a). Benefits of modernisation interventions include **improved efficiency, flexibility, increased safety, resilience and reduced environmental impacts when environmental measures are implemented.**

The IEA's first Hydropower Special Market Report, published in 2021, forecasts 8 % growth in total installed capacity in Europe by 2030 from new hydropower projects and from the modernisation of existing structures (IEA, 2021). Similarly, the International Hydropower Association's *2022 Hydropower Status Report* calls for modernisation and refurbishment, as one of the core strategies to meet the hydropower capacity and production increase that is required to achieve climate targets, particularly in regions where the scope for new projects is limited as in the EU (IHA, 2022).

Given the territorial distribution of the current fleet (discussed in **Section 4.2**), the modernisation strategy is highly relevant to rural and remote areas and is expected to provide additional benefits that can affect local communities positively, such as optimisation of water use for multiple purposes (Branche, 2017), mitigation of environmental impacts, and increased resilience to climate change and energy market disruptions (Quaranta et al., 2021a).

This assessment follows the approach adopted in previous studies to estimate the hydropower modernisation potential at the European level (Quaranta et al., 2021, 2023) introducing significant improvements related to the completeness and quality of the input data and to the accuracy of the gap-filling approach for key variables, allowing for a more detailed appraisal of current and potential hydropower production. Starting from the consolidated JRC hydropower database presented in the previous section, the following modernisation strategies were considered (see **Table A4.1** in **Annex 4** for the detailed methodology):

- **digitalisation of operations,** accounting for efficiency gains of 1% for all power plants, with an additional 2% in reservoir-type power plants,
- **recovery of wasted energy,** which can be exploited with an efficiency of 30–50% depending on the assumed turbine and configuration type,
- **replacement of electro-mechanical equipment,** for an increased weighted efficiency of between 4% and 6%, depending on the configuration and turbine type,
- **retrofitting of waterways and penstocks,** with 5% additional energy generation in reservoir-type hydropower plants.

The spatial distribution of the potential efficiency gains from plant modernisation inherently follows the current plant distribution, showing higher rates in rural areas, where 75% of the modernisation potential is found, followed by towns and suburbs (18%) and cities (7%). Of all the EU's municipalities with installed hydropower, 1634 (or 62 %) rural municipalities show potential for modernisation. At the country level, the Member States with the highest potential in rural areas are Sweden, France and Spain, followed by Italy, Austria, and Germany (see **Table A4.3** in **Annex 4**). Country-level results and their spatial distribution are depicted in **Figure 38** (and **Table A4.2** in **Annex 4**) and **Figure 39,** which shows the current estimated energy generation from the combined hydropower database with potential energy gains. **The maximum achievable production increase is about 12% at the EU scale,** corresponding to nearly **47 TWh of additional annual energy generation.**

The reported figures provide an estimate of the maximum potential that could be reached by implementing all the most suitable and up-to-date modernisation strategies. Nonetheless, it must be noted that specific local constraints and site-specific CFs may affect the actual achievable efficiency gains at any plant location. Furthermore, this analysis considers the current market and hydrological conditions, which may vary significantly in the coming decades (especially for pumped hydropower operations).

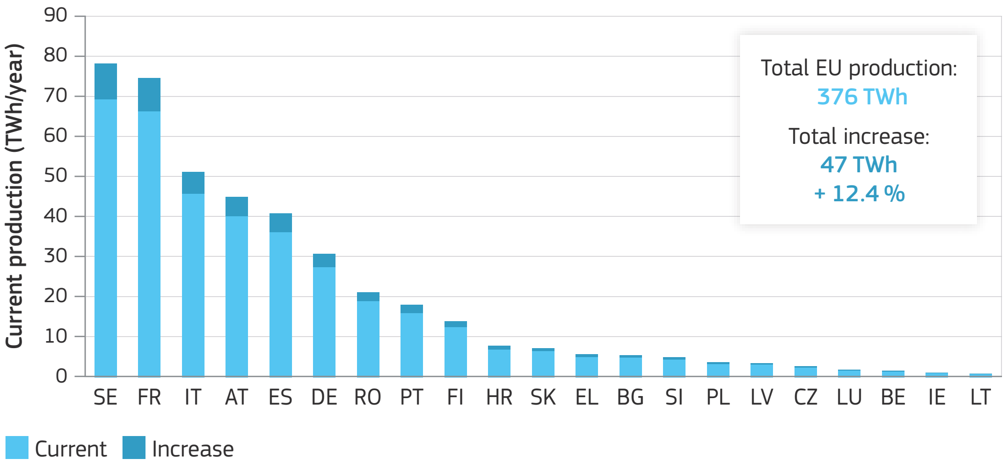


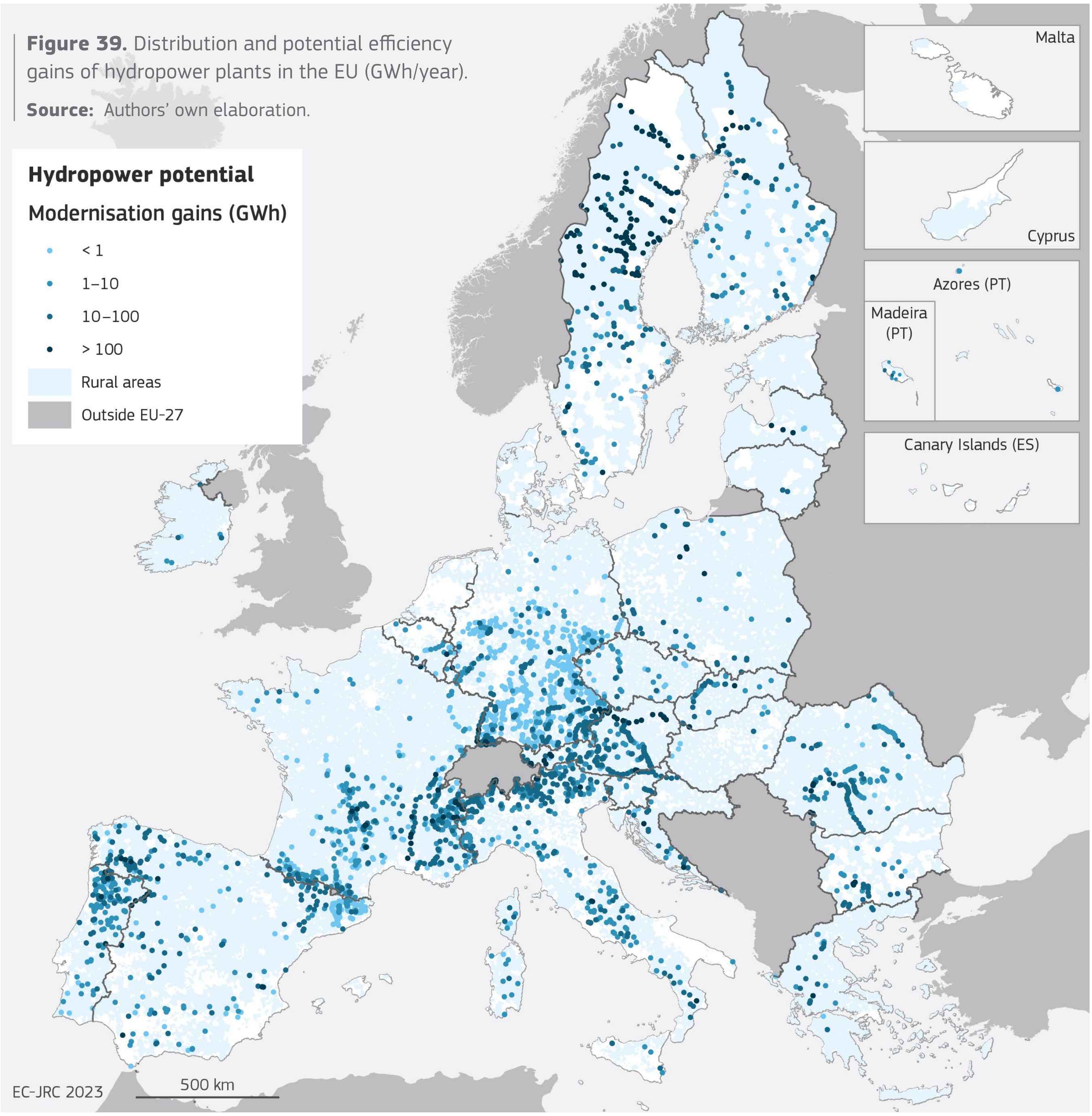
Figure 38. Current estimated annual energy generation (including pumping) and potential increase (TWh/year).

Note: Only coutries with reported hydropower production are displayed.

Source: Authors' own elaboration.

Figure 39. Distribution and potential efficiency gains of hydropower plants in the EU (GWh/year).

Source: Authors' own elaboration.



4.3.2 COUPLING FLOATING PHOTOVOLTAIC SYSTEMS WITH HYDROPOWER RESERVOIRS

FPV systems are a rapidly emerging technology and market in the field of PV applications, in which the PV panels are sited directly on the surface of suitable water (Lee et al., 2020). PV panels are most often installed on artificial reservoirs, resulting in **an integrated FPV-hydropower system, which can provide a mutually beneficial configuration** with several benefits. Proximity to water has a cooling effect, which can increase panels' efficiency by up to 5 %, while the shielding effect of the panels can reduce evapotranspiration, retaining water for other uses and increasing hydropower generation (Almeida et al., 2022). Additionally, coupling FPV with hydropower can improve flexibility and increase the annual energy generation of the hydropower plant, further reducing the carbon footprint of the plant and supporting energy-intensive processes such as water pumping and treatment (Lee et al., 2020; Quaranta et al., 2021b). When they are paired with pumped-storage systems, the resulting hybrid system can address the challenge of storing intermittent solar energy at times of high production (Cazzaniga et al., 2019; Javed et al., 2020; Lee et al., 2020; Quaranta et al., 2021b; Kakoulaki et al., 2023). Furthermore, FPV can provide a solution to land competition and land shortage in regions with limited scope for ground-mounted PV and help the shift towards the water–energy nexus concept with the multipurpose use of reservoirs (Branche, 2017; Kakoulaki, 2023).

This assessment draws on previous work carried out to estimate the benefits of coupling floating solar PV with hydropower reservoirs in Europe at the regional and national levels (Kakoulaki et al., 2023; the reader can refer to that study for further insights). Starting from the localisation of 337 eligible water bodies in Europe and selecting those already equipped with hydropower structures and installed capacity larger than 5 MW (thus reducing transmission costs), Kakoulaki et al. (2023) assessed the potential electricity output of the resulting FPV systems under different area coverage scenarios (100 %, 10 % and 1 %). While the optimal FPV surface cover is highly site specific, in the current analysis we opted for the **10 % reservoir surface coverage scenario,** as an optimal trade-off value between environmental impact, evaporation reduction, investment costs and feasibility (Lee et al., 2020; Kakoulaki et al., 2023; Quaranta et al., 2023). Reservoirs located in Natura 2 000 protected areas were excluded, as a conservative approach to maximise efficiency and reduce potential environmental impacts (see **Figure 43** in **Section 4.3.4** for site locations). Moreover, in our assessment we have applied a solar irradiation threshold (below 1 100 kWh) in the same way as to the ground-mounted PV systems, excluding reservoirs at higher latitudes characterised by weak sunlight.

We find that covering 10 % of the EU hydropower eligible reservoirs with floating solar arrays would add approximately 85 GW of peak installed capacity and produce **82 TWh/year** of electricity – equivalent to about one-third of the EU's total energy generation from solar PV in 2022 (250 TWh). Of this estimated production, about **30 TWh (36 %) is in rural areas** (261 municipalities), 49 TWh (60 %) in towns and suburbs (35 municipalities) and the remaining 3 TWh (4 %) in cities (11 municipalities), mainly in eastern Europe (Romania, Bulgaria, Poland) (see **Table A4.4** in **Annex 4**). Moreover, the integration of FPV could increase the volumes of water discharged by the European hydropower fleet and produce an additional 280 GWh/year thanks to the reduced evaporation losses (Quaranta et al., 2021b).

4.3.3 SMALL-SCALE HYDROPOWER IN EXISTING STRUCTURES

Small-scale hydropower (SHP, conventionally < 10 MW) has been an important source of electricity generation in many European countries, and a common way of generating electricity in remote regions, since the end of the 19th century (Carasco et al., 2020). According to the European Small Hydropower Association, SHP still **contributes to about 8 % of the renewable energy mix** and supplies electricity for 13 million households (over 13 GW of installed capacity in the EU-27), thus helping to reduce CO_2 emissions by 29 million tonnes a year (ESHA, 2012a). SHP is also considered to be one of the most cost-effective energy technologies, particularly for decentralised sustainable electrification of remote areas (Paish, 2002; UNIDO and ICSHP, 2022), and the main prospect for future hydro developments in Europe, where large-scale sustainable opportunities have mostly already been exploited (Ioannidou et al., 2018; Manzano-Agugliaro et al., 2017).

Installation of modern turbines in pre-existing barriers on small rivers (weirs, mills) or in existing water utilities, such as drinking water or wastewater networks, are among the SHP opportunities that have recently received growing attention, owing to their negligible environmental impact on wildlife and ecosystems and their higher social acceptance (ESHA, 2012a, Quaranta et al., 2022b; Manzano-Agugliaro et al., 2017). Thanks to its versatility and low investment costs, SHP is thus a promising option for producing sustainable, inexpensive energy in rural or remote areas.

4.3.3.1 Hydropower from water utility structures

Because hydropower generation depends on two key factors (water flow and hydraulic head, i.e. elevation difference), SHP can be implemented in any system where these factors are met. This can include any water network where pipes provide water flow at a certain pressure (Carasco et al., 2020). Studies have shown that micro- or small-scale hydropower presents opportunities for energy recovery and CO_2 reductions in the water utility sector (Mitrovic et al., 2021; Quaranta et al., 2022b), which is associated with significant energy consumption (e.g. for pumping or treatment) and resultant CO_2 emissions[13]. Technological solutions have been investigated for the recovery of energy and exploitation of head difference using micro-hydropower turbines in water utilities. The present study has conducted a large-scale assessment of the hydropower potential in water distribution networks (WDNs) and wastewater treatment plants (WWTPs) at the municipality level across Europe. The strategies considered here (see **Table A4.1** in **Annex 4** for detailed description of the methodology) consist in:

[13] This represents 2–3 % of their total energy consumption (Mitrovic et al., 2021), Briefing note. Reducing the Energy Footprint of the Water Sector, EurEau 2019.

— **waste energy recovery** by exploiting the available extra-pressures in WDNs, which are normally dissipated by means of pressure reduction valves and can be replaced by turbines to recover energy;
— **exploiting available head differences** with the associated water discharges in WWTPs.

For WDNs, the same procedure as described by Quaranta et al. (2022b) was implemented with some significant improvements. The available power potential of the WDN infrastructures was calculated at the municipal scale using a modified version of the meta-models proposed by Quaranta et al. (2022b) and as a function of WDN length (EurEau, 2021) and elevation range on the sea level derived from the European Digital Elevation Model (see **Table A4.1** in **Annex 4** for WWTP available power equation). The annual potential production from WDNs, is then given by power (or capacity) multiplied by the CF and hours in a year, as shown in equation (4):

$$WDN\ prod\ [\mathrm{MWh}] = Pw\ \left[\frac{\mathrm{Kw}}{\mathrm{kp}}\right] \cdot \frac{p}{1000} \cdot \frac{0.57}{1000} \cdot 365 \cdot 24 \qquad \text{(Eq. 5)}$$

where *Pw* is the WDN power potential for every 1 000 people (expressed as kW/kp), *p* is the population and 0.57 is the CF[(14)]. Population is derived for each municipality from the LUISA base map (Pigaiani et al., 2021).

For WWTP applications, the same model as used by Quaranta et al. (2022b) and developed originally by Mitrovic et al. (2021) was used, where the hydropower available power in wastewater plants is correlated to the served population at the municipal level. The annual potential production from WWTPs is then calculated by equation (5):

$$WWTP\ prod\ [\mathrm{MWh}] = Pww\ \left[\frac{\mathrm{Kw}}{\mathrm{Mp}}\right] \cdot \frac{p}{10^6} \cdot \frac{0.355}{1000} \cdot 365 \cdot 24 \qquad \text{(Eq. 6)}$$

where *Pww* is the WWTP power potential for every million people (expressed as kW/Mp), p is the population and 0.355 is the CF (from Quaranta et al. 2022b).

Both equations assume efficiency of 50 %. In addition, Mitrovic et al. (2021) found that 50 % of the potential was represented by the installations above 15 kW, which are deemed to be the most cost-effective. Therefore, in our analysis we took a conservative approach and implicitly excluded structures with power below 2 kW, which would not be economically convenient. At the EU level, the final estimated **potential energy generation in WDNs and in WWTPs is about 1.5 TWh/year and 0.09 TWh/year,** respectively, of which about a quarter in rural areas for both WDNs and WWTPs. The available power and potential production in the EU and in rural municipalities in each Member State are reported in **Tables A4.5** and **A4.6** in **Annex 4.**

14 The CF of hydropower turbines in WDN is very site-specific and difficult to assess, with limited studies and literature to date. Therefore, the value of 0.57 is derived from the judgement of experts (E. Quaranta, H. M. Ramos and A. McNabola), who suggested considering 5 000 operating hours per year.

It should be noted that, in general, WWTPs and WDNs are not designed as stand-alone systems at the municipal level but rather serve larger functional areas. Therefore, figures would be more meaningful if aggregated, for instance following definitions of functional (rural or urban) areas. However, our results can be interpreted as the energy produced in each functional territorial unit and then redistributed among the rural municipalities.

4.3.3.2 Hydropower from small historical barriers

Watermills are part of the European industrial and cultural heritage and have had a central role in shaping the development of the European landscape (Punys et al., 2019; Brykala et al., 2020). However, their preservation and management are challenging given their state of abandonment, the lack of knowledge about their value and the lack of economic incentives for their restoration, together with the complexity of legislation and authorisations (ESHA, 2012a). A few studies have tried to bridge this knowledge gap, providing data and tools to support feasibility analyses and techno-economic assessments, to help decision-makers estimate the potentials, benefits and costs of repowering traditional watermills (Quaranta et al., 2023; Punys et al., 2019)

To this end, **the Restor Hydro project**[15] **was launched in 2012 with the aim of raising local rural communities' awareness of the attractiveness of SHP** and contributing to increasing renewable energy generation from small and micro hydropower sites that are currently inoperative (ESHA, 2012b). Moreover, the reactivation of small hydroelectric power plants is often considered environmentally unproblematic where existing barriers cannot be demolished or are in artificial channels – even more so when, at the same time, ecological improvements, such as restoring fish passage, can be achieved (EC, 2018).

The Restor Hydro project has identified about 65 000 old hydraulic structures in the EU that are deemed suitable for refurbishment, of which about 29 000 are watermills (Punys et al., 2019; Quaranta and Wolter, 2021). Therefore, the current assessment only provides representative data and a rough estimate of the achievable potential. The exercise already carried out by Quaranta et al. (2022b) was reproduced in this study with some improvements, assuming that watermills would be repowered by installing suitable turbines instead of limiting the refurbishment only to modern water wheels. The following methodology was applied to assess the potential available power capacity and additional energy generation (see **Table A4.1** in **Annex 4** for detailed description of the methodology):

- only mills reported to be in good and advanced restorability status were considered suitable, corresponding to 19 393 geo-localised sites;
- restorable mills were assumed to be repowered with any type of turbine among those suitable for low-head applications (Quaranta et al., 2022b), which allows them to exploit all the available flowrate;

15 Renewable Energy Sources Transforming Our Regions Hydro project, co-funded by the Intelligent Energy Europe Programme of the European Union (2012–2015) (*https://data.mendeley.com/datasets/fcz6s7dfyc/1*).

— when information on the available power was missing, a refined gap-filling procedure was implemented to estimate the available power and corresponding potential production, increasing the sample size considered in the analysis.

Finally, the energy generation was calculated by multiplying the estimated available power by the number of operating hours (assumed to be 5 000 h per year). If all the restorable mills are considered (including those with projected values), the **estimated total annual generation is about 3.3 TWh/year at EU scale, 70 % of it in rural areas.** Indeed, while mills have been an important trait of the industrial and urban landscape, most of the structures in urbanised areas have been dismantled during the urbanisation process, so nowadays most of the remaining structures characterise the rural landscape. Indeed, in our database **75 % of the historical sites suitable for repowering are in rural areas,** 20 % in towns and suburbs and only 5 % in cities. The countries with the highest rural potential from mill repowering are France (940 GWh/year), Austria (237 GWh/year), Germany (230 GWh/year), Italy (225 GWh/year) and Sweden (203 GWh/year) (see **Tables A4.7** and **A4.8** in **Annex 4** for total and rural potential, respectively).

In quantitative terms, the recovery of historical watermills provides a limited contribution to overall energy generation. Nonetheless, it may be relevant in the context of rural development policies, and as part of a wider long-term strategy to promote the sustainable energy transition of rural areas and the preservation of cultural and industrial heritage. Repowering abandoned sites can, therefore, result in the generation of green decentralised hydroelectric power, both for local use and for injection to the European grid, leading to increasing overall electricity production from renewable sources, energy independence and grid stability. Besides enhancing energy supply security, the creation of local energy sources can give a boost to local economies, possibly acting as a local trigger for the development of small business and cultural and recreational activities, supporting tourism and heritage preservation (ESHA, 2012b). This can be particularly attractive for regions with many historical structures, as found in Belgium, Germany, Greece, France, Italy and Austria. Some successful case studies can be found on the Restor-Hydro project website; see also Agarwal (2006) and Quaranta et al. (2020).

4.3.4 TOTAL HYDROPOWER UNTAPPED POTENTIAL

We found that **the total potential production from all the strategies addressed in this study amounts to 133 TWh/year.** The contributions from different strategies are shown in **Figure 40.** In some countries, such as Sweden, Spain, Greece, Poland and Lithuania, the total potential production corresponds to at least 50 % of the current production, and it is above 35 % in Portugal, Romania and Slovakia (**Figure 41**). The largest share of the total untapped potential (61 %) comes from the hybridisation of hydropower reservoirs with FPV systems, with an output equivalent to 22 % of the current total hydropower production, to which rural areas contribute 37 %. Next, modernisation strategies account for 35 % of the total estimated potential and can increase current production by 12 %, with a significant contribution coming from rural areas (76 %). At the Member State level, the greatest potential from FPV is found in Sweden, Spain, Portugal, and Romania, mainly in towns and suburbs (across 35 municipalities) and secondly in rural areas (across 261 municipalities), as seen in **Figure 41** and **Figure 42** (see also **Table A4.4** in **Annex 4**).

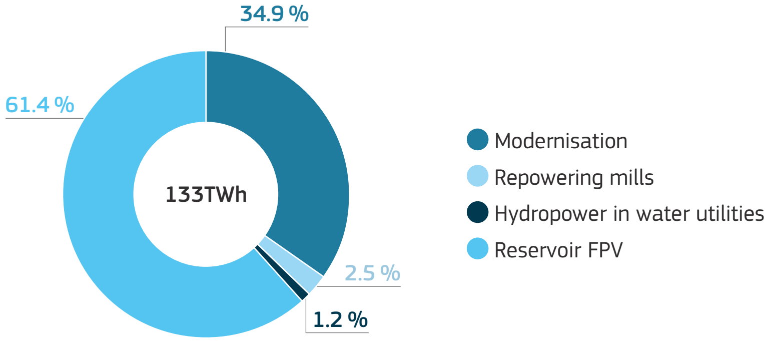


Figure 40. Annual hydropower potential production in the EU-27 by strategy.

Source: Authors' own elaboration.

The greatest rural FPV potential is found in Spain (15.6 TWh/year in 79 municipalities), Greece (3.2 TWh/year in 14 municipalities), Romania (2.3 TWh/year in 34 municipalities), Portugal (2 TWh/year in 21 municipalities) and France (1.5 TWh/year in 37 municipalities). For modernisation, the highest potential at the Member State level is found in Sweden (9.4 TWh/year), France (8.6 TWh/year), Italy (5.4 TWh/year), Spain (4.9 TWh/year), Austria (4.8 TWh/year), Germany (2.9 TWh/year) and, predominantly in rural and mountainous areas, southern Sweden, the Alps, the Pyrenees and central Europe.

Figure 41. Current and cumulative potential production from hydropower in EU Member States (GWh/year).

Source: Authors' own elaboration.

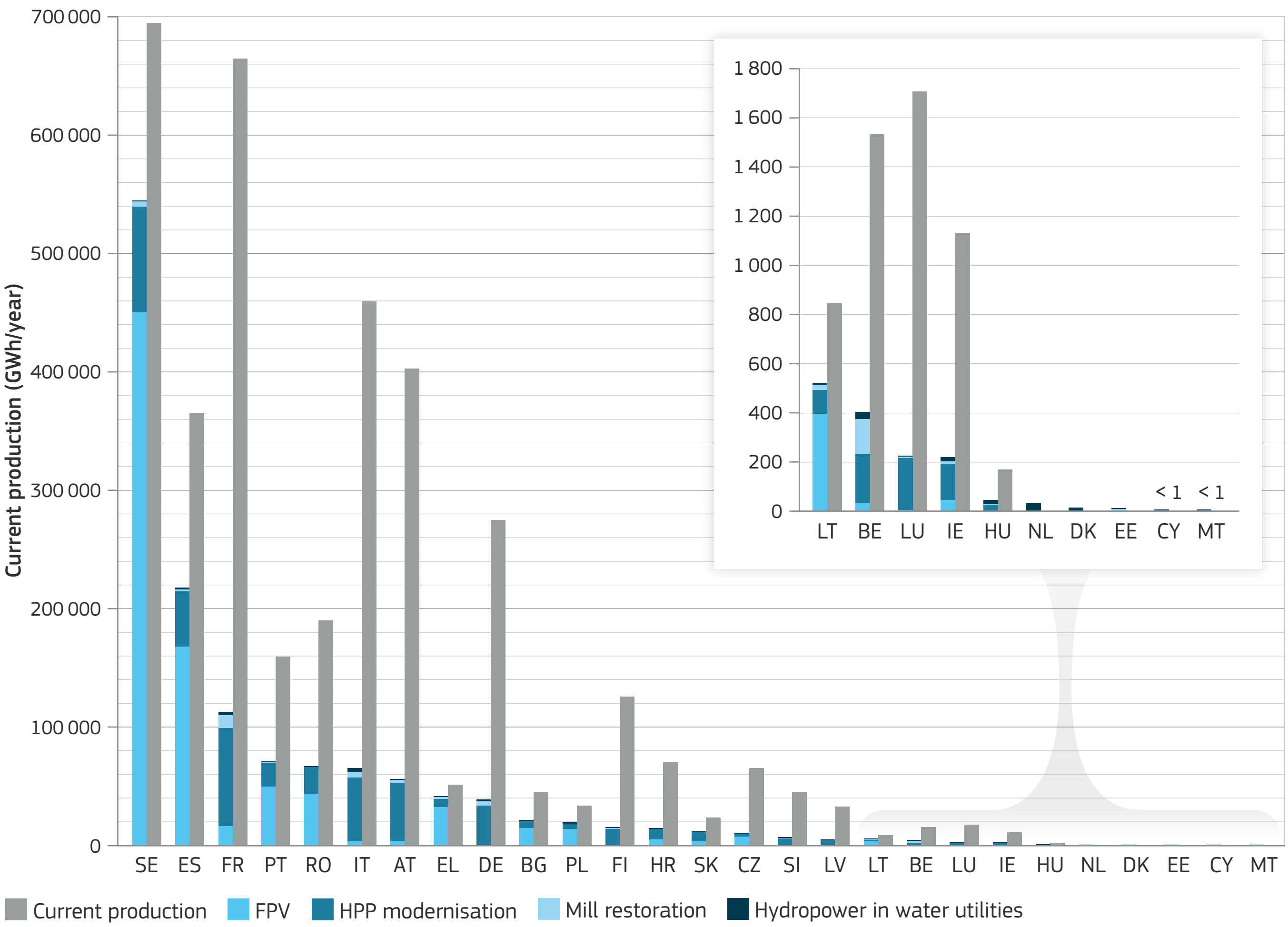
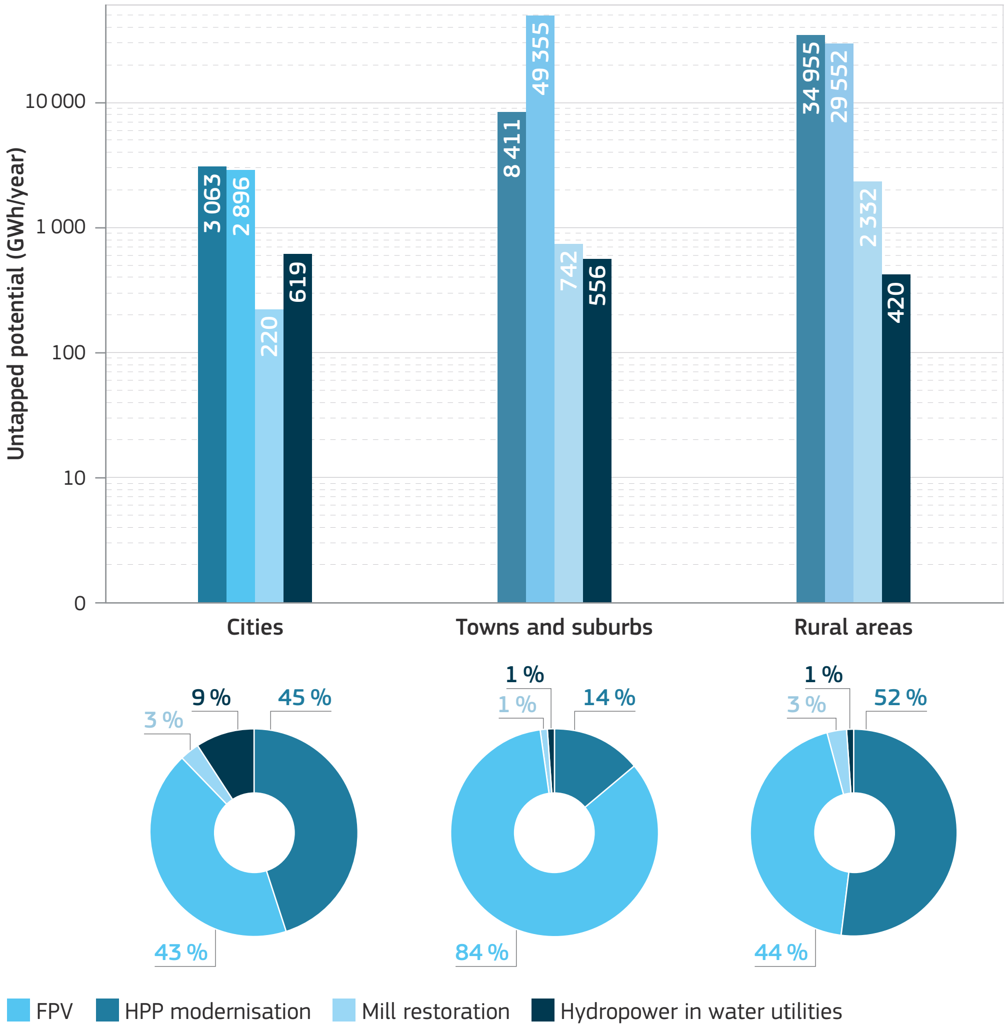


Figure 42. Untapped potential production (GWh/year) from hydropower by strategy and by degree of urbanisation.

Note: graphical visualisation using logarithmic scale.

Source: Author's own elaboration.



By contrast, the contribution from SHP is negligible in quantitative terms if we look at the EU's production of green electricity. Mill repowering accounts for only 2.5 % of the total hydropower potential and largely concerns rural areas (70 %), where most of the historical structures are found. These structures are especially significant in France (940 GWh/year), Austria (237 GWh/year), Germany (230 GWh/year) and Italy (224 GWh/year). Similarly, the potential in water utilities accounts for only 1 % of the total, of which one-quarter (25 %) is in rural municipalities, mainly in France, Italy, Germany, Austria and Poland. Greater potential is found in more densely populated areas, where the discharged water volumes and water networks are larger, such as capital regions (e.g. Paris, Rome), southern Spain, western Bulgaria and Benelux (see **Figure 45**). Nonetheless, **SHP technologies are highly dispatchable and cost-effective solutions** that can provide significant input towards decentralising electricity production and decarbonising some energy-hungry sectors such as water utilities, while supporting local development opportunities for rural regions.

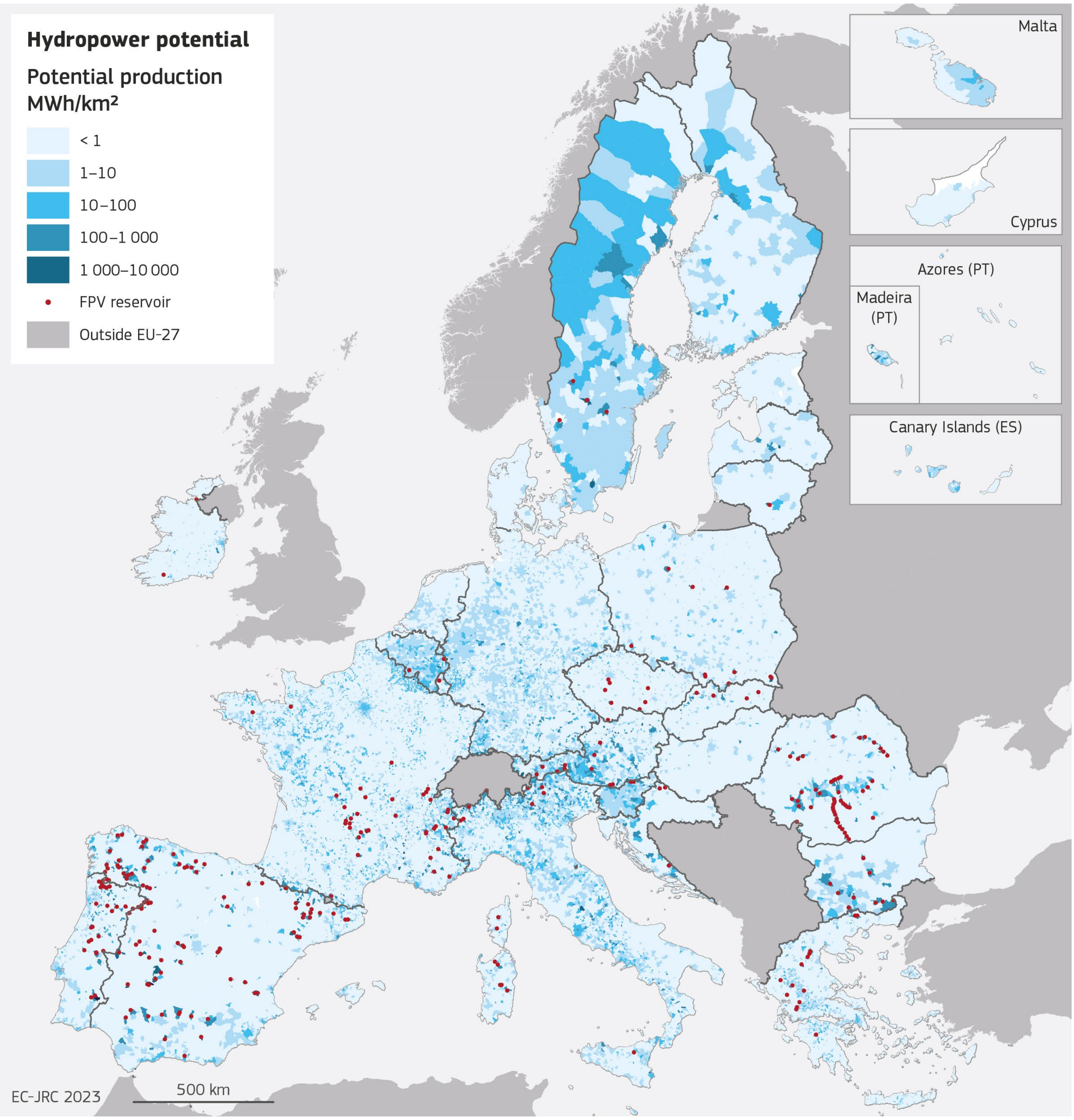


Figure 43. Total estimated cumulative hydropower annual potential production per unit area in the EU's municipalities.

Note: Red dots represent suitable hydropower reservoirs for FVP systems.

Source: Authors' own elaboration.

In absolute values, rural areas hold the largest hydropower potential by virtue of having more space, structures and resources for hydropower expansion. **Figure 43** shows the spatial distribution of the total normalised hydropower potential in the EU at the municipal level, alongside the locations of the eligible reservoirs for FPV system installations. In **Figure 44,** the potential production by municipality unit area and by degree of urbanisation is shown for the EU's countries. This area-relative potential shows great variability across countries and across territorial typologies. Rural areas show the highest average potential production per unit area in Luxembourg, Spain, Austria and Portugal, with more than 50 MWh/km² per year.

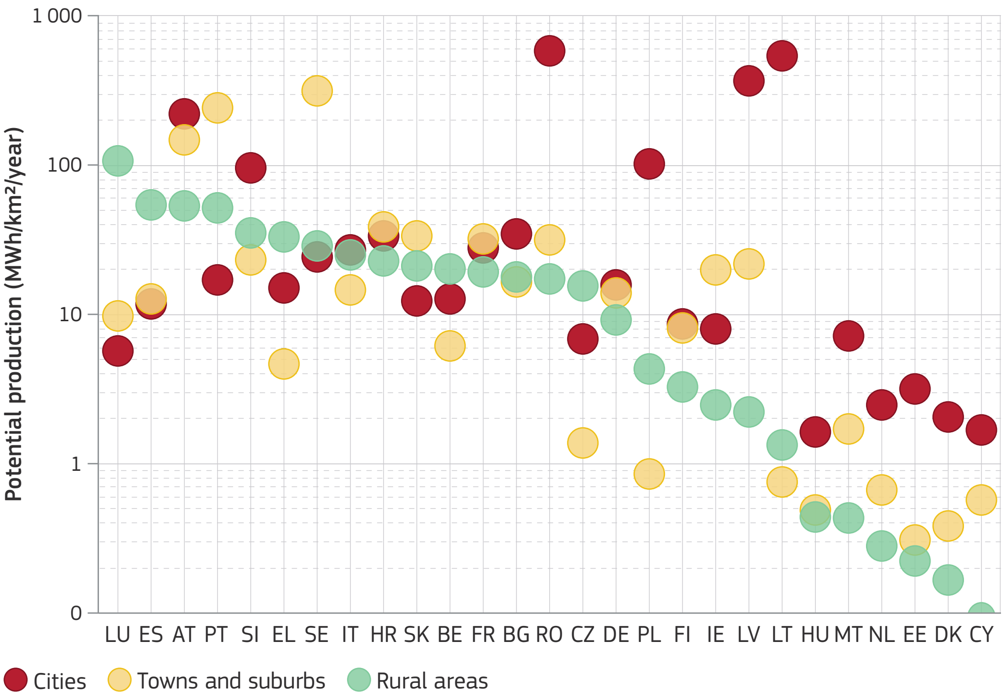


Figure 44. Total hydropower potential production by degree of urbanisation.

Note 1: Graphical visualisation in logarithmic scale.

Note 2: Yearly production in MWh is shown per unit area.

Source: Author's own elaboration.

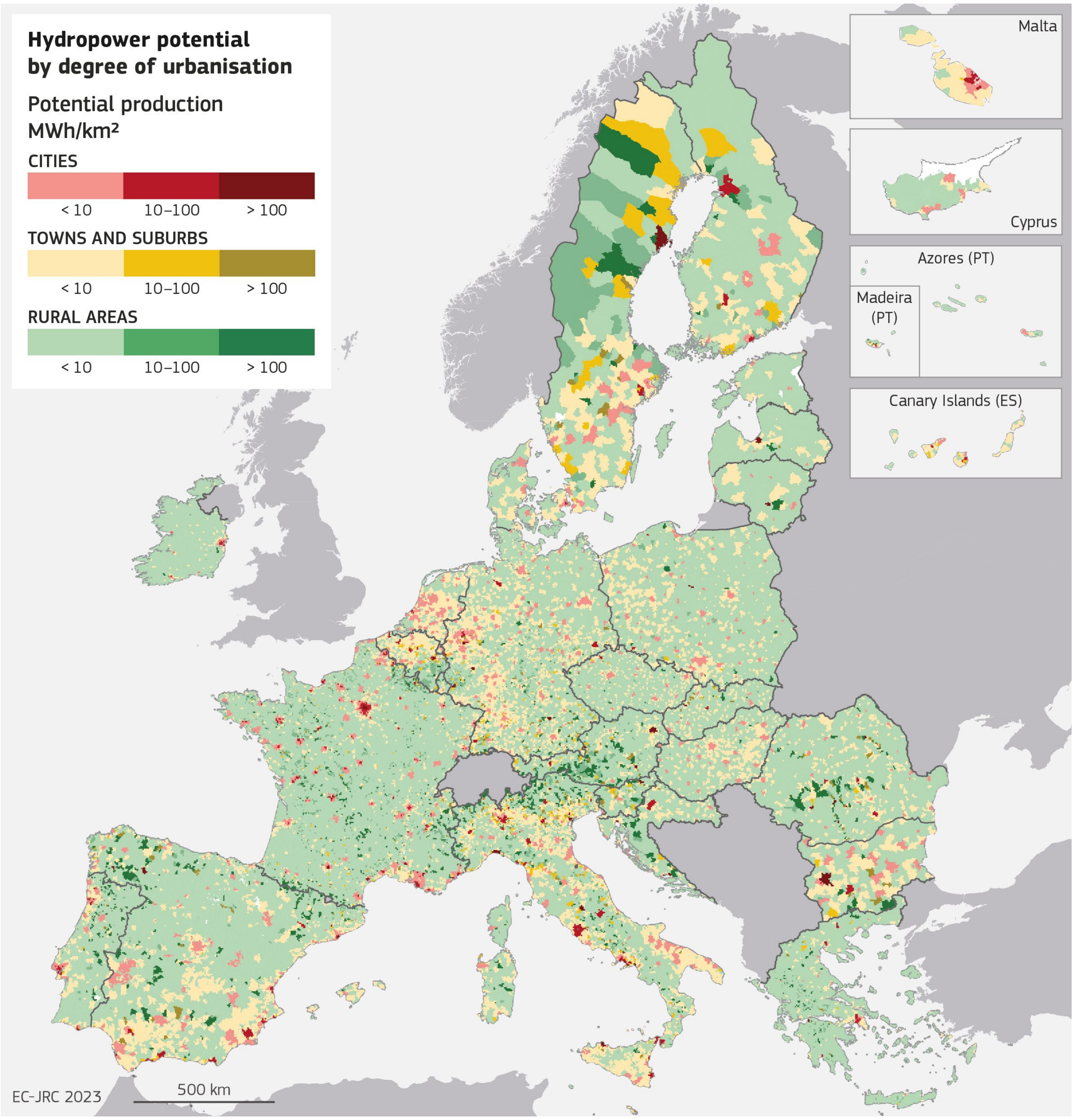
Figure 45 shows the spatial distribution of the total normalised potential production of hydropower (expressed as MWh/km² per year) by degree of urbanisation. On average, towns and suburbs display higher production rates relative to the municipality size and could potentially produce about 33 MWh/km² per year, closely followed by cities (32 MWh/km² per year). Rural areas, where hydropower infrastructures are likely to be more scattered, could produce about 19 MWh/km² per year. The estimated hydropower potentials for all the strategies addressed and their relative magnitudes are summarised in **Table 3.**

It must be stressed that the results reported in this assessment do not correspond to exact values; rather, they provide an indication of where the potential for further hydropower development is hidden and thus should be interpreted as an order of magnitude of what is reasonably achievable. Indeed, real CFs are very

Table 3. Summary of hydropower potential by strategy.

Source: Authors' own calculations.

Strategy	Total potential (TWh/year)	Rural potential (TWh/year)	Rural share (%)	EU net electricity consumption (%)	EU net energy consumption (%)
Floating PV	82	30	37	3.2	2.9
Modernisation	46	35	76	1.8	1.7
Water utilities	1.6	0.4	25	0.1	0.1
Repowering mils	3.3	2.3	70	0.1	0.1
Total	**133**	**67.7**	**51**	**5.2**	**4.8**



site specific and depend on hydrological conditions, the status of the equipment and other operational aspects, which are difficult to assess at the local scale, and are expected to change in the future with the changing role of hydropower. Moreover, when considering varying environmental and social factors (e.g. social acceptance), the true feasible potential for development will most likely be lower than estimated.

Figure 45. Total estimated hydropower annual potential production per km² in the EU's municipalities by degree of urbanisation.

Source: Authors' own elaboration.

4.4 CONCLUSIONS

Despite its limited untapped potential compared with other emerging RESs such as wind and solar, hydropower has a crucial role to play in the future energy transition and in long-term decarbonisation scenarios, owing to its peculiar characteristics and dispatchability. Indeed, hydropower is the world's largest and most **reliable energy storage** technology, and a vital enabler for further penetration and integration of intermittent energy sources in the energy mix (IHA, 2018). In particular, pumped-storage hydropower capacities (which were out of the scope of the report) play a balancing role in power systems, as net generation and load must be continuously balanced to maintain system reliability. Given this, hydropower is well positioned to be the backbone of the entire energy system.

In this chapter we have analysed the production and potential of hydropower in the EU at the municipal level, excluding the construction of new dams and plants because we have adopted a conservative and sustainable approach. Nonetheless some new hydropower projects will still occur in the future in the EU, but their potential contribution to the overall energy generation from hydropower has not been accounted for in this assessment. We selected four strategies aiming at expanding the EU's installed capacity and energy production, while looking at solutions that are more relevant to rural areas and following policy recommendations and market trends. These suggest minimising environmental impact and taking advantage of existing structures. In numerical terms, the dominant strategies are FPV installation on reservoirs and modernisation.

Modernisation strategies are particularly important to increase production in regions where there is limited scope for new development. Indeed, the IEA forecasts to 2030 estimate that modernisation will account for nearly 90% of total investment in hydropower modernisation in North America and Europe (IEA, 2021). We estimated that **current production of electricity from hydropower could increase by 12%** (equivalent to 47 TWh/year) at the EU scale **thanks to refurbishment, with 75% of the increase located in rural areas.** Most of the modernisation potential is in the mountainous and rural regions of southern Sweden, in the Alps across France, Italy and Austria, in the Pyrenees, in the Carpathian Mountains and in western Germany.

FPV on waterbodies is an emerging hybrid system that presents several advantages. We have assessed the potential of installing solar arrays on 307 hydropower reservoirs in the EU, by covering 10% of the available water surface, resulting in **energy generation of about 82 TWh/year,** 36% of it stemming from rural areas. The highest FPV potential is concentrated in a small number of towns and suburbs in southern Sweden, northern Portugal, Spain (Galicia, Catalonia and central Spain) and the Olt River region in Romania, thanks to the presence of large reservoirs. Despite its large potential, it must be noted that FPV is still a young technology with limited installations. Given this, social, environmental and economic trade-offs still need to be carefully analysed to avoid unforeseen impacts and public opposition (Almeida et al., 2022; Spencer et al., 2019).

Our findings also suggest that **small-scale hydropower** can be an ally for rural communities, and especially suitable for communities in remote locations. SHP opportunities are particularly relevant in the light of European nature regulations, which place limitations on the expansion of large-scale hydropower in European water bodies. In this study, hidden opportunities for developing SHP in existing infrastructures, namely in WDNs, WWTPs and existing low-head barriers (i.e. watermills), have been investigated. Using these infrastructures could result in new renewable electricity generation from hydropower with minimum civil engineering works (and associated costs) and negligible social and environmental impact compared with conventional hydropower. Moreover, SHP solutions could play a positive role in terms of grid balancing and energy insecurity (e.g. from outages) in rural and remote areas due to their **high levels of dispatchability and reliability.** However, the total **technical potential** associated with these technologies is limited to approximately **5 TWh/year** in the EU.

It is worth mentioning that climate change effects were not considered in this study, although hydropower is highly interconnected with climate changes: on one hand, hydropower generation depends on water availability, and may suffer from water shortage in long dry periods. On the other hand, optimal management of hydropower reservoirs, along with a better inflow and weather forecast, can help in mitigating climate change effects, for example through drought and flood control, irrigation and firefighting, playing a key role particularly in regions with high climate variability (Quaranta et al., 2022a). Several studies have tried to assess the impact of climate change in the hydropower sector, but evidence and large-scale scenarios are still limited (Wasti et al., 2022; Wan et al., 2021). In general, climate changes are expected to increase water availability in the north of Europe and decrease it in the south of Europe. On the other hand, certain regions could even benefit from increased water flows due to glaciers melting in the short term (Terrier et al., 2011). As power generation by hydropower plants varies according to hydrological conditions, **future hydropower operability and planning will have to integrate climate change scenarios** (IHA Climate Resilience Guide, 2019).

Finally, hydropower can generate several benefits and services besides energy generation (e.g. water management and flood control, or cultural, recreational and economic values). However, it also entails competing use of water and land (food and irrigation, environmental services, leisure, etc.). Going forward, new hydropower capacity, as well as new wind and solar installations, should **embed sustainability principles and standards,** to ensure that energy and climate benefits are not undermined by negative environmental or social impacts. Therefore, the future development of hydropower is intertwined with some major challenges, notably defining and applying stricter sustainability standards, successfully integrating it with new emerging RESs, and incorporating climate resilience into the planning and operation of hydropower (IRENA, 2023).

Allowing for these cautions and a margin of error, this assessment shows that the EU's already mature hydropower sector also holds a wealth of untapped potential to deliver the large capacity and production increases needed to contribute towards the net zero target. It also contributes to revealing the whereabouts of such untapped potential, showing that greater opportunities for development are in rural areas, where further innovative use and penetration of hydropower technology can contribute not only to the energy transition but also to bringing about additional local benefits.

5 Possible trajectories of the untapped potential of solar photovoltaics, onshore wind and hydropower

The EU's 2030 energy target has been recently increased to 42.5 % of renewables in the energy mix (EC, 2023c). In 2021, this share amounted to 22 % (Eurostat, 2021c), so major efforts are required in the near future to meet the target. Onshore wind, hydropower and solar PV are currently the most prominent technologies in terms of power generation, accounting for, respectively, 36 %, 33 % and 15 % of the electricity produced in the EU from all renewable sources in 2021.

In **Chapters 2, 3** and **4** we have assessed the current level of electricity production and the untapped potential for each of these three sources. In this chapter we combine these results to assess their overall current level of electricity production and potential. In 2023 the EU's electricity production from the analysed sources reaches 975 TWh (375 TWh from hydropower, 350 TWh from onshore wind and 250 TWh from solar PV). As shown in **Figure 46, 72 % of the electricity from solar PV, onshore wind and hydropower is generated in rural areas,** followed by towns and suburbs (22 %) and cities (6 %).

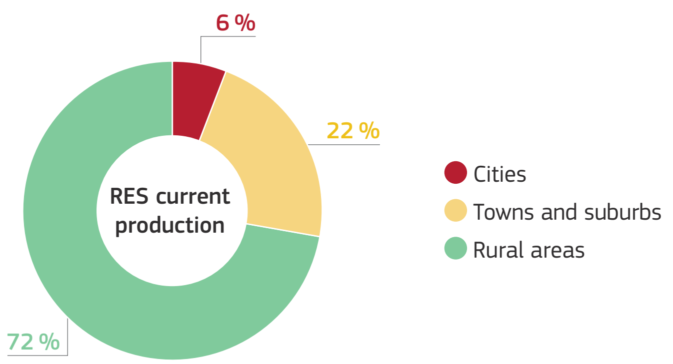


Figure 46. Share of the estimated current electricity production from solar PV, onshore wind and hydropower in the EU-27 by degree of urbanisation.

Source: Authors' own elaboration from Wiki-solar (WolfeWare Ltd, 2023), Open Street Map (Dunnett et al., 2020) and the 'Fit for 55' package (EC, 2021a), World wind farms (Wind Power, 2023) and JRC-Hydropower database (EC-JRC, 2019).

At the country level, the Member States with the highest production from these RESs are Germany (184 TWh/year), Spain (142 TWh/year), France (133 TWh/year), Italy (104 TWh/year) and Sweden (99 TWh/year) (**Figure 47**). The share of each source in each Member State varies widely: for instance, hydropower is especially important in Latvia, Slovakia, Luxembourg and Slovenia, where it accounts for more than 80 % of the electricity generated by the three sources. Solar PV is key in Malta, where there is no onshore wind or hydro production, and in Hungary, where it accounts for 85 % of the electricity generated from these sources. Onshore wind is most prominent in Denmark (77 %) and Ireland (72 %).

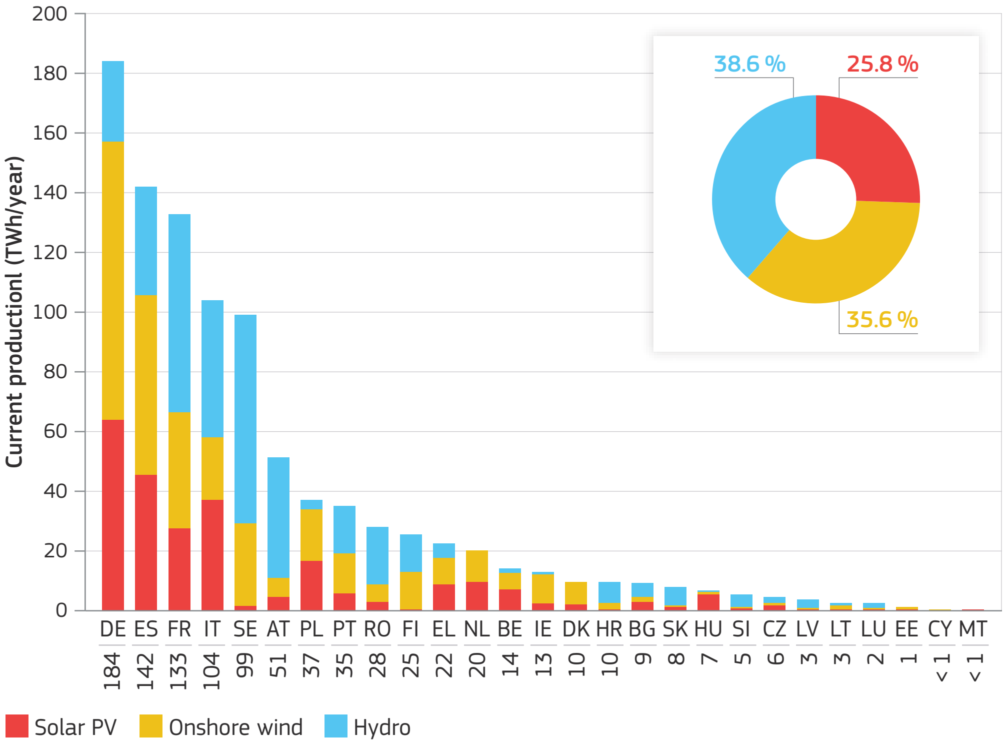


Figure 47. Estimate of the current production of electricity with solar PV, onshore wind and hydropower in the EU-27, 2023.

Source: Authors' own elaboration from Wiki-solar (WolfeWare Ltd, 2023), Open Street Map (Dunnett et al., 2020) and the 'Fit for 55' package (EC, 2021a), World wind farms (Wind Power, 2023) and JRC-Hydropower database (EC-JRC, 2019).

The theoretical total untapped potential is about 12 500 TWh/year. This figure is derived from the sum of the maximum potential of each technology, with the leading contribution stemming from solar PV (11 000 TWh/year), followed by onshore wind (1 400 TWh/year) and hydropower (133 TWh/year) (see **Table 4**). Considering that overlapping suitable areas for onshore wind and ground-mounted PV can be used to install only one of the two technologies, the real untapped potential is slightly lower, but, in any case, higher than 11 200 TWh/year, which is achieved by allocating contested land to the most productive technology only.

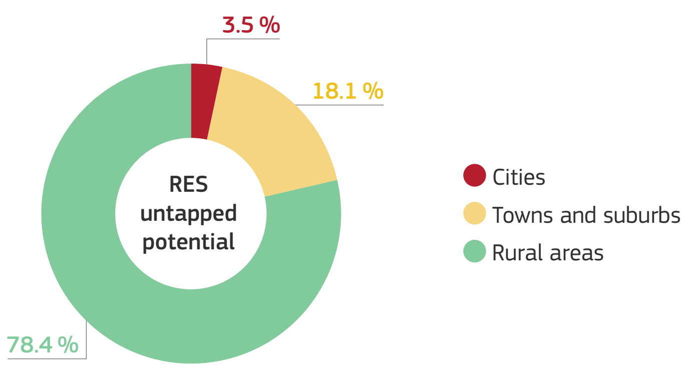


Figure 48. Share of untapped potential production of electricity with solar PV, onshore wind and hydropower in the EU-27 by degree of urbanisation.

Source: Authors' own elaboration.

Combining the current production of electricity with the untapped potential, **the EU could produce 13 000 TWh/year from these sources,** which is more than five times the electricity consumed in 2021, and **even more than the total**

EU energy consumption in the same year (11 257 TWh) (Eurostat, 2021h). The Member States with the highest untapped potential are Romania (2 439 TWh/year), Spain (2 274 TWh/year) and France (1 600 TWh/year), which together account for 56 % of the EU's combined untapped solar PV, onshore wind and hydropower potential.

Our analysis shows that **the untapped potential of solar PV is about 10 times as much as that of onshore wind, which in turn is approximately 10 times as much as the untapped potential of hydropower.** For hydropower, our assessment excludes the installation of new dams and large hydrological barriers, owing to environmental concerns, and it considers only alternative solutions providing limited additional capacity (see **Chapter 4**). In the case of onshore wind energy, its lower potential than solar PV stems from the difference in capacity per unit area for the two technologies. Following expert literature (Dalla Longa et al., 2018), in this assessment we employed a potential capacity density of 5 MW/km² for onshore wind turbines, 93 MW/km² for ground-mounted PV systems and 200 MW/km² for rooftop PV panels. Therefore, the much larger potential capacity by unit area of PV panels explains its much higher overall potential. These results are in line with previous EU-wide studies (Ruiz et al., 2019). The main figures are summarised in **Table 4.**

Table 4. Current and untapped potential electricity production with solar PVs, onshore wind and hydropower in the EU-27.

Source: Authors' own calculations.

EU-27	SOLAR PV		ONSHORE WIND		HYDRO	
	Current	**Potential**	**Current**	**Potential**	**Current**	**Potential**
Capacity	200 GW	10 000 GW	180 GW	530 GW	150 GW	88 GW
Production	250 TWh/year	11 000 TWh/year	350 TWh/year	1 400 TWh/year	375 TWh/year	133 TWh/year

Both onshore wind and ground-mounted PV systems require substantial amounts of land for new installations. On the basis of important environmental and agricultural constraints, we estimate that the maximum suitable area for ground-mounted PV installations is 2.3 % of the EU's surface (see **Chapter 2**) and for onshore wind 2.8 % (see **Chapter 3**).

The total suitable land that could be used for ground-mounted PV and/or onshore wind is 142 000 km², or **3.4 % of the EU's surface.** Agricultural areas at high risk of abandonment, with severe erosion and of low productivity represent 76 % of this total suitable land, or 6.2 % of the EU's total agricultural land. Onshore wind projects do not necessarily require a large-scale repurposing of their used land, as the physical footprint of wind farms can be minimal, making it possible for them to co-exist with agriculture. In the case of solar PV systems, innovative solutions such as agri-PV could also allow a multipurpose use of the agricultural land (Chatzipanagi et al., 2023).

Orographic constraints also play a significant role in the definition of suitable areas for wind and solar, as ground-mounted PV favours south-facing areas, and onshore wind is best hosted in sites with low terrain inclination. Areas that are suitable for both wind and solar installations cover 65 000 km², which amounts to 70 % of the suitable land for ground-mounted PV and 57 % of the suitable land for onshore wind.

Rural areas hold 78 % of the total EU's untapped potential (10 000 TWh/year), followed by towns and suburbs (18 %, 2 300 TWh/year) and cities (3.5%, 440 TWh/year), as seen in **Figure 48.** As seen in **Figure 49,** solar PV is the largest source of untapped potential, followed by onshore wind and hydropower. In rural areas, ground-mounted PV systems account for 85 % of the untapped potential, followed by onshore wind (12 %), rooftop PV (2.6 %) and hydropower (0.69 %). In towns and suburbs, and in cities, rooftop PV shows more untapped potential than onshore wind, as built-up areas are larger. Floating PV is responsible for the largest share (84 %) of untapped hydropower potential in towns and suburbs, while in cities and rural areas modernisation and utilisation of small hydrological barriers are more important, accounting for more than 55 % of the untapped hydropower potential.

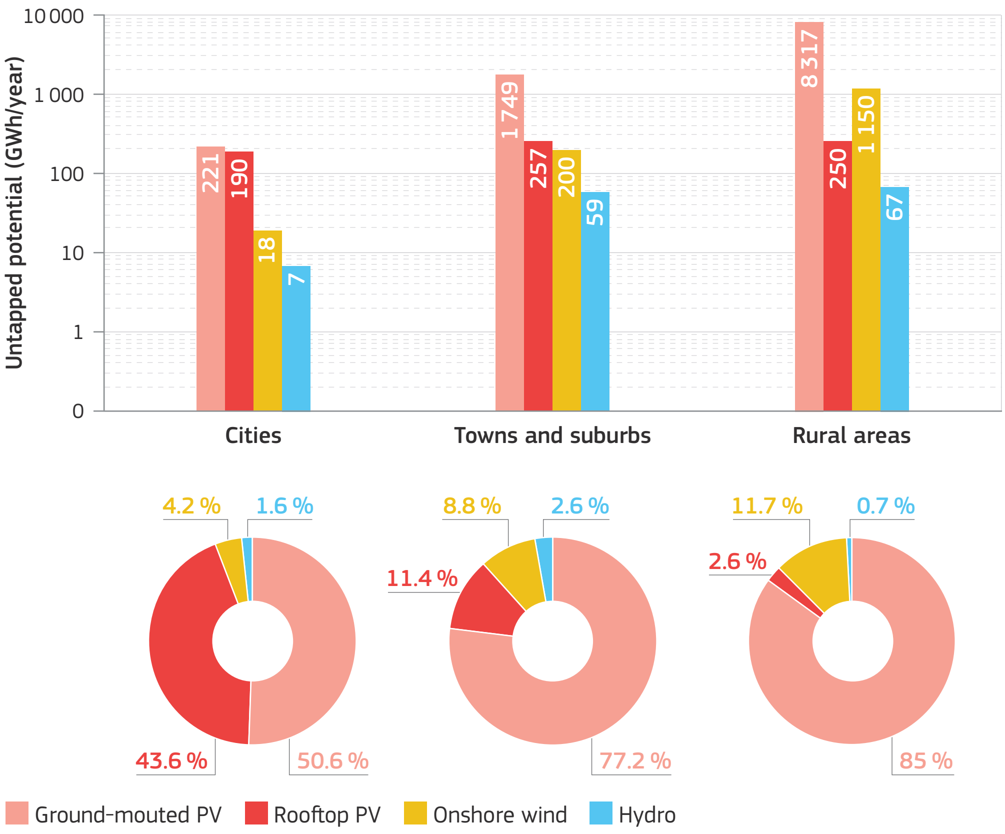


Figure 49. Untapped potential production of electricity with solar PV (rooftop and ground-mounted systems), onshore wind and hydropower (hydropower modernisation and small barriers, floating photovoltaics) in the EU-27 by degree of urbanisation.

Note: Graphical visualisation in logarithmic scale.

Source: Authors' own elaboration.

The contribution of each RES of untapped potential in Member States is depicted in **Figure 50,** while **Figure 51** shows the leading source for each municipality. **Ground-mounted PV is the leading source of untapped potential in 51 % of the EU's municipalities.** 12 % of these have significant potential from onshore wind as well (at least 30 % as much potential as ground-mounted PV). These municipalities could, therefore, benefit from a combination of the two technologies. Depicted in light green in **Figure 50,** they are mostly located in large areas of Estonia, Latvia and Lithuania (more than 80% of the countries' municipalities), in Denmark (51% of its municipalities), in Poland (43%, predominantly in the north of the country) and in Sweden (42%, predominantly in southern and coastal regions).

Municipalities that would benefit most from installing only ground-mounted PV systems are prominent in Bulgaria (83%), Romania (78%) and Hungary (74 %). They also cover large parts of Luxembourg, Spain, Czechia, Portugal and Slovakia, where they represent more than 50% of the countries' municipalities.

Rooftop PV holds the highest potential in highly built-up areas. In Malta, Belgium and the Netherlands, rooftop PV is the leading source of untapped potential in more than 85% of the countries' municipalities. The percentage is also above 50% in Cyprus, Austria, Slovenia, Germany, Italy and Croatia. Rooftop PV can also be the only source of renewable energy potential in municipalities where suitable areas for land-intensive installations are small (for instance, in mountainous regions with high slopes and large protected areas) and no hydrological resources are present. These patterns can be observed in **Figure 51.**

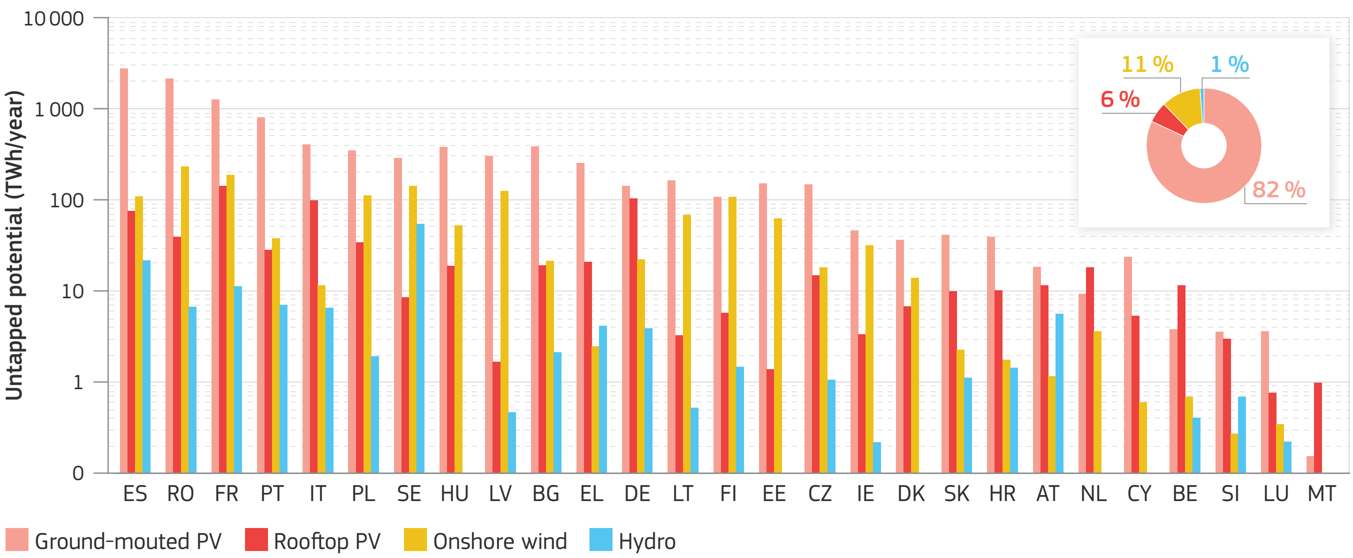
Onshore wind is the leading source of RES potential in large areas of Finland (42% of its municipalities) and Sweden (11% of the country's municipalities), especially in northern regions, where solar irradiation is below the threshold required for PV installations (see **Annex 2, Table A2.2** for details). Onshore wind also leads in 25% of Ireland's municipalities. This percentage falls below 1% in the rest of the Member States.

In the case of hydropower, even if its untapped potential is low at the EU scale, it can be extremely important in municipalities with abundant hydrological resources. In **Figure 51,** it emerges that **hydropower is the main source of untapped potential in municipalities located mostly in mountainous areas,** especially in the Alps, the Pyrenees and the Carpathian Mountains. These account for 1.4 % of all EU's municipalities.

Figure 50. Untapped potential production of electricity from solar PV (ground-mounted and rooftop), onshore wind and hydropower in EU Member States.

Note: Graphical visualisation in logarithmic scale.

Source: Authors' own elaboration.



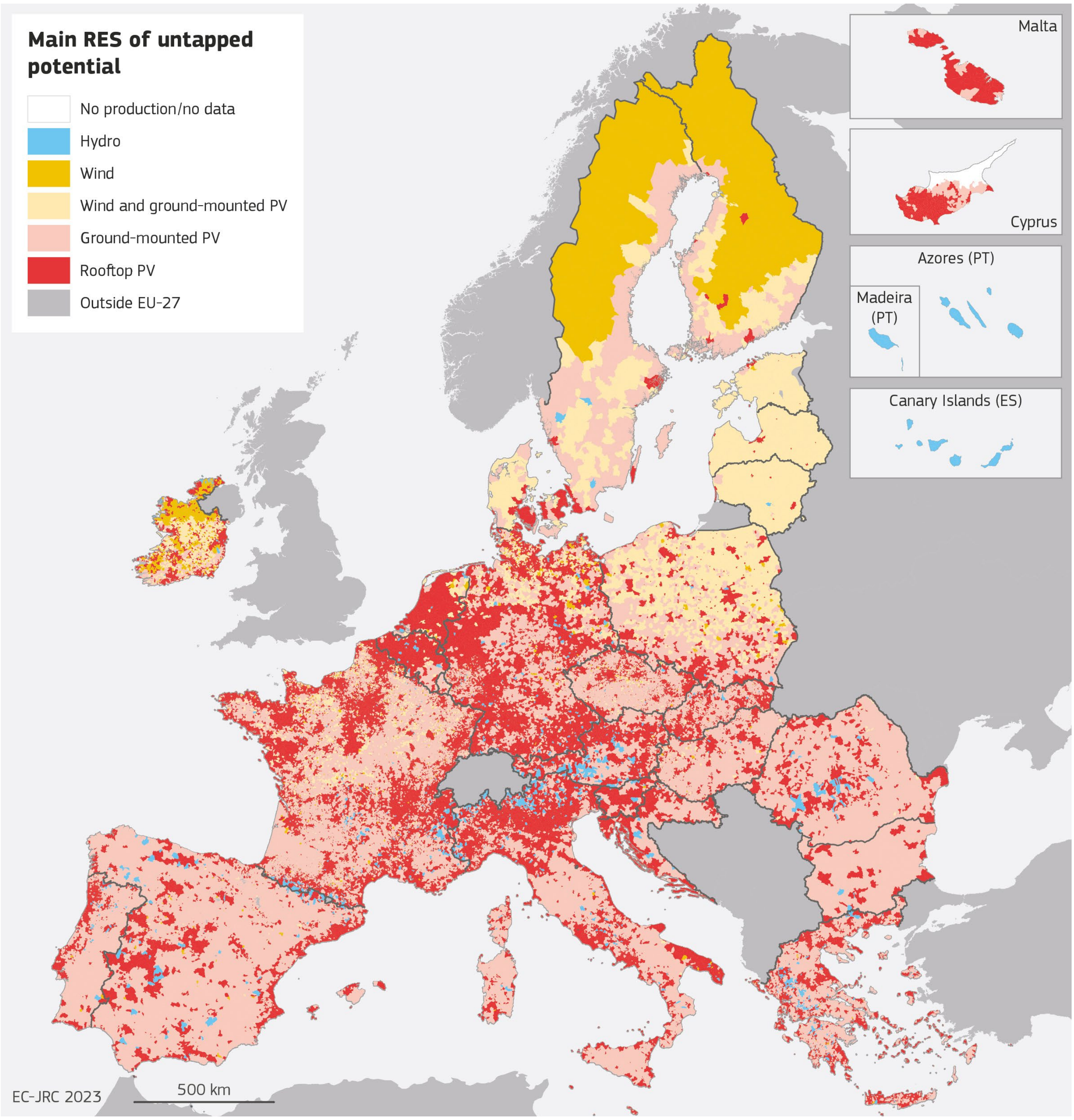


Figure 51. Main renewable energy sources (RES) of untapped potential in the EU's municipalities.

Source: Authors' own elaboration.

6

An **energy transition: local benefits** and **value creation** in rural areas

Renewable energy expansion has been recently highly prioritised in EU Member States as a means of addressing environmental and energy security issues, but also as a potentially significant source of development and job creation, especially in rural areas. Indeed, an important question for representatives and policymakers is **whether and how renewable energy can assist the development of rural economies.** Findings from previous studies suggest that territorial policies that aim at coupling the potential of renewable energy with rural development should focus on leveraging the existing regional and local specialisations and responsibilities, adopting cross-sectoral and place-based approaches, away from top-down and heavily subsidised national strategies (OECD, 2012).

The roll-out of RESs in **EU Member States requires a facilitating and coherent regulatory framework** to remove the existing bottlenecks. With this aim, the European Commission has provided recommendations and guidance to Member States on how to speed up the permit-granting process and promote faster and shorter administrative authorisation procedures (EC, 2022e). Several **barriers have been identified that hinder RES penetration,** such as weak support schemes, market entry barriers, administrative obstacles and grid-related issues. According to the RES study (EC, 2023a), in recent years administrative and grid-related obstacles have become increasingly important, making up about 46 % of all identified barriers. The RES simplify study identifies three main groups of barriers:

- **process-related barriers** are reported to be the most significant, and include administrative burdens, lack of legal consistency, poor spatial planning coordination among different administrative levels and scarcity of experienced staff;
- **conflicting public goods and values** are related to conflicting public interests, for instance environmental regulations, military/air defence (particularly relevant to wind installations) or groups of affected people / stakeholders, which in turn can lead to wider public opposition;
- **technical barriers,** such as grid connection and IT issues, arise mainly from inadequate grid capacity and IT readiness to integrate RES volatile energy inputs, and secondly from disputes with grid operators over interpretation of the grid and market regulations.

From a rural perspective, **process-related barriers are even more significant in small rural municipalities, which often have limited human capital and financial resources.** These regions would noticeably benefit from a clear and consistent definition of roles and process, and from an integrated spatial planning and zoning system to streamline the identification of suitable sites. On top of that, these municipalities would benefit from ad hoc supporting schemes providing targeted technical and financial support, training and consultancy services. Moreover, while some rural areas are favoured places for the physical RES infrastructures, they can be also places of opposition to those same infrastructures. It has been increasingly recognised that early engagement with and participation of the local population and administration, together with the provision of community benefits stemming from renewable energy development, are crucial for fostering acceptance by society and stakeholders. In this respect, project acceptance measures can be financial or non-financial in nature, such as actions to promote rural residents' engagement and awareness, or various forms of local compensation for negative impacts. Measures of a financial nature have been shown to be the most effective in fostering acceptance and are often in the form of a payment, per kilowatt-hour or per unit of installed capacity, from the RES producer. Ideally such income originating from RESs should be linked to specific public policies that benefits rural residents directly, such as social services (e.g. kindergarten, health services) or infrastructure (e.g. streets or public transport) (EC, 2023a; Aitken, 2010).

The adoption of a well-designed and timely **participatory approach** also plays a vital role in increasing the acceptability of and trust in RES projects, allowing residents and stakeholders to influence the entire process, rather than just presenting the final outcomes (EC, 2023a). Moreover, alongside large private RES development, various **community ownership models are emerging in EU Member States** that enhance RES acceptance. To capitalise on these grassroots initiatives, the EU has integrated them into a more coherent and supportive policy framework.

The remainder of this chapter will specifically address this topic, with a particular focus on renewable and citizen energy communities. It **provides an overview of the concept, policy framework and practical perspective on energy communities.** It briefly describes the main activities that they can perform, the different drivers and enabling factors to engage an energy community, and the main challenges and benefits that might arise during the different phases of a renewable energy project developed in a rural area. Based on several case studies and on relevant literature review and official sources, a preliminary guide to best practices and recommendations is included for the development and success of rural energy communities.

6.1 EU POLICY FRAMEWORK TO PROMOTE RENEWABLE AND CITIZEN ENERGY COMMUNITIES

The European Commission supports a just and sustainable transition, which means ensuring that regions are not left behind in the clean energy transformation. Moreover, the Commission is committed to ensuring that rural areas benefit from the new economic opportunities from renewable energy (EC, 2021b). Renewables are well suited for decentralised[16] and local energy generation by increasing the number of small-scale energy projects to promote sustainable energy production (Caramizaru et al., 2020). The concept of **energy communities** has emerged in policy across Europe since the 1990s; more recently, the revised renewable energy directive (RED II, Directive (EU) 2018/2001)[17] and the electricity market directive (EMD, Directive (EU) 2019/944)[18] added new electricity market rules to enable Europe to meet its climate and energy targets and enable more active participation of citizen, public authorities, and small and medium-sized enterprises (SMEs) through energy communities. EU law recognises two types of energy communities[19]: the **REC** in RED II; and the **citizen energy community** in the EMD (RECAH, 2023a; Abouaiana, 2022).

With the clean energy package, particularly RED II and the EMD, the EU's energy legal framework supports renewable and citizen energy communities as new actors in the energy transition[20]. RED II defines a **renewable energy community** as a legal entity with open and voluntary participation of citizens, local authorities and SMEs located in close proximity to the communities' activities, through which they can set up and operate projects to produce, consume, store and sell renewable energy, and engage in other energy-related activities. The EMD envisages the category of **citizen energy community** to allow for the engagement of a broader variety of actors including large enterprises, and associations as members, although leaving effective control of the community with members or shareholders that are natural persons, local authorities and small enterprises. Citizen energy communities are also allowed to develop activities related to non-renewable energy and are not restricted in their activities to the neighbourhood of their energy projects. RECs can contribute to increasing public acceptance of renewable energy projects and make it easier to attract private investments in the clean energy transition. At the same time, they have the potential to provide direct benefits to citizens by increasing energy efficiency, lowering their electricity bills

16 A decentralised energy system allows for more optimal use of renewable energy and combined heat and power, reduces fossil fuel use and increases eco-efficiency (Friends of the Earth, 2020). Decentralised systems can significantly reduce the EU's fossil fuel dependency and accelerate into a future of renewable, zero-carbon, flexible, smart and localised energy (EC, 2022a).

17 *https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001*

18 *https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L0944*

19 Three directives describe the key elements of the two types of energy communities: RED II (Article 2(16)), the recast EMD (Article 2(11)) and the recast gas market directive (Article 2(70)).

20 Cohesion policy, particularly in its policy objective 2 'Greener Europe', demands that programmes comply with certain elements of RED II (e.g. 2020 targets, using them as a baseline for progress to 2030', in share of RESs) to get funding support.

and creating local job opportunities. Energy communities are very heterogeneous and can take the form of any legal entity such as an association, a cooperative, a partnership, a non-profit organisation or an SME[21]. The most common type is energy cooperatives that have been established since the introduction of renewables support schemes (Caramizaru et al., 2020).

The European Parliament provides funding to various projects that contribute to the dissemination of best practices and provide technical assistance for the development of concrete energy community initiatives across the EU. **RECAH,** as one of them, **was launched in 2022 to accelerate the development of sustainable energy community projects in European rural areas.** The main activities of RECAH are the identification of best practices and the development of guidance documents to support local authorities, businesses, farmers and citizens to set up their own rural energy communities. It also provides technical assistance and networking opportunities to the energy communities and local stakeholders. With specific technical and financial support, energy communities can develop into actors contributing to energy security in rural areas in a sustainable way, while also providing economic benefits and employment opportunities.

Renewable and citizen energy communities could contribute to the energy transition in line with the initiatives and objectives of the Green Deal. They could especially play a part in renewable energy production and supply, and the promotion of energy efficiency (RECAH, 2023a, 2023b) including building renovation[22]. Energy communities entail the engagement of local authorities, enterprises and citizens, along with the integration of key policies related to the common agricultural policy, rural development and farm modernisation. **The active participation of local authorities and citizens and the operationalisation of local development plans can help rural areas not to be left behind, fostering a just and inclusive energy transition.** Well-designed energy communities can help to facilitate access to stable and affordable prices, and ensure energy autonomy, resilience and security. They can also contribute to generating local revenue, jobs and industries. At the core of the energy communities, the energy justice concept is present in two dimensions: the fair distribution of risks and benefits, and procedural inclusiveness. It recognises different perceptions and values, and promotes equal opportunities to participate and engage in the decision-making process, so that the desired just and green energy transition does not create new disparities (Caramizaru et al., 2020).

21 *https://energy.ec.europa.eu/topics/markets-and-consumers/energy-communities_en*

22 *https://citizen-led-renovation.ec.europa.eu/index_en*

6.2 ENERGY COMMUNITIES IN NUMBERS

The number of energy community projects in Europe is continuously growing as renewable energy initiatives gain momentum. The exact number can vary over time, but there are numerous active projects across the continent. Although no accurate numbers are available, it is estimated that there are over **4 000 renewable energy cooperatives with 900 000 members in the European Union in 2023,** mainly concentrated in the north-west of Europe, and a high proportion of these involve rural communities (Koltunov et al., 2023). They take many different forms depending on the national and local contexts (ENRD, 2020; REScoop, 2013, 2014; Rescoop MECISE, 2019).

In 2021, RECAH received **47 eligible applications**[23] **for technical assistance** (RECAH, 2023c). The requests came from rural energy communities across **13 European countries.** The highest number of applications came from Spain (11), followed by Italy, Hungary and Ireland (6, 6 and 5, respectively), as well as from Greece, Latvia, Romania, France, Croatia, Poland, Belgium, Cyprus and Portugal. Twenty-five RECs from across Europe were selected from the 47 applications to get technical assistance. Of the eligible applicants, 13 rural energy communities were established during or before 2021, and the other 34 were established in 2022 or after. During the application phase, the rural energy communities indicated the main activities they intended to focus on: (1) self-consumption, (2) energy sharing, (3) energy production, (4) community network and energy efficiency, (5) the local energy system and energy generation. Investment and financial support was the most popular form of technical assistance requested, followed by legal and regulatory support, technology- and system-related advice, capacity development and knowledge transfer, and communication support. Finally, 44 out of the 47 applicants indicated that solar was one of the energy technologies that they focused on.

Recently, a **Europe-wide inventory of citizen-led energy initiatives** has been created to capture the nature and scope of collective citizen-led action in the energy transition in Europe (Wierling et al., 2023). The inventory lists over **10 000 initiatives and 16 000 production units in 29 countries,** focusing on the past 20 years, and includes past and current initiatives. The data consist of a broad range of variables, for instance initiatives operating their own units to produce renewable electricity, or the operation of charging stations for electric mobility. The inventory can be valuable to all key actors concerned with citizen engagement in the energy transition, from policymakers, through academics and advocacy organisations, to the citizen-practitioners themselves. Furthermore, by including past initiatives and mapping the 'waves' of community energy projects, the authors provide a view of contextual factors influencing the emergency, growth, disappearance and shrinking of these projects. This kind of interesting positioning can also be found in the work of De Moor (2013).

23 An application is eligible if the applying energy community itself and/or its activities are located in a rural area according to the definition of the degree of urbanisation classification. Energy communities that have activities related to the energy technology biogas (e.g. pumping) would be automatically classified as rural energy communities as well.

6.3 MAIN ACTIVITIES AND DRIVERS OF AN ENERGY COMMUNITY

6.3.1 MAIN ENERGY COMMUNITY ACTIVITIES

Energy communities can perform different activities and they are gradually taking on new roles and more complex business models, involving a wider range of energy-related services. National regulations, organisational forms and governance models for RECs are different across EU Member States, which influences the selection of the energy activities they perform (Caramizaru et al., 2020; Tounquet et al., 2020). Although a large majority of initiatives are engaged in energy generation, this section summarises many other activities that RECs might undertake.

- **Energy generation.** Communities can collectively own generation assets (e.g. solar, wind, hydro). They can offer electricity for sale, purchase or auction on electricity markets (CEER, 2019).
- **Energy supply.** The sale (and resale) of RESs to customers (electricity, wood pellets, biogas, etc.) could be allowed in certain Member States. Operating as a supplier (other than a power purchase agreement, sale on the wholesale market or to a supplier, or as part of a peer-to-peer agreement) might, however, require a supplier licence, and hence fulfilment of the linked responsibilities, including balancing responsibility.
- **Aggregation.** Communities can have a large number of customers and may also engage in aggregation activities, combining flexibility of customer loads and of generation assets. The community can hence participate, through aggregation, in several market services at the transmission system operator level (wholesale market, frequency reserve, etc.) and in the upcoming DSOs (distribution system operators) service market.
- **Energy consumption and sharing.** The energy produced by the energy community can be used and shared inside the community. This includes both consumption (individual and collective self-consumption) and local sharing among members of energy that is produced by the generating installations owned by the community. In some Member States, energy sharing cannot be done for payment, as some have classified this as supply and hence insist on a supplier licence.
- **Energy efficiency.** The energy community could promote energy efficiency and raise awareness of energy conservation.
- **Provision of energy-related services.** The community could work towards energy efficiency or energy saving (e.g. energy auditing, consumption monitoring, support with the renovation of residential buildings); flexibility, energy storage and smart grid integration; or electro-mobility (car sharing, charging stations, etc.).
- **Consultancy services.** With the growing interest in REC initiatives, an emerging business is related to consultancy services, whereby local expertise and best practices are shared with other communities, and administrative and management tools could be offered as a service.

- **Community engagement and participation.** These communities encourage the active involvement of local residents, fostering a sense of ownership and shared responsibility, as well as creating social cohesion. Within the community, education activities could be offered not only related to the energy field but also on digitalisation, sustainability, etc.

6.3.2 DRIVERS AND ENABLING FACTORS

As in many other bottom-up citizen-led initiatives, recognising the enabling factors is crucial for the success and uptake of the policy instrument, and is relevant for the identification of best practices and for the design of the regulatory and technical framework. Inevitably, such enabling factors are extremely site specific, and the heterogeneity of the various governance structures demonstrates how RECs can differ in terms of the members' individual motivations and level of engagement. Notwithstanding the complexity and heterogeneity of the REC landscape, the following dimensions can be identified as driving the success and value creation of energy communities.

- **Territorial and socioeconomic context.** In general, it has been observed that high-income countries and regions are more prone to engage in grassroots initiatives. Moreover, wealthier regions often show higher levels of education, which in turns influences cultural orientation towards and trust in collective action; awareness and perception of the environment and climate challenges; sense of belonging; and empowerment. The economic context also influences ability and willingness to invest, and the level and type of entrepreneurship.
- **Site-specific factors and infrastructures.** The availability of environmental resources (RESs and land) is of course the first territorial site-specific factor, while the technological dimension and existence of infrastructures (e.g. roads, grid connection) or the pre-existence of some form of power generation (e.g. hydroelectric) are often important favouring conditions. In addition, the availability of technical assistance services has proved to be an important driver supporting the emergence of RECs in rural areas.
- **Institutional and regulatory context.** Local institutional capacity and willingness to promote, lead or support community projects, and national policy providing a clear and supportive regulatory framework (e.g. to receive grid access without unjustified delays) are both vital enablers.
- **Energy policies and market.** Policy tools promoting renewables, such as feed-in-tariffs, tax incentives and grants, and policy measures with preferential treatment for local ownership, are all considered critical for the rise of prosumers and community ownership schemes.
- **Individuals' engagement.** Personal motivations of the community's members can cover a wide spectrum, going from prevalent environmental concern to personal economic benefit, passing through inclination towards collective social engagement and personal beliefs and values (e.g. self-sufficiency). The ambition to protect the environment and the desire to be socially, ecologically and economically self-sufficient are particularly prevalent among housing communities and bio-villages.

It is also worth noticing that each dimension has an impact, but some dimensions are more critical than others for certain energy community types. For example, energy policies and regulations together with technological readiness are more relevant to RECs that also deliver grid services, while for the more traditional RECs of co-owned energy generation the capability and willingness to invest are of higher importance.

6.4 CHALLENGES AND BENEFITS OF ENERGY COMMUNITIES IN RURAL AREAS

6.4.1 IDENTIFYING CHALLENGES IN RURAL ENERGY COMMUNITIES

Creating supportive policy frameworks, improving access to financing, fostering community engagement and providing technical support are key strategies for overcoming some of the challenges and promoting the growth of rural energy communities. A key consideration is that rural energy communities should be set up to comply with the requirements of an energy community to benefit from an enabling framework that can help overcome the following challenges.

- **Grid connection and infrastructure.** Rural areas often lack appropriate or sufficient electrical infrastructure and face challenges in connecting to the grid. The expansion of the grid infrastructure to accommodate renewable energy projects can be costly, forming a significant obstacle for rural energy communities, especially for remote ones.
- **Community engagement and acceptance.** Engaging the local community is essential for the success of rural energy communities. However, achieving strong support and addressing concerns or conflicts related to visual impact, noise, land use or perceived risks can be challenging. A lack of understanding about what a REC does and about the foreseen benefits might create local opposition to its implementation. Energy projects have direct or indirect impacts on nature and local populations.
- **Access to financing. Financing a renewable energy project can be challenging for rural energy communities.** Financing and funding are needed from the pre-planning stage through the development, investment and operation phases. The initial costs of developing renewable energy projects can be high, and financing from traditional sources may be difficult, especially for communities with limited resources or less favourable investment conditions. While good renewable projects normally face no challenges in getting financed, in some Member States energy communities face difficulties in getting access to bank loans.
- **Regulatory and policy barriers.** Complex regulations and policies, or delays in incorporating European directives into national law (and slow implementation of the resultant national laws) can hinder the development of rural energy community projects. Ambiguities in legal frameworks, lengthy permit-issuing processes and administrative burdens can create barriers to and delays in project implementation.

- **Technical considerations.** Technical challenges include optimising renewable energy generation based on local resources and choosing appropriate technologies. In addition, integrating energy storage systems and managing the complex interplay between energy supply and demand require technical expertise and careful planning.
- **Skills and knowledge gaps.** A design and feasibility study will be crucial to get finance, local permissions and some other aspects related to definition of the selected activity, business plan and the local resources available. All these aspects require specialised skills and knowledge. Rural communities may face a shortage of qualified professionals and technicians with expertise in renewable energy technologies, energy management and project development. Energy communities will have to buy the missing expertise on the market.
- **Access to information and resources.** Rural areas may have limited access to information, resources and expertise, especially regarding relevant data, technical and financing knowledge, regulations and project development processes.
- **Lack of transferability of acquired experience.** Replicating a successful rural energy community project in other communities can be challenging. Each community has unique characteristics and requires tailored approaches, which are sometimes difficult to share without clear guidance.

Several of the above challenges apply to any (small) business aiming to develop a renewable energy project or set up a flexible service offer. Most barriers should therefore be addressed in an organisation-independent manner such that they would serve all potential actors that could contribute to the energy transition.

6.4.2 CHALLENGES RELATED TO THE OPERATION OF ENERGY COMMUNITIES

Energy communities can bring many environmental, social and economic benefits to the community members and the area they operate in. However, several activities or support mechanisms may also cause unintended consequences, and for some aspects of energy communities further research is needed to fully understand how to shape energy communities optimally. These aspects include the following, among others.

- **Energy democracy.** The term ‘energy democracy’ has been extensively used to justify various energy policy measures. Although there is no consensus on the meaning of energy democracy, Szulecki and Overland (2020) have recently delivered one of the most extensive assessments of it. While energy democracy is linked to wider participation, it is not necessarily linked to the broader meaning of democracy. Based on their research, they produce three conceptual interpretations of energy democracy: (1) a process driven forwards by a popular movement; (2) an outcome of decarbonisation; and (3) a goal or ideal to which stakeholders aspire. It is important that further research be conducted to create a consensus definition of energy democracy.
- **Energy poverty.** Poverty in general and energy poverty specifically are not well understood by many. As Hanke et al. (2021) elaborate, it is not

self-evident that energy communities contribute to alleviating energy poverty. Membership fees are often an important hurdle, but a lack of understanding also means that activities and services that the communities develop may not be relevant to people in poverty. Examples of structural collaboration with poverty organisations (e.g. coöperatie GOED; see **Section 6.5.5**), or with communities by local authorities aiming to provide cheaper energy to people in need, are inspirational but remain the exception.

— **Social impact.** Evidence of the social impact of energy communities is still fragmented and the underlying narrative that they have an intrinsic social value needs to be re-evaluated (Bielig et al., 2022; van der Waal, 2020). Several projects have indeed resulted in increased social cohesion, but it is not evident that they will, and generally it reaches only a small share of the members. As part of social impact, inclusiveness is another challenge that communities often face. Attracting a diversity of members requires knowledge of these groups, and an appealing offer that would induce them to join. However, even the boards of most energy communities are predominantly male, a challenge that should be easy to address.

— **Impact on non-members.** Tariff exemptions or REC investments in public buildings and infrastructure hold a risk of a negative financial impact on non-members. Research shows that the organisational form of energy communities does not affect the operational or capital costs of the distribution or transmission grid (Vandevyvere et al., 2021; Peeters et al., 2021); hence, reducing the tariff for a few without a reduction in a cost component implies that the cost is to be paid by the non-participants. Similarly, local authorities should ensure that selecting an energy community that aims to pay its members a dividend should not result in a higher cost of the project than a project with financing or a bank loan. If not, one risks paying a benefit to a selected group that has the financial means to buy a share, at the expense of all other citizens. Finally, it must be recognised that not everyone wants to join an energy community (Rogers et al., 2008; Conradie et al., 2021).

None of these challenges should hinder the further development of renewable energy communities, although they call for a profound (upfront) dialogue to contribute to energy communities being just and inclusive.

6.4.3 SOCIAL, ECONOMIC AND ENVIRONMENTAL BENEFITS

Various benefits may come from energy communities around five capital spheres, which correspond to the five main forms of capital in rural territories: natural, physical, social, human and economic (Romero-Castro et al., 2022). Note that this classification is instrumental, as all spheres are deeply interlinked by causal relationships. From a socio-technical understanding, communities can bring the following benefits (Caramizaru et al., 2020; RECAH, 2023a).

— **Local value.** Energy communities can help implement local sustainability projects that can achieve energy independence and reduce carbon emissions and fuel poverty. Other added natural benefits can arise, such as better water or forest management and a general increase in environmental awareness, leading to other ecological and energy-saving behaviours (e.g. in mobility or building efficiency). Moreover, local energy projects can bring about the construction of new and needed infrastructures as a prerequisite for energy community development, allowing for safe and reliable interactions with the surrounding distribution system (e.g. smart meters, voltage control, enforced grid lines).

— **Community empowerment and education.** Rural energy communities empower citizens to actively take part in the energy transition, fostering a sense of community and local identity. This could reinforce social cohesion by developing joint actions to combat climate change alongside municipalities and local authorities. Connecting people and communities through a common bond, building a sense of place and belonging, encouraging self-engagement, promoting fairness through the inclusion of vulnerable groups and reducing energy poverty by means of renewable energy technology could be part of the social benefits of a REC. Investments in education and training, as an opportunity derived from RECs, can promote social innovation and change in the population structures, reversing trends of depopulation and ageing.

— **Economic development.** These initiatives can bring local economic growth by creating jobs, attracting investments and keeping revenue within the community. RECs have the potential to create local job opportunities by stimulating the local renewable energy-related business sector, promoting local demand for new skills and quality of employment, and avoiding the outflow of financial resources from the region (Kunze and Becker, 2014). In terms of energy provision, members of an energy community can benefit from financial gains either from lower energy bills, because of reduced grid fees and energy costs, or from direct revenues.

— **Energy citizenship.** Citizens have control over energy investments by becoming co-owners of renewables installations, usually through the principle of one member, one vote. Participation in renewables ownership and decision-making can be either direct – in which case members approve decisions in assembly meetings and decide how the surplus is distributed (Hanna, 2017) – or indirect, through a board of directors. It must be noted that the use of digital tools and distance voting could be ways to increase participation in decisions.

— **Generating financial returns for the community.** Community assets (wind turbines, solar panels) are used to generate profits locally, within the community. Members have local control over financial resources and profit sharing. Surpluses can be reinvested in community benefit funds and other activities. Co-investments can also help create local jobs and generate stable returns for investors.

— **Environmental impact.** These energy communities can contribute to the preservation of the environment and the mitigation of climate change in various ways. Rural energy communities reduce dependency on fossil fuels by generating clean, renewable energy locally. This enhances energy security and reduces GHG emissions.

6.5 ENERGY COMMUNITIES FROM THE PERSPECTIVE OF PRACTICE AND SUCCESS

Six selected recent case studies demonstrate the successful implementation of renewable energy projects in rural areas, driven by community engagement, collaboration and innovative financing models. They highlight the potential for rural energy communities to achieve energy self-sufficiency, economic benefits and environmental sustainability (RECAH, 2023b; Legambiente, 2021; Blauw, 2023).

6.5.1 ENERGY COMMUNITY OF ÉOLIENNE CITOYENNE DE CHAMOLE (FRANCE)

The Éolienne citoyenne de Chamole is a rural energy community that originated in 2007 and had evolved into a citizen project by 2015. The commune has around **170 inhabitants and is compliant with the EU definition of energy communities.** The main motivation behind the construction of a **wind farm** was an awareness of the need for energy transition in France, rather than financial considerations. An association called Vents du Grimont was created in 2011, with the goal of informing the inhabitants of the commune about the energy community and of bringing them on board.

The project consists of a single wind turbine in an installation of six turbines in total. These turbines have a nominal power of 3 MW each. Counting the six turbines, this makes the total production of the farm 18 MW. For it to function, the wind speed must reach 12.5 m/s, or 45 km/h. The annual production expected of a turbine of this type is the quantity of electricity consumed a year by more than 2 000 households, totalling 6 000 inhabitants. Therefore, the entirety of the farm covers the needs of 12 000 households of 36 000 inhabitants. **The first year of exploitation of the citizen-owned turbine was 2019, when the output exceeded 7 000 MWh.**

The Chamole wind farm involves five bodies; it is jointly owned by the local commune, a purpose-made citizen cooperative, a citizen territorial tool (which supports collectives and finances the development of public and citizen projects on renewable energy production), a regional company and a national fund. The cooperative brings together more than 600 citizens of all ages through over 40 investment clubs that contributed to buying the turbine along with the other bodies involved.

Authorisation for the wind farm in Chamole was secured in 2015 following independent and in-depth preliminary studies. These included studies on the natural environment and wildlife (such as protected species of woodpeckers and bats), studies on the local heritage and landscape (alongside acoustic investigations) and studies on the potential for wind production. Besides environmental aspects, the commune of Chamole, as the public owner, can expect **an income of EUR 550 000 over 15 years.** A minimum of 60 % of any profits remains in the cooperative, to go towards the development of other projects. While the inhabitants do not receive a direct reduction in the energy tariff, they do receive aid paid to them to reduce their energy bills, as well as to foster energy cooperatives. From the social perspective, there is also a great focus on promoting the wind farm as an educational tool to promote the benefits of renewable energy. There is an emphasis on inclusive participation in running the cooperative, based on a principle of solidarity and social utility, with democratic and participatory management methods. This principle also puts at the centre the local energy poverty problem and finding ways to solve it. Owing to the awareness of a negative perception of wind turbines in France, educational visits, extensive communication and training sessions are also organised to inform citizens about the scientifically proven impacts of wind turbines.

Finally, this project involves much analysis of drivers, financial, innovative and organisational factors, and other considerations. Its initial consideration of **cultural, social, environmental, political and infrastructural factors enabled the success of the rural energy community.** As a citizen-driven REC is an innovative project, technological complexities of setting up a wind farm and financial barriers generally need to be addressed when setting one up. It is noteworthy that there was no previously existing infrastructure for the wind farm in the commune, which was another key point in the initial phase.

6.5.2 RURAL ENERGY COMMUNITY OF VIURE DEL L'AIRE (SPAIN)

Viure del l'aire – Eolpop is a REC located in the municipality of Pujalt, in Anoia county in Catalonia, Spain. The municipality has a population of 204, being a rural area with a population density of 6.5 inhabitants per square kilometre. In 2009, the community started a lengthy administrative process before finally **installing a wind turbine in 2017.** The community was established to involve local people in the collective ownership of the **energy transition, promote renewable energy and drive forward energy democratisation,** as well as to address the need to **tackle energy poverty, air pollution and climate change.** The municipality of Pujalt was chosen for the site of the wind turbine owing to its optimal wind conditions and easy connections to the grid.

Overcoming bureaucratic challenges to obtain the building permit took 4 years. As part of this process, the community had environmental impact studies conducted, including assessing impacts on noise, the landscape and cultural heritage. The community also had challenges in finding a wind turbine, as most companies do not sell individual turbines, and in connecting the turbine to the grid. The turbine began operating in March 2018 as the first community-owned wind turbine in Spain and in southern Europe.

Viure del l'aire – Eolpop is made up of 595 participants, including individuals and families, as well as approximately 30 companies and other organisations. Organisations, including small businesses, were welcome to join the community from the outset. The Pujalt Town Council has strongly supported the project since its inception, facilitating arrangements with the landowner and the electricity company. It collects the corresponding taxes and duties, and benefits from the positive promotion of the municipality's role in the energy transition.

The turbine operates for 2 405 hours each year and generates 5 653 MWh/year, which is estimated by the community to be the **equivalent of the energy demand of 2 000 families, saving an estimated 6 000 tonnes of CO_2 per year.** The offsetting of emissions therefore benefits the community in terms of reducing contributions to climate change and pollution. The income made from the sale of generated electricity to the distribution company is returned proportionally according to the investment made by each member, based on the market sale price. At the end of 2021, a return of 20 % was made, totalling EUR 569 932. Viure del l'aire energy community had a high level of beneficial social impacts, being a pioneering project emphasising a participatory nature to **engage local citizens to actively take ownership of the energy transition.**

Contextual, financial, innovative and organisational factors were taken into consideration for the successful establishment of the REC. The success can certainly be attributed to the key driving factor of the strong movements in Catalonia that have been advocating renewable energy, owing to an awareness of the pressing need to tackle pollution, climate change and energy poverty, and in order to bring the means of energy generation into the ownership of citizens and drive forward a decarbonised energy system. Besides this, the local government implications and an efficient financial cost–benefit analysis also played a strong role at the beginning and during the project.

6.5.3 ANGITOLA AND BICCARI RENEWABLE ENERGY COMMUNITIES (ITALY)

These two **energy communities in Italy promote the use of solar PV installations** as a form of active participation in renewable energy projects, saving and production of energy, and environmental education and awareness.

Filadelfia is a Calabrian municipality of about **5 000 inhabitants** in the province of Vibo. The rural energy community is in one of the poorest areas of Italy, the Angitola area. The objective of the REC project is to promote protection of the environment, energy saving, the diffusion of renewable energy sources, production of energy in the area and the energy self-sufficiency of the citizen members (Legambiente, 2021; RECAH, 2023a). The project fits into the larger context of alleviating energy poverty by spreading energy communities and the self-consumption of energy generated. It consists of **five solar PV installations, with a capacity of 200 kW** each and a total peak installed capacity of 1 000 kW, **on the roofs of residential buildings and car parks.** The objective is for the energy produced to cover 50 % of the requirements of community members, including providing energy to electric vehicle charging stations.

The second case is in the municipality of **Biccari, a village of about 2 700 inhabitants in the province of Foggia,** in the Apulia region of southern Italy. Today, the municipality already boasts great attention to sustainability, with over **200 kW of PV panels on public buildings** and public lighting using LED lamps and **PV streetlamps located in rural areas and peripheral districts.** Today, the administration intends to continue along this path thanks to the establishment of a REC with the support and collaboration of the energy cooperative ènostra[24]. The project is proposed as a pilot to study social impacts and environmental, as well as economic, development in the territory. In particular, the aim is to achieve savings on energy bills for the participants, while stimulating citizen participation and disseminating environmental education practices. Thanks to its collaboration with Arca Capitanata (the regional public housing agency), the project promotes the installation of other PV systems on housing properties and the legal constitution of energy communities including all citizens involved, which should be about 70 households each.

6.5.4 ENERGY COMMUNITY EOLIENNES EN PAYS DE VILAINE (FRANCE)

Created in 2003, in the region of Pays de Vilaine (France), **the Eoliennes en Pays de Vilaine (EPV) association** is focused on producing renewable energy locally and reducing energy consumption. Its guiding principles over the last 20 years have been increasing local energy production and helping reduce energy consumption, while contributing to local income and job creation.

The project began with a **wind turbine project based around a few villages in the rural area** of Redon Agglomération, with around 80 000 inhabitants. It was the first project in France co-financed and managed by local citizens (EUR 42 million of investment). Financing proved challenging from the start, as banks were reluctant to help, but regional and local authorities were positive about the initiative and lent their support.

Currently three **wind farms with 13 turbines in total** (2 MW each) produce about 25 % of the region's electricity demand. Two new projects are currently under development, as well as **solar energy projects.** Local volunteer members, representing stakeholders including citizens, local authorities, municipalities, the citizen investment fund for renewable energy and local third sector companies, form independent cooperatives that oversee the installation and management of the production units. The energy produced feeds into the national grid, and a feed-in tariff has been guaranteed through contracts with EDF or Enercoop, a provider of 100 % renewable energy, for 15 years.

EPV organises regular activities, including workshops, information meetings, school class activities and other interactive events, for citizens who have invested in or live near the various production units. The wind farm cooperatives finance the salaries of the staff who deliver these activities. The cooperatives also finance activities such as a car-sharing scheme, group purchasing of e-bikes, and installation and maintenance of solar panels for the local community. Two regional networks have been created, supporting about 80 citizen and community projects in renewable energy. EPV has also co-created a national network (Energie Partagée).

EPV's **business model is sustainable,** and its success is based on a conservative estimate of the production potential (wind) as well as a guaranteed feed-in tariff

24 *https://www.enostra.it*

for 15 years. Dividends are paid to the investors from 5 years after production started, and the business plan allows for the creation of reserves to reimburse citizen investments and to cover the costs of the decommissioning of the wind farms at the end of their life. Frequent public meetings and monitoring commissions with participation by local inhabitants during the development and operational phase allow it to develop citizen engagement and improve general acceptance of new projects. EPV's experience demonstrates that citizen engagement can facilitate renewable energy projects (particularly wind farms), as it thoroughly addresses concerns expressed by the inhabitants living near the proposed future installations.

Best practices include dialogue, contact and communication with people who will be affected by new projects. Increasing the dissemination of information and building trust between citizens and project owners create a positive attitude to participation, investment and local authority acceptance. Engagement of local citizens increases credibility and is a key factor in project success. This project is respectful of the **environment and its inhabitants,** with transparent and **socially responsible governance.**

6.5.5 COÖPERATIE GOED (NETHERLANDS)

Coöperatie GOED is an **energy community in the north of the Netherlands, active in the area of Groningen.** It started in 2019 under a different name (Zon op alle daken, meaning Sun on All Roofs), with an invitation from the deputy major of the city of Groningen to develop rooftop solar energy. After a EUR 50 000 subsidy and lengthy preparation, the first **400 PV panels were installed on the roofs of two housing cooperatives and two care institutions in 2021.** The first models used by the cooperative applied the *Postcoderegeling,* a rather bureaucratic system enabling co-investment in renewable energy generation assets in its region.

Following the change of the *Postcoderegeling* into the *Subsidieregeling Coöperatieve Energieopwekking* (SCE), the cooperative continued with its investment projects. As the PV projects also included a **ground-mounted PV set-up,** the name changed to coöperatie GOED (which stands for *groen opwekken én delen,* 'generating and sharing green energy'). The approach is different from what other cooperatives and energy communities do. Projects are developed by the commercial company Robin Doet. This company works 50 % for public authorities and the like, using a normal commercial tariff. The remaining 50 % of the time, the team works on developing projects for the cooperative.

Payment for these projects is based on a rate of EUR 0.05/W_p on projects that are effectively launched. The whole, and risk-prone, preparatory phase is covered by this rate, which leads to projects with a low upfront cost. The financing of these projects is generally based on unpaid participation of members in the vicinity of the project, as the SCE requires one connected member per 5 000 W_p. Members of coöperatie GOED do not pay a membership fee and normally do not participate financially in a PV project unless the owner of the roof or land specifically requests it. Nearly all projects start with an owner contacting the cooperative. The local community is engaged and jointly decides what local good cause it would like to support. This could be a football club that wants to be able to offer specific tariffs for vulnerable households, or an organisation working with people in poverty. Robin Hoet then starts developing the technical and financial aspects of the project, aiming for as low as possible financing cost **to enable a maximum profit to be given to the selected project or organisation.** As soon as the project is ready for implementation, it moves from Robin Hoet to coöperatie GOED. The SCE subsidy ensures a guaranteed minimum price for injected energy, which is provided as a top-up of the commercial injection price and is only allocated when injection prices are too low. Because prices on the market are high in 2023, no SCE payment is currently provided. The SCE subsidy is hence a de-risking measure that aims to increase investment appetite.

Today, **the cooperative has 0.8 MW installed on roofs and another 0.4 MW of roof-mounted PV in development,** and is currently implementing a solar park of 1.6 MW. There are 500 members, who can participate physically or online in the annual meeting but can also vote by post. It is hence a renewable energy community that is truly participatory and removes all barriers to participation. Inclusiveness is further realised in the use of the profits of each project.

6.6 BEST PRACTICES OF ENERGY COMMUNITIES

Best practices can guide the development and success of rural energy communities. Not all cases described are effectively replicable, generally because of the specific financial support received or the sandbox environment they were able to develop in, but even such cases provide valuable insights (Peeters et al., 2023). Energy projects inspired by best practices will have to be adapted to the specific context, resources and needs of each community. Learning from the analysed case studies and some other sources of information (REScoop, 2013, 2014; RECAH, 2023a, 2023b; Friends of the Earth et al., 2020), a (non-exhaustive) selection of best practices has been identified to provide valuable insights for the implementation of renewable energy projects in rural areas. They have been grouped by thematic areas as follows.

1. **Community engagement and participation**
   - → Communicate effectively to involve rural residents in energy projects by building widespread support. At the same time, engage as much as possible with citizens of all ages and backgrounds, as their enthusiastic participation can act as a multiplier.
   - → Foster inclusive and transparent decision-making processes that involve the local community from the early stages of project development, taking advantage of existing movements in their regions that may trigger involvement of citizens (environment, energy poverty and independence, etc.).
   - → Organise regular community meetings, workshops and information sessions to educate residents about renewable energy and its benefits. Local leaders will be best placed to mobilise their communities, using their local expertise to develop effective strategies.

- → Encourage active participation and create opportunities for residents to contribute their ideas, concerns and expertise.
- → Start, if possible, with small projects that by their success draw media attention and create goodwill in the community towards quickly creating more ambitious projects.
- → Respect those who do not (yet) want to participate.

2. **Collaboration and partnerships**

- → Collaborate with local authorities, energy agencies and other relevant stakeholders to explore legal and regulatory frameworks, secure permits and access funding opportunities. Local leaders can build close relationships with the local authorities and promote the advantages of local energy production.
- → Establish partnerships with other energy communities, industry experts, research institutions and non-profit organisations to leverage their knowledge, resources and experience.
- → Get and stay in contact with other rural energy communities that can provide support and share experiences, lessons learned and best practices in the set-up and development phase.
- → Work with non-profit organisations that have expertise in energy poverty and in minority groups or other vulnerable consumers.
- → Collaborate with local municipalities to bring valuable benefits to renewable energy initiatives in rural areas, such as facilitating administrative procedures, providing local expertise or other resources (e.g. site location).

3. **Financing and business models**

- → Explore various financing options, including public grants, crowdfunding, cooperative models and private investments.
- → Develop a robust financial plan to cover project costs, ensuring financial sustainability and long-term viability.
- → Use business structures with which the local community, in particular SMEs, are familiar. Engage local SMEs in the operation of the energy community to ensure expertise and entrepreneurship. Technicians as well as businesspeople are needed to operate a rural energy community.
- → Develop innovative business models such as community ownership, whereby local residents have a stake in the renewable energy projects, ensuring local benefits and reinvestment of profits.
- → Think outside the box on services that could be delivered to various stakeholders, such as one-stop shops for renovation by ensuring the engagement of qualified experts.
- → Consider models requiring very limited or no payment from members, enabling everyone to participate.
- → Engage in energy trading and explore revenue streams beyond energy production, such as energy services, tourism or agriculture.

4. **Technical considerations**

→ Perform detailed assessments of the renewable energy potential in the area, considering local resources. Analyse technical, economic and environmental factors to determine the most suitable technologies and project scale.

→ Embrace technological advancements and monitor the market for cost-effective and efficient solutions.

→ Assess the potential of innovative technologies such as demand-side management, car charging or energy storage systems, to optimise the use of renewable energy and enhance energy resilience.

→ Ensure that the people driving the energy technology developments in the community have prior experience in the energy sector so that they can understand the complex contexts of the sector and are able to manage operations and project phases.

5. **Education and awareness**

→ Promote capacity building and awareness campaigns to educate and inform the community about the importance of renewable energy and energy efficiency.

→ Provide education and training for members and non-members alike so they can contribute effectively to the development of their communities. Participants can inform the public about the nature and benefits of cooperation.

→ Offer training programmes and workshops to empower community members with skills related to renewable energy development, maintenance and energy management.

→ Establish partnerships with local educational institutions to incorporate renewable energy topics into curricula and foster future generations' interest in sustainable energy.

→ Encourage open dialogue, address concerns and build consensus to ensure project support and ownership. Communication and education also create a sense of local pride in and ownership of renewable energy and the energy transition.

6. **Environmental and social considerations**

→ Conduct thorough environmental impact assessments and ensure compliance with environmental regulations.

→ Prioritise the protection of natural habitats, wildlife and cultural heritage in project planning and implementation.

→ Consider social aspects, such as fair sharing of benefits, job creation and addressing potential impacts on local communities, including noise, visual aesthetics or land-use conflicts.

→ Perform comprehensive studies on the implications and benefits of an energy community to help to protect the environment and counter misinformation.

7. **Monitoring, evaluation and transferring**

- → Implement robust monitoring systems to track the (financial) health of the energy community and evaluate the performance of renewable energy projects, including energy production, emissions reduction and cost-effectiveness.
- → Evaluate regularly the social, economic and environmental impacts of the projects, seeking feedback from the community and adapting strategies accordingly.
- → Share project results and lessons learned with other communities and stakeholders, to contribute to knowledge sharing and replication.
- → Document good and poorer project experiences, lessons learned and success stories, to facilitate knowledge sharing. Share insights with other rural communities, policymakers and stakeholders to inspire replication and scaling up of similar projects. Foster a supportive community of practice to accelerate the growth and replication of rural energy initiatives.

8. **Local, regional and national aspects**

- → Seize the support and knowledge that wider regional and national entities can bring about useful information and sources of funding. Explore various funding sources with financial institutions.
- → Simplify and streamline the administrative processes for the establishment of RECs. Slow bureaucratic procedures in the public administration pose a major barrier. Work closely with authorities to expedite permitting, licensing and grid connection processes, reducing administrative burdens and delays.
- → Take advantage of the support of regional organisations to help in providing regional financial and technical assistance.

7 Conclusions

As the EU strives to become the first carbon-neutral economy by 2050, a dramatic increase of green energy production is needed in the coming decades. In this report we have assessed **the current and potential production of renewable electricity in the EU at a high level of geographical granularity, focusing on the role of rural areas as key actors in the energy transition.** The opportunities for rural areas to benefit from renewable energy sources, with a particular focus on Energy Communities, have also been presented.

The report focuses on the three technologies that are currently delivering the highest shares of renewable energy in the EU: **solar photovoltaics, onshore wind and hydropower.** Numerous sources of geolocalised data, characteristics of existing plants, land uses and natural resources have been integrated to determine the current and potential production from these RESs. To our knowledge, this is the **first high-resolution analysis** of the status and outlook of solar PV, onshore wind and hydropower energy in the EU.

To ensure a sustainable roll-out of new infrastructures for renewable energy, suitable areas for their development have been identified after considering strict agricultural, environmental and biodiversity constraints, so that existing resources are preserved throughout the entire energy transition.

RURAL AREAS: the EU's powerhouse – today and in the future

Our assessment shows that, up to the first quarter of 2023, the EU was producing 375 TWh/year of electricity from hydropower, 350 TWh/year from onshore wind and 250 TWh/year from solar PV. The electricity production from these three sources, altogether, is equivalent to 38 % of the total electricity consumed in the EU in 2021, and to 9 % of the total energy consumed in the EU in the same year. **72 % of the electricity from these renewable sources is generated in rural areas,** with towns and suburbs contributing 22 % and cities 6 %.

The EU's untapped theoretical potential from RES (i.e. the maximum additional electricity production under the assumptions of this analysis) **could reach 12 500 TWh/year, with 11 000 TWh/year stemming from solar PV, 1 400 TWh/year from onshore wind and 130 TWh/year from hydropower.** This should be regarded as a theoretical limit derived from the sum of the maximum potential of all technologies. Considering that overlapping suitable areas would be used for either ground-mounted PV or onshore wind installations only, the real untapped potential would be lower, but still above 11 200 TWh/year, which is achieved by allocating contested land to the most productive technology.

Combining the current production of electricity from these renewable sources with their untapped potential, t**he EU could reach production of 13 000 TWh/year, more than five times the electricity it consumed in 2021, and even more than the total energy consumption of the EU in the same year** (11 257 TWh). Offshore wind, agri-PV, new hydropower plants and reservoirs, and other RESs that are not part of this study are also expected to further increase our estimated technical potential.

The untapped potential from solar PV, onshore wind and hydropower is predominantly located in rural areas (78 %), followed by towns and suburbs (18 %) and cities (3.5 %). Therefore, rural areas are and will continue to be key actors in the generation of renewable energy, a role that can be further strengthened in the future, as EU territories are increasingly asked to contribute towards the energy transition.

SUSTAINABLE ROLL-OUT OF RENEWABLES: preserving biodiversity and agriculture

The deployment of renewable installations often requires the use of land resources. This is especially the case for ground-mounted photovoltaic systems and for onshore wind farms. To ensure a sustainable green transition, **the agricultural and environmental resources of rural areas need to be preserved throughout the entire process of RES development.** Following these considerations, the European Commission's guidelines recommend excluding biodiversity-rich areas and natural reserves as suitable sites for RES deployment, favouring instead built-up and artificial surfaces and degraded land with limited agricultural prospects. In line with these recommendations, we have excluded Natura 2 000 sites, key biodiversity and bird areas and high-value natural farms – among other protected areas – in our assessment to identify suitable land for land-intensive RES deployment. Agricultural land has been deemed unsuitable for RES deployment. Only arable land, mixed crops and livestock systems that are already in an advanced state of erosion, and showing low productivity and high risk of abandonment, have been selected as suitable.

When considering all these factors, our analysis, performed at 100 m resolution, shows that 93 000 km² of EU land may be available for ground-mounted PV systems (2.3 % of the EU's surface), and 110 000 km² (2.8 %) for onshore wind farms. Given that a share of the available land is suitable for both wind and ground-mounted PV installations, **the total suitable available land for RES deployment amounts to 3.4 % of the EU's area.** Remarkably, **around 80 % of this land is in the EU's rural areas**.

SOLAR PHOTOVOLTAICS: the EU's fastest-growing source

Plummeting solar panel prices have driven large increases in capacity in recent years. In 2022, the EU registered the highest-ever increase in solar PV capacity, 60 % over 2021 (EC, 2023b). Our estimates for 2023 yield **current production of solar PV in the EU of 250 TWh/year,** with Germany currently delivering 65 TWh/year, followed by Spain and Italy, both producing more than 35 TWh/year.

The high density of installed capacity per unit area, together with its ability to exploit built-up areas (rooftops) as well as the ground, makes **solar energy the source offering the largest untapped potential in the EU, which could reach 11 000 TWh/year.** The EU's untapped solar PV potential is about 10 times that of onshore wind and about 100 times that of hydropower.

Ground-mounted PV: leading source of potential in rural areas

Ground-mounted PV systems are the leading source of untapped potential in the EU as a whole, and in rural areas. Using around 2.2 % of its total land for new installations, **the EU could produce an additional 10 400 TWh/year of electricity from ground-mounted PV, 85 % of it in rural areas.**

At the Member State level, Spain and Romania, together, hold 48 % of the EU's total untapped ground-mounted PV potential. Ground-mounted PV is the main source of untapped potential in 51 % of the EU's municipalities.

Rooftop PV: opportunities for cities and land-scarce areas

The installation of PV panels on rooftops is a unique opportunity to generate renewable energy in built-up areas. It becomes especially relevant in highly urbanised areas, as well as in municipalities where suitable areas for land-intensive installations are small (for instance, in mountainous regions with high slopes and large protected areas). Using 26 % of the EU's built-up areas, which represents 0.17 % of its total surface, rooftop PV could produce an additional 730 TWh/year of electricity, distributed similarly among rural areas (36 %), towns and suburbs (37 %) and cities (27 %). **Rooftop PV is the most important source of RES potential in 46 % of the EU's municipalities,** with particular significance in Malta, Belgium and the Netherlands, where it is the leading source of untapped RES potential in more than 85 % of the countries' municipalities.

ONSHORE WIND: power for northern Europe

Electricity generation from onshore wind has been steadily growing in the EU during the last two decades. According to this analysis, as of the first quarter of 2023, **onshore wind accounted for a production of 350 TWh/year,** with Germany, Spain and France leading EU production (respectively, 93, 60 and 39 TWh/year).

Using 2.3 % of the EU's land, new onshore wind farms could provide an additional 1 400 TWh/year, corresponding to 53 % of the EU's electricity consumption in 2021. **Rural areas hold 85 % of the untapped potential for onshore wind,** as well as 83 % of the suitable land available for new installations.

Onshore wind can be particularly important for municipalities in northern Europe. In large areas of Finland, Sweden and Ireland, mainly in northern regions of these countries, onshore wind is the leading source of untapped RES potential. In Estonia, Latvia and Lithuania, more than 80 % of the municipalities hold untapped wind potential that is similar in magnitude to their ground-mounted PV potential. These areas, which are also significant in Denmark and Poland, can benefit from the combination of onshore wind and ground-mounted PV during the energy transition.

HYDROPOWER: revamping reservoirs through modernisation and floating PV

With the construction of large hydropower plants being discouraged on the grounds of environmental concerns and large financial investments required, the EU's capacity to generate electricity with its hydrological resources is assumed to be almost fully exploited, or not environmentally viable. However, we have found that **the current hydro production of 375 TWh/year could increase by 133 TWh/year by incorporating alternative technologies.** The largest share (61 %) of this untapped potential can be achieved by covering 10 % of power-plant reservoirs with floating PV systems. The remaining untapped potential can be obtained from the modernisation of existing power plants (35 %) and from small hydropower solutions such as the (re)powering of watermills, water distribution networks and waste-water treatment plants (4 %).

Rural areas currently produce 75 % of the EU's hydropower electricity and hold 51 % of the untapped potential. Even though at the EU scale the untapped potential of hydropower is small compared with onshore wind and solar, it remains the leading source of RES potential in 1.4 % of the EU's municipalities, located predominantly in mountainous areas, where hydrological resources are richer and can be further exploited. Despite its limited contribution compared with wind and solar, hydropower is a reliable, flexible and dispatchable source of energy generation, which can play an essential role in combination with more volatile or intermittent RESs.

ENERGY COMMUNITIES for a just and inclusive energy transition

Rural Energy Communities provide unique opportunities for rural areas to retain the value of their natural resources and benefit from the green energy transition through the production of renewable energy. These communities are joint projects involving a variety of stakeholders such as citizens, farmers, agricultural businesses and local authorities, and are currently supported by the European Commission through various initiatives including the Rural Energy Community Advisory Hub and the Energy Communities Repository.

The establishment of an Energy Community involves the coming together of citizens and local actors to set up a renewable energy project (for example, one or several wind turbines), which is then (at least partially) owned by the Energy Community itself. The revenue generated by the electricity produced by RES projects can be then administered in different ways: for instance, it can be used to return citizen's investments (and generate profits afterwards), reduce residents' and stakeholders' energy bills, or be reinvested in the community to further develop the project. Besides retaining RES revenue at the local level, **Energy Communities in rural areas can also attract investments, increase local demand for new skills and improve the quality of employment.** Moreover, they can give rise to remarkable social benefits, driving community empowerment and education, and promoting democratic and inclusive practices. They provide a positive environmental impact as well, reducing greenhouse gas emissions and helping mitigate climate change.

From the analysis of case studies of different Renewable Energy Communities, in this work we have listed **guidelines for best practices,** with the aim of providing inspiring examples and guidance to local communities aiming to set up their own projects. These include recommendations to foster community engagement and participation, establish collaborations and partnerships, set up business models, promote education and awareness, and ensure environmental protection, among others.

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List of abbreviations

CF	Capacity factor
DEGURBA	Degree of urbanisation
EC	European Commission
EMD	Electricity market directive (Directive (EU) 2019/944)
EPV	Eoliennes en Pays de Vilaine
EU-DEM	European digital elevation model
FPV	Floating photovoltaic
GHG	Greenhouse gas
GW	Gigawatt
ha	Hectare
HNV	High nature value
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IHA	International Hydropower Association
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre
LUISA	Land Use-based Integrated Sustainability Assessment
MS	Member states
MW	Megawatt
NUTS	Nomenclature of territorial units for statistics
PV	Photovoltaics
REC	Renewable energy community
RECAH	Rural Energy Community Advisory Hub
RED II	Revised renewable energy directive (Directive (EU) 2018/2001)
RES	Renewable energy source
RUSLE	Revised universal soil loss equation
SCE	Subsidieregeling Coöperatieve Energieopwekking
SHP	Small-scale hydropower
SMEs	Small and medium-sized enterprises
WDN	Water distribution network
WWTP	Wastewater treatment plant

MEMBER STATES OF THE EUROPEAN UNION

AT	Austria
BE	Belgium
BG	Bulgaria
CZ	Czechia
CY	Cyprus
DE	Germany
DK	Denmark
EE	Estonia
EL	Greece
ES	Spain
FI	Finland
FR	France
HR	Croatia
HU	Hungary
IE	Ireland
IT	Italy
LT	Lithuania
LU	Luxembourg
LV	Latvia
MT	Malta
NL	Netherlands
PL	Poland
PT	Portugal
RO	Romania
SE	Sweden
SI	Slovenia
SK	Slovakia

Glossary

Agricultural area describes the area already used for farming, or that could be brought back into cultivation using the resources normally available on an agricultural holding. It includes arable land, permanent grassland, permanent crops, kitchen gardens, unutilised agricultural areas and special holding areas (Eurostat, 2023a). Agricultural land used in the analysis can be for either (1) production of food, feed and fibre (arable land, mixed crops and livestock, permanent crops, and livestock production) or (2) production of bioenergy crops. For the spatial modelling of dedicated energy crops, elements such as land demand, availability and suitability were defined, as well as a policy-based categorisation for sustainable cultivation (Jacobs-Crisioni et al., 2017; Perpiña Castillo et al., 2015).

Agricultural land abandonment, as defined by the LUISA territorial modelling platform, is when land that was previously used for crop or pasture production has no more farming functions, which basically means a total cessation of agricultural activities. It is constructed through the aggregation of a set of factors classified in the following three groups: (1) biophysical land suitability, (2) farm structure and economic agricultural viability and (3) population and regional context. These factors are combined to build a European map describing risk of agricultural land abandonment at the grid level (100 m spatial resolution) (Perpiña Castillo et al., 2020).

Built-up areas comprise residential land, industrial land, quarries, pits and mines, commercial land, land used by public services, land of mixed use, land used for transport and communications, or for technical infrastructure, and recreational and other open land (Eurostat, 2023b). In this analysis, the concept of built-up areas is similar to that of artificial lands (i.e. buildings and roads).

Capacity factor is a unitless ratio of the electrical energy produced by a generating unit in the period considered to the electrical energy that could have been produced at continuous full power operation during the same period, normally measured over a year. It is a direct measure of the efficiency of a power generation system.

Current estimates of installed capacities and electricity production refer to the first quarter of 2023 for which recent geolocalised solar and wind installations are included in both data sources.

Degree of urbanisation is defined in **Box 1.**

Energy consumption (primary) measures the total energy demand of a country. It covers consumption by the energy sector itself, losses during transformation and distribution of energy, and the final consumption by end users (Eurostat, 2023b).

The **'Fit for 55' policy package** includes three core policy scenarios built upon the climate target plan to serve as common tools for analysis across the impact assessments supporting the 'Delivering the European Green Deal' policy initiatives. These model-based projections represent an energy system and economy-wide GHG emissions balance compatible with at least 55 % GHG reductions by 2030 in three representative policy mixes. The core policy scenarios were produced with the same modelling suite as the one used for the EU reference scenario 2020, ensuring consistency with the baseline situation of the policy initiatives as well as consistency of treatment for all Member States (European Commission, 2021a).

Gigawatt-hours (GWh) is a unit of energy representing 1 billion watt-hours and is equivalent to 1 million kilowatt-hours. Gigawatt-hours are often used as a measure of the output of large electricity power stations (Eurostat, 2023b).

Go-to areas for the production of energy from wind and solar utility-scale PV plants are specific locations, whether on land or sea, particularly suitable for the installation of plants to produce energy from renewable sources, where the deployment of a specific type of renewable energy is not expected to have significant environmental impacts. They give priority to artificial and built surfaces, such as rooftops, transport infrastructure areas, parking areas, waste sites, industrial sites and mines, and to degraded land not usable for agriculture. Conversely, they exclude Natura 2000 sites, nature parks and reserves, and identified bird migratory routes (European Commission, 2022c). The Energy and Industry Geography Lab, from May 2022, provides an attractive visual representation of consolidated information on a wide range of relevant energy and environmental factors (JRC, 2023).

Gross national electricity consumption includes the total gross national electricity generation from all fuels (including auto-production), plus electricity imports, minus exports (Eurostat, 2023b).

Gross electricity generation or **gross electricity production** refers to the process of producing electrical energy. It is the total amount of electrical energy produced by transforming other forms of energy, for example nuclear or wind power. It is commonly expressed in GWh (Eurostat, 2023b).

Ground-mounted PV systems are traditional solar panels that are installed on frames or poles attached to the ground. Ground-mounted PV systems are generally large, utility-scale PV power stations that convert sunlight into electricity. There are ground mounts at the residential and commercial levels, but the systems are smaller and the number of PV modules per column may be fewer. For the ground-mounted systems, the PV system mounting configuration was assumed to be free-standing racks facing south at an inclination angle of 20° (40° for locations north of 60° N). The area required was calculated assuming 5.5 m² per kWp of PV modules, that is, 18.2 % efficiency. The distance between the module racks was calculated to avoid one rack shadowing other modules, especially in winter, with balance-of-system losses of 10 % (Bódis et al., 2019a). For this analysis, commercial and industrial PV systems with capacities between 20 kW and 1 MW are included in the category of ground-mounted systems.

High nature value (HNV) farmlands tie biodiversity together with the continuation of farming on certain types of land and the maintenance of specific farming systems. They comprise areas in Europe where agriculture is a major (usually the dominant) land use and where that agriculture supports, or is associated with, a high level of species and habitat diversity and/or the presence of species of European conservation concern (EEA, 2022).

Installed capacity, sometimes termed peak installed capacity or rated capacity, describes the maximum capacity at which a system is designed to run. For example, wind turbines use installed capacity to describe how much electricity may be generated by a turbine in optimal wind conditions: how many watts of electricity the turbine hardware can possibly produce.

Land cover refers to the observed (bio)physical cover of the Earth’s surface (Eurostat, 2023b).

Land use refers to the socioeconomic purpose of the land. Areas of land can be used for residential, industrial, agricultural, forestry, recreational, transport and other purposes. Often the same land is used for several purposes at the same time (Eurostat, 2023b).

Megawatt peak (MW_p) refers to the output of a solar array that, when operating at its peak power under standard test conditions, produces 1 million W direct current (*https://wiki-solar.org*).

Production of energy (primary) is any extraction of energy products in a useable form from natural sources. This occurs either when natural sources are exploited (e.g. in coal mines, crude oil fields, hydropower plants) or in the fabrication of biofuels. Transforming energy from one form into another, such as electricity or heat generation in thermal power plants, or coke production in coke ovens, is not primary production (Eurostat, 2023b).

Renewable energy sources, also called renewables, are energy sources that replenish (or renew) themselves naturally. They include the following: non-combustible renewables (hydropower, tide, wave, ocean energy, geothermal energy, wind energy, solar energy, ambient heat pumps) and combustible renewables (biofuels and renewable municipal waste) (Eurostat, 2023b).

Rooftop PV systems are photovoltaic systems that have their electricity-generating solar panels mounted on the rooftops of residential or commercial buildings or structures. The various components of such a system include PV modules, mounting systems, cables, solar inverters and other electrical accessories. Rooftop mounted systems are small compared to utility-scale solar ground-mounted PV power stations with capacities in the megawatt range; hence they are a form of distributed generation and grid-connected PV power systems. Rooftop PV systems on residential buildings typically feature a capacity of about 5–20 kW. In this analysis, rooftop PV refers to small-scale installations (< 20 kW).

Suitability maps for agricultural production systems, as defined in the LUISA territorial modelling platform, take into consideration the biophysical suitability of the land for being cultivated to produce food, namely arable, mixed crops and livestock, or only livestock. Each production system has a dedicated suitability layer, whose main components are related to soil characteristics, climate, current agricultural patterns and potential application of fertilisers. Each of these suitability layers is expressed on a scale from 0 (not suitable) to 1 (very suitable).

Suitable land for new solar (ground-mounted PV systems) and wind onshore installations is defined as the available land/locations after the exclusion of all land-use, environmental, orographic and geographical criteria (**Figure 14** and **Figure 24**). Each criterion is at least represented by one factor as a spatial layer (vectorial or raster format) such as slope, aspect, distance to roads, distance to urban centres, protected areas, capacity factors, solar irradiation and wind speed (see the complete list in **Tables A2.1, A2.2** and **A2.3** in **Annex 2**). The combination of these spatial factors identifies the maximum amount of suitable land for the deployment of solar and wind infrastructures in the EU-27.

Technical potential is the achievable capacity (MW), generation (GWh) and suitable land area (km²) for a particular generation technology given system performance and topographic, environmental, and land-use constraints. In short, technical potential considers available suitable surface area, system technical performance and sustainability criteria (Bódis et al., 2019b).

Untapped potential is defined in this analysis as the difference between the maximum achievable technical potential (GWh per year) and the current production (GWh) in 2023, calculated for the three RESs, namely solar energy, onshore wind energy and hydropower. This concept refers to the amount of potential electricity production that can be further exploited at the local level.

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Annex 1
Solar photovoltaic

ANNEX 1.1. EQUATIONS TO COMPUTE CURRENT ESTIMATED INSTALLED CAPACITY AND ELECTRICITY PRODUCTION IN 2023

For both capacity and production, rooftop PV systems are represented by equations (A1.1) (IC_{SSSP}) and (A1.4) ($PV\ prod_{SSSP}$), respectively. On the other hand, installed capacity (IC) of ground-mounted PV systems is represented by the results of equations (A1.2) (IC_{MSSP}) and (A1.3) (IC_{LSSP}), while current production from ground-mounted PV ($PV\ prod$) is the result of adding up equations (A1.5) ($PV\ prod_{MSSP}$) and (A1.6) ($PV\ prod_{LSSP}$). Each equation is described as follows:

$$IC_{SSSP}\ [\mathrm{MW}] = \left(0.25 \cdot \frac{\sum Urban\ area_M}{\sum Urban\ area_N} + 0.75 \cdot \frac{\sum solar\ PV\ panel\ area_M}{\sum solar\ PV\ panel\ area_N}\right) \cdot Cap_N\ [\mathrm{MW}] \quad \text{(Eq. A1.1)}$$

$$IC_{MSSP}\ [\mathrm{MW}] = \left(\frac{\sum solar\ PV\ panel\ area_M}{\sum solar\ PV\ panel\ area_N}\right) \cdot Cap_N\ [\mathrm{MW}] \quad \text{(Eq. A1.2)}$$

$$IC_{LSSP}\ [\mathrm{MW}] = \sum Cap_M\ [MW_{ac}] \quad \text{(Eq. A1.3)}$$

where IC_{SSSP} refers to small-size solar plants; IC_{MSSP} refers to middle-size solar plants and IC_{LSSP} refers to large-size solar plants. For the IC_{SSSP} (equation (A1.1)), two components have been established to distribute the total national (N) capacity at the municipality (M) level by degree of urbanisation (i.e. cities, towns and suburbs, and rural areas). The first one considers the sum of urban areas per municipality as a proxy for proportionally distributed national capacities (Cap_N), assuming that the greater the extent of urban areas, the higher the potential of rooftop installations. Urban areas are calculated using the LUISA base map at 100 m spatial resolution (see **Annex 2**). The second component of equation (A1.1) is based on the panel area (m^2) using the existing location of solar plants from the harmonised global datasets (Dunnet et al., 2020). This second component is given more weight in the whole equation, as it is observed data. Equation (A1.2) only considers the panel area to distribute the national capacities Cap_N from the same data source. The last equation above, (A1.3), is based on the sum of the installed capacity of all point-location solar plants in each municipality from the utility-scale project (Wiki-Solar).

$$PV\ prod_{SSSP}[\mathrm{MWh}] = IC_{SSSP}\ [\mathrm{MW}] \cdot CF_M \left[\frac{\mathrm{MWh}}{\mathrm{MW_p}}\right] \quad \text{(Eq. A1.4)}$$

$$PV\ prod_{MSSP}\ [\mathrm{MWh}] = IC_{MSSP}\ [\mathrm{MW}] \cdot CF_M \left[\frac{\mathrm{MWh}}{\mathrm{MW_p}}\right] \quad \text{(Eq. A1.5)}$$

$$PV\ prod_{LSSP}\ [\mathrm{MWh}] = IC_{LSSP}\ [\mathrm{MW}] \cdot CF_M \left[\frac{\mathrm{MWh}}{\mathrm{MW_p}}\right] \quad \text{(Eq. A1.6)}$$

where the installed capacity has been previously calculated by equations (A1.1), (A1.2) and (A1.3) at the municipality level and by degree of urbanisation. To estimate the current solar production at the municipality level, equations (A1.4), (A1.5) and (A1.6) are multiplied by a grid-level CF derived from solar irradiation (PVGIS, 2022) after being aggregated at the municipality level (CF_M). This grid-level CF is a raster layer of 1 km spatial resolution developed by the JRC (C2 unit).

ANNEX 1.2. MEMBER STATE RESULTS FOR SOLAR PHOTOVOLTAIC

	GROUND-MOUNTED PV					ROOFTOP PV				
Member State	Suitable land (km²)	Potential production (TWh/year)	Potential capacity (GW)	Current production (GWh/year)	Current capacity (MW)	Suitable surface (km²)	Potential production (TWh/year)	Potential capacity (GW)	Current production (GWh/year)	Current capacity (MW)
AT	196	18	18	216	180	151	14	30	4 371	3 706
BE	53	4.0	4.9	2 377	2 213	183	14	37	4 920	4 618
BG	2 967	386	276	2 555	1 902	150	19	30	367	277
CY	117	24	11	137	78	26	5.4	5.2	1.6	0.9
CZ	1 776	149	165	1 481	1 342	185	15	37	343	311
DE	2 211	159	206	48 428	45 017	1 521	116	304	15 606	14 563
DK	678	38	63	2 087	2 038	120	7.0	24	130	126
EE	2 832	152	263	513	529	27	1.4	5.3	69	72
EL	1 606	256	149	7 790	5 163	128	22	26	848	565
ES	16 359	2 796	1 521	44 216	26 628	461	77	92	1 216	773
FI	1 863	107	173	8.2	8.9	102	5.8	20	8.9	8.7
FR	12 185	1 270	1 133	23 954	18 256	1 344	144	269	3 418	2 620
HR	326	39	30	481	358	85	10	17	63	49
HU	3 649	383	339	4 005	3 191	190	20	38	1 595	1 264
IE	767	47	71	2 343	2 417	56	3.4	11	198	204
IT	2 757	419	256	28 296	19 038	752	104	150	8 914	6 250
LT	2 897	165	269	338	338	58	3.3	11.5	5.2	5.1
LU	45	3.6	4.2	2.8	2.7	9.4	0.8	1.9	5.3	5.0
LV	5 527	305	514	17	16	30	1.7	6.0	2.2	2.2
MT	0.8	0.2	0.1	7.1	4.2	5.3	1.1	1.1	197.7	117.9
NL	186	13	17	7 564	7 242	283	20	57	2 169	2 085

Member State	GROUND-MOUNTED PV					ROOFTOP PV				
	Suitable land (km²)	Potential production (TWh/year)	Potential capacity (GW)	Current production (GWh/year)	Current capacity (MW)	Suitable surface (km²)	Potential production (TWh/year)	Potential capacity (GW)	Current production (GWh/year)	Current capacity (MW)
PL	5 092	358	474	16 598	15 564	468	34	94	105	98
PT	4 651	803	433	5 619	3 412	170	28	34	154	94
RO	18 304	2 161	1 702	2 671	2 087	354	40	71	153	119
SE	5 221	289	486	879	895	157	8.8	31	939	964
SI	39	4.1	3.6	1 010	825	29	3.0	5.7	24	20
SK	463	42	43	922	769	108	10	22	301	256
EU	**92 767**	**10 391**	**8 627**	**204 514**	**159 514**	**7 151**	**729**	**1 430**	**46 124**	**39 175**

Table A1.1. Estimates of potential and current production and capacities for ground-mounted and rooftop PV systems in the EU-27 and its Member States.

Source: Authors' calculations (figures are rounded).

Table A1.2. Estimates of technical potential and current production of solar PV systems by degree of urbanisation in the EU-27 and its Member States.

Source: Authors' calculations (figures are rounded).

	POTENTIAL PRODUCTION (TWh/year)			CURRENT PRODUCTION (GWh/year)			SUITABLE LAND (km²)		
Member State	Cities	Towns & suburbs	Rural areas	Cities	Towns & suburbs	Rural areas	Cities	Towns & suburbs	Rural areas
AT	2	6	24	928	2 697	963	26	64	257
BE	3	10	5	567	5 630	1 101	42	126	67
BG	52	117	236	486	1 446	990	402	888	1 826
CY	4	3	22	1	5	132	21	15	108
CZ	3	15	145	89	580	1 156	42	182	1 737
DE	30	76	168	3 961	21 056	39 016	404	1 004	2 323
DK	3	10	32	21	437	1 760	47	183	568
EE	1	9	144	2	258	322	10	166	2 683
EL	7	20	251	47	1 461	7 131	39	121	1 574
ES	144	708	2 022	4 945	15 111	25 376	799	3 890	12 131
FI	2	35	76	7	4	6	41	605	1 319
FR	57	65	1 292	3 156	4 576	19 640	530	591	12 408
HR	2	9	38	34	110	400	18	80	313
HU	8	74	321	484	3 091	2 025	79	699	3 061
IE	1	1	49	141	361	2 038	15	16	793
IT	44	230	250	5 404	21 424	10 381	299	1 502	1 708
LT	1	28	139	1	98	245	15	499	2 441
LU	0	1	4	0	5	2	2	8	45
LV	1	31	275	0	1	18	10	561	4 986
MT	0	1	0	17	186	1	2	3	1
NL	9	14	10	2 251	5 141	2 341	123	197	148
PL	10	55	327	765	3 701	12 237	140	785	4 635
PT	14	78	740	224	804	4 745	83	447	4 291
RO	14	312	1 875	111	248	2 465	119	2 635	15 904
SE	14	136	147	782	861	175	259	2 468	2 651
SI	1	2	5	9	31	994	5	19	43
SK	2	9	41	54	387	782	22	95	454
EU	**429**	**2 053**	**8 637**	**24 488**	**89 712**	**136 438**	**3 591**	**17 850**	**78 477**

Annex 2 **Restrictions** and **suitability factors** for ground-mounted photovoltaic and onshore wind

In this annex we detail the constraints used to determine suitable land for new ground-mounted PV and onshore wind installations. Land-use, environmental and infrastructure factors, detailed in **Table A2.1,** have been applied to identify suitable land available for both technologies. On the other hand, orography and climate constraints are specific to each technology. These are shown in **Table A2.2** for ground-mounted PV and in **Table A2.3** for onshore wind.

Table A2.1. Land use, environmental and infrastructure factors and constraints employed to determine suitable areas for both ground-mounted PV systems and onshore wind farms.

LAND USE	
Artificial land uses	Land devoted to residential, industrial and infrastructure uses cannot be used for land-intensive RES installations, and it is therefore excluded from suitable areas (Tercan et al., 2021; Perpiña Castillo et al., 2016). Buffer zones around land with artificial uses to avoid noises, visual effects and other problems during the construction phase and after are also implemented in the analysis, with minimum distances of 700 m and 500 m from urban and industrial areas, respectively (Doljack et al., 2017; Perpiña Castillo et al., 2016; Tercan et al., 2021). Distances are computed from each artificial feature based on the LUISA base map (**Annex 5**) at 100 m spatial resolution (Pigaiani et al., 2021).
Forests, water bodies and natural vegetated areas	Forest areas, wetlands and water bodies were excluded as suitable land for new solar and wind installations (Tercan et al., 2021) based on the LUISA base map at 100 m spatial resolution (**Annex 5**). Forest classes include coniferous, broad-leaved and mixed forests (**Figure A2.1**). Other natural areas such as beaches, glaciers, dunes and sands are also excluded using the LUISA base map (Pigaiani et al., 2021). Natural vegetated areas on the LUISA base map, namely scrub and/or herbaceous vegetation associations (natural grasslands, moors and heathland, sclerophyllous vegetation and transitional woodland-shrub), are considered suitable sites for new wind and solar installations.
Agricultural land	Permanent crops (vineyards, fruit production and olive production) and rice fields are excluded as suitable areas using the LUISA base map (**Figure A2.1**). Only arable land, mixed crops and pastures are included, under certain strict conditions, namely if they show low productivity, high risk of abandonment and high levels of erosion (Sacchelli et al., 2016; Perpiña Castillo et al., 2016 and 2020; Dias et al., 2019; Choi et al., 2020; Tahri et al., 2015).

Abandoned land	Agricultural land at moderate, high and very high risk of abandonment of was included as potential places for electricity production. In particular, abandoned land in arable and pasture production systems was included as defined in the 2017 LUISA scenario (Perpiña Castillo et al., 2020; Jacobs-Crisioni et al., 2017).
Suitability maps for agricultural production systems	Only low-productivity agricultural land was selected as potential places for energy production, to avoid conflicts with food and feed production (Hernandez et al., 2014; Perpiña Castillo et al., 2016; Sacchelli et al., 2016; Tahri et al., 2015). Three composite suitability maps of arable, mixed-crops and pasture production systems were used to identify the values below which 20 % of data fall (quantiles). The readings with the lowest 20 % of values correspond to the agricultural locations with the lowest productivity, identified at 100 m resolution (Jacobs-Crisioni et al., 2017).
Eroded agricultural land	Areas with soil-loss rates per year greater than 11 t/ha (severely eroded) are selected if they are on a gentle slope (< 2.1 °). The slope threshold reduces the risk of increasing erosion rates and ground instability, which are not desirable in sites for RES installations, and solar infrastructures can reduce the acceleration of soil degradation, protect crops and benefit revegetation processes (Verheijen et al., 2023; Choi et al., 2020; Tahri et al., 2015). The raster layer is based on the revised universal soil loss equation (RUSLE) methodology at 100 m spatial resolution and gathered from the European Soil Data Centre (ESDAC, 2016; Panagos et al., 2020; EEA, 2016; Borrelli et al., 2022).
ENVIRONMENT	
Protected areas	These are specific locations (renewables go-to areas), whether on land or sea, particularly suitable for the installation of plants to produce energy from renewable sources, without expecting significant environmental impacts. This means the exclusion of Natura2000 network areas, nationally designated protected areas, ecologically significant marine areas, bird areas, biodiversity areas and peatlands (EC, 2022c), as shown in **Figure A2.1.**
High nature value (HNV) farmland	The designation of farmland as HNV indicates the link between extensive farming systems and the conservation of high biodiversity in agricultural landscapes. HNV farmland was therefore excluded (**Figure A2.1**) from potential places for PV installations, as it holds a special biodiversity value that must be protected and maintained. This spatial layer was gathered from the EEA at 100 m resolution (EEA, 2022).
INFRASTRUCTURE	
Distance to roads	Easy access to PV systems and wind installations is a relevant factor for both construction and operation phases, particularly for maintenance purposes. For these reasons, we consider locations further than 5 km from roads to be unsuitable (Tercan et al., 2021; EEA, 2015; Perpiña Castillo et al., 2016; Tahri et al., 2015). For this purpose, the European transport network from the MultiNet (Tele Atlas, 2020) was used to identify poorly accessible sites.

Distance from industrial areas and infrastructure	A 500 m buffer from industrial areas and infrastructure (taken from the LUISA base map) is set up and used to exclude sites for new installations (Tercan et al., 2021; Höfer at al., 2016).

Table A2.2. Orography and PV-specific factors used to determine suitable sites for ground-mounted PV installations.

OROGRAPHY – SOLAR	
Slope	Sites with slopes greater than 10° (approx. 18 %) are excluded because of difficulties during installation, construction and maintenance (Perpiña Castillo et al., 2016; Doljak et al., 2017; Tahri et al., 2015; Azoumah et al., 2010). Slope is a derived product from the European digital elevation model (EU-DEM) v1.0 from the Copernicus programme. Slope layer was resampled at 100 m spatial resolution (Copernicus, 2023).
Aspect	North-facing sites (± 67.5° north) are excluded, as they are not appropriate for large-utility PV installations (Tercan et al., 2021; Ruiz et al., 2019; Tahri et al., 2015). Aspect is a derived product from the EU-DEM from the Copernicus programme and averaged at 100 m spatial resolution (Copernicus, 2023), as shown in **Figure A2.2.**
SOLAR FACTORS	
Solar irradiation	This is the amount of solar energy that falls on a surface per unit area, measured in kWh/m² (**Figure A2.2**). Yearly average annual global irradiance on an optimally inclined surface (kWh/m²), 2005–2020, is used with a roughly 5 km spatial resolution layer. Areas with annual solar irradiation under 1 100 kWh/m² have been excluded as potential sites for new PV installations because of low potential yield (PVGIS, 2020; Gracia Amillo et al., 2021; Tahri et al., 2015; Šúri et al., 2007).
PV module efficiency	This is the amount of solar energy that is converted into electricity by the PV module. It is measured in kilowatt-hour per kilowatt-peak (kWh/kW_p). It was assumed that 5.5 m² was needed to install 1 kW_p, which amounts to a module efficiency of 18.2 %. This layer was gathered from the JRC with a 5 km spatial resolution (PVGIS, 2020; Kakoulaki et al., 2021).

Table A2.3. Orography and wind-specific factors used to determine suitable sites for onshore wind installations.

OROGRAPHY – WIND	
Slope	Places with slopes greater than 2.1 ° (approximately 4 %) were excluded because of difficulties in the installation and construction phases (Dalla Longa et al., 2018). Slope is a derived product from the EU-DEM v1.0 (digital surface model) from the Copernicus programme, originally at 25 m spatial resolution (Copernicus, 2023). The slope layer was resampled at 100 m spatial resolution as shown in **Figure A2.3.**
WIND FACTORS	
Capacity factors	Capacity factors (CFs) make it possible to compute the annual energy production of a wind installation, given its installed capacity and its location. Grid-level CFs (International Electrotechnical Commission class 2) from the Global Wind Atlas were used, originally at 300 m spatial resolution, and resampled to 100 m spatial resolution (**Figure A2.3**). A threshold of CF > 20 % was established for potential wind energy areas (DTU, 2023; Dalla Longa et al., 2018).
Potential installed capacity density	Potential installed wind capacity was set to 5 MW/km², following Ruiz et al. (2018) and Dalla Longa et al. (2018).
Setback distance	Onshore wind installations must be set up at a distance (setback distance) from human settlements to avoid high levels of noise. Setback distances are not subject to EU-wide regulations, and are therefore country-specific, ranging from 400 to 1 250 m. Here, we employ a 700 m setback distance from all urban areas in the LUISA base map. It constitutes the distance at which the noise from large wind turbines typically falls below 40 dB (Dalla Longa et al., 2018).

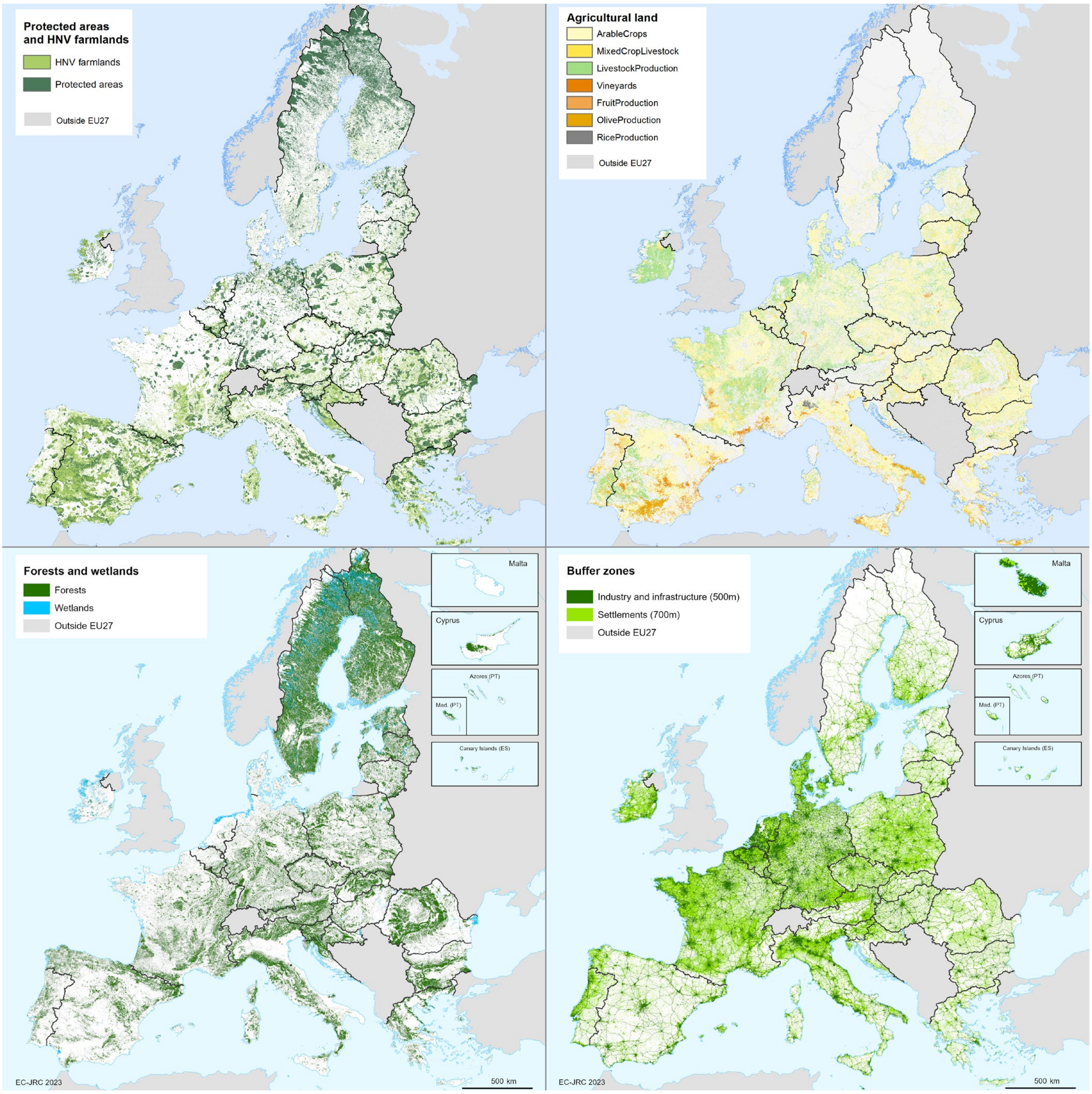

Figure A2.1. Land use and environmental factors used in the determination of available areas for ground-mounted PV and onshore wind installations.

Sources: Authors' own elaboration from sources described in Table A2.1.

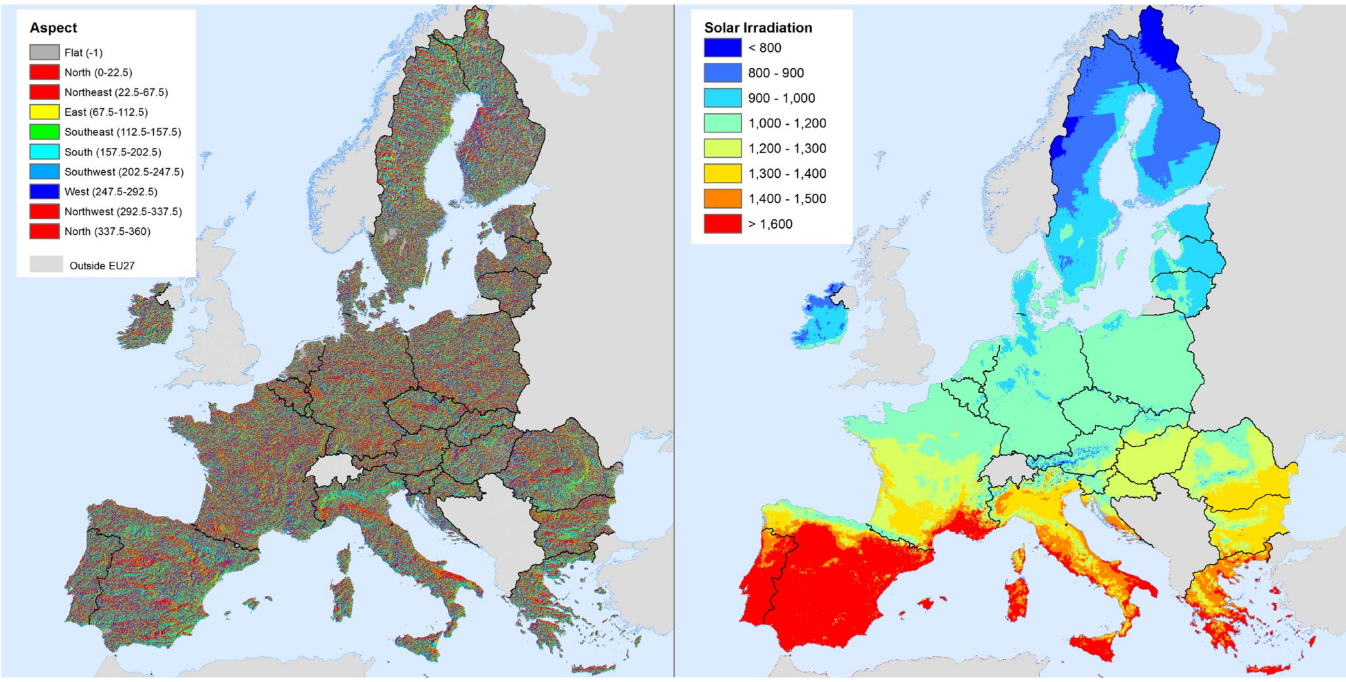

Figure A2.2. Orographic and climate factors used to determine available areas and potential production of ground-mounted PV installations (see Table A2.2).

Sources: Authors' own elaboration. Left, based on Copernicus (2023); right, based on PVGIS (2020).

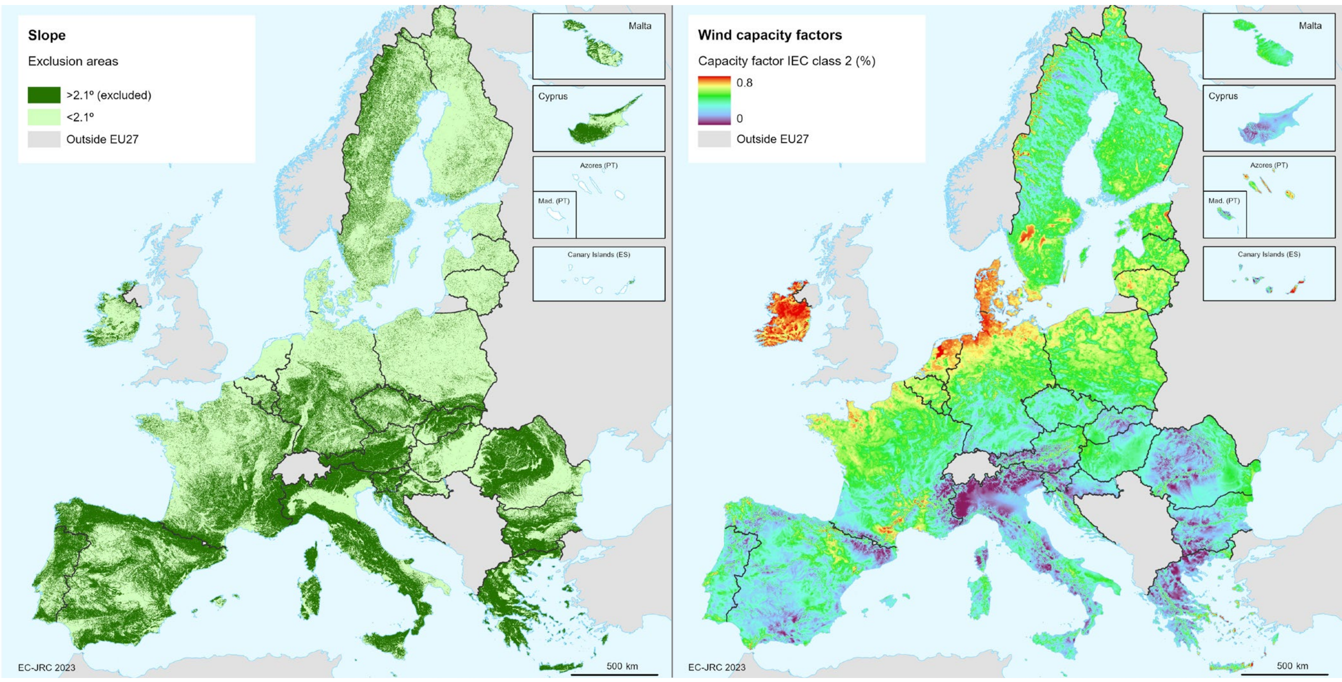

Figure A2.3. Orographic and climate factors used to determine available areas and potential production of onshore wind installations (see Table A2.3).
IEC, International Electrotechnical Commission.

Sources: Authors' own elaboration. Left, based on Copernicus (2023); right, based on DTU (2023).

3

Annex 3
Onshore wind

ANNEX 3.1. CAPACITY FACTORS AND ESTIMATION OF LOSSES

For the estimation of onshore wind current and potential production, grid-level capacity factors from the Global Wind Atlas were used (DTU, 2023) These correspond to reference turbines of 3.45 MW capacity, with rotor diameter 126 m and hub height 100 m, and for wind conditions of International Electrotechnical Commission (IEC) class 2. The capacity factors are provided at 300 m resolution and reflect wind conditions, making it possible to compute the production that a certain installed capacity of reference turbines would provide at a given location. In estimating the potential production, we also introduce an additional factor of 15 % of losses (Dalla Longa et al., 2018). These power losses can arise from a variety of factors such as wake effects, turbine availability and downtime, electrical losses, environmental variations and market-driven incentives, which are not included in the capacity factors.

In the estimation of the current production, the capacity factors used can lead to overestimation of production due to the technology of existing turbines being less efficient than the reference turbine, especially in countries where development of wind power started earliest, which thus have older turbines. For these reasons, we adjust our results of the current production with an estimated total loss factor at the country level, which accounts for power losses and corrects the overestimation due to turbine technology assumptions. Loss factors, which can be found in **Table A3.1,** are computed by comparing the average Global Wind Atlas capacity factor of wind installations in a country with the country-level capacity factors derived from Eurostat data on production and capacity of onshore wind in 2021 (Eurostat, 2021b, 2021f). On average, the loss factor in the EU is 47 %.

MEMBER STATE	GLOBAL WIND ATLAS CF	EUROSTAT CF	LOSS FACTOR
AT	0.40	0.23	0.43
BE	0.45	0.22	0.52
BG	0.33	0.23	0.30
CY	0.25	0.18	0.30
CZ	0.39	0.20	0.48
DE	0.46	0.18	0.60
DK	0.56	0.20	0.63
EE	0.51	0.27	0.48
EL	0.48	0.26	0.46
ES	0.41	0.25	0.38
FI	0.39	0.30	0.25
FR	0.45	0.22	0.50
HR	0.39	0.24	0.39
HU	0.37	0.23	0.36
IE	0.61	0.26	0.58
IT	0.36	0.21	0.41
LT	0.47	0.23	0.51
LU	0.43	0.26	0.39
LV	0.46	0.21	0.54
MT	—	—	—
NL	0.53	0.22	0.59
PL	0.45	0.27	0.41
PT	0.43	0.28	0.35
RO	0.35	0.25	0.29
SE	0.45	0.26	0.44
SI	0.41	0.19	0.54
SK	0.48	0.14	0.70
EU-27	**0.43**	**0.23**	**0.47**

Table A3.1. Capacity factors and estimated loss factors for onshore wind current production in EU Member States.

Note: No production of onshore wind is recorded in Malta.

Source: Authors' own calculations from Global Wind Atlas (DTU, 2023) and Eurostat (Eurostat, 2021b, 2021f).

ANNEX 3.2. MEMBER STATE RESULTS FOR ONSHORE WIND

Table A3.2. Estimate potential and current production and capacities for onshore wind in the EU-27 and its Member States.

Note: The current status is estimated using data up to April 2023.

Source: Authors' calculations (figures are rounded).

MEMBER STATE	SUITABLE LAND (km²)	POTENTIAL PRODUCTION (GWh/year)	POTENTIAL CAPACITY (MW)	CURRENT PRODUCTION (GWh/year)	CURRENT CAPACITY (MW)
AT	135	1 748	675	6 469	3 222
BE	64	1 052	318	5 244	2 748
BG	2 122	21 769	10 609	1 817	768
CY	71	606	357	233	165
CZ	1 591	18 248	7 956	602	340
DE	2 346	38 359	11 731	92 765	57 544
DK	1 018	20 744	5 092	7 521	4 185
EE	4 111	63 209	20 554	851	381
EL	251	2 813	1 253	8 727	4 052
ES	11 719	123 791	58 597	60 180	28 408
FI	9 283	117 371	46 413	12 518	5 478
FR	14 911	199 809	74 553	38 969	20 127
HR	246	2 446	1 232	2 088	979
HU	4 566	52 552	22 829	800	384
IE	1 558	32 808	7 792	9 439	4 219
IT	1 399	14 427	6 996	20 980	11 425
LT	4 177	69 380	20 885	1 511	739
LU	29	423	147	352	152
LV	7 958	124 769	39 788	202	112
MT	0.4	5.6	2.0	0.0	0.0
NL	274	5 211	1 371	10 367	5 490
PL	7 599	119 196	37 997	17 205	7 317
PT	3 688	38 222	18 442	13 352	5 571
RO	21 641	235 499	108 206	6 092	2 699
SE	13 052	165 950	65 258	27 628	13 798
SI	29	275	147	5.3	3.2
SK	206	2 247	1 031	3.4	3.1
EU-27	**114 046**	**1 472.933**	**570 230**	**345 920**	**180 311**

Table A3.3. Estimate potential and current production of onshore wind by degree of urbanisation in the EU-27 and its Member States.

Source: Authors' calculations (figures are rounded).

	POTENTIAL PRODUCTION (GWh/year)			CURRENT PRODUCTION (GWh/year)			SUITABLE LAND (km^2)		
Member State	Cities	Towns & suburbs	Rural areas	Cities	Towns & suburbs	Rural areas	Cities	Towns & suburbs	Rural areas
AT	0	74	1 675	13	618	5 839	0.0	5.9	129.2
BE	5	333	715	736	2 756	1 753	0.3	20.8	42.5
BG	1 997	3 883	15 889	21	1 435	361	217.2	396.5	1 508.1
CY	6	84	516	0	0	233	0.7	10.4	60.5
CZ	61	1 182	17 005	0	38	564	5.6	105.8	1 479.9
DE	274	5 091	32 994	2 196	16 776	73 793	18.6	328.6	1 999.0
DK	603	4 381	15 760	241	1 893	5 387	29.5	218.6	770.4
EE	95	3 411	59 703	77	0	774	5.9	230.5	3 874.5
EL	5	238	2 570	5	461	8 261	0.4	17.5	232.8
ES	6 171	27 679	89 941	1 527	8 099	50 554	594.2	2 790.4	8 334.7
FI	2 289	22 697	92 385	0	1 785	10 734	190.5	1 783.4	7 308.8
FR	1 685	3 854	194 271	316	836	37 816	122.8	330.6	14 457.1
HR	15	447	1 985	0	176	1 911	1.7	47.7	197.2
HU	553	10 197	41 802	3	88	710	47.9	880.6	3 637.3
IE	4	87	32 717	0	137	9 302	0.2	4.2	1 553.9
IT	1 290	6 738	6 399	779	5 501	14 700	130.9	654.8	613.5
LT	35	11 951	57 394	12	330	1 169	2.3	710.6	3 464.0
LU	0	35	387	0	0	352	0.0	2.6	26.8
LV	24	12 732	112 013	0	0	202	1.5	789.8	7 166.1
MT	0	4	1	0	0	0	0.0	0.3	0.1
NL	157	2 013	3 041	1 762	4 459	4 146	8.9	106.6	158.6
PL	301	14 530	104 365	30	2 522	14 653	22.9	935.4	6 641.1
PT	233	4 242	33 747	309	1 243	11 800	19.5	402.0	3 266.9
RO	752	32 370	202 378	154	640	5 299	72.3	3 009.6	18 559.3
SE	4 000	50 993	110 956	596	9 980	17 052	265.8	3 861.1	8 924.8
SI	0	59	216	0	2	4	0.0	6.3	23.0
SK	45	371	1 831	0	0	3	4.4	32.4	169.3
EU	**20 600**	**219 676**	**1 232 656**	**8 777**	**59 774**	**277 369**	**1 764**	**17 682**	**94 599**

4

Annex 4
Hydropower

Table A4.1. Factors, formulas and parameters to assess hydropower energy potential.

STRATEGY	VARIABLE	DESCRIPTION	FORMULA/PARAMETER	REFERENCE
Modernisation	Energy gain from digitalisation	Digitalisation can increase efficiency by 1 % and allows up to + 10 % more energy generation due to a reduction of spills in reservoir-type power plants, thanks to a better inflow forecast and reservoir management. Therefore, 1 % of additional energy generation was added to all power plants, and 2 % to the power plants with storage capacity, as a parsimonious estimate. This strategy makes it possible to increase energy generation by better exploiting the available power. Additional benefits from digitalisation are: better operations and maintenance, damage prevention, security and improvement of environmental performance (Quaranta et al., 2023). These are not considered in this study because they are very site specific but could be highly relevant to increasing local hydropower production.	1 % 2 % (if reservoir-type)	Quaranta et al. (2021a); Quaranta and Muntean (2023)
Modernisation	Energy gain from recovery of wasted energy	The hydrokinetic energy downstream of the draft tube is generally lost, while it could be exploited through hydrokinetic turbines with an efficiency of 30 %. This strategy is applicable to power plants equipped with Francis and Kaplan turbines. The exploitation of the power associated with the residual head below the casing of Pelton turbines was also considered for power plants equipped with Pelton turbines and assumed to be exploited with an efficiency of 50 % (low-head applications). These calculations could be performed only when the head was known. It was also assumed to recover the heat losses from the generator and to use them to provide heat to buildings or for district heating, considering additional (thermal) energy amounting to 0.8 % of the installed power. This value represents both additional power capacity and energy generation.	30 % hydrokinetic energy (Francis and Kaplan turbines) 50 % residual head power (Pelton turbines) 0.8 % installed power (thermal energy)	Quaranta et al. (2021); Quaranta and Muntean (2023)

STRATEGY	VARIABLE	DESCRIPTION	FORMULA/PARAMETER	REFERENCE
Modernisation	Energy gain from replacement of electro-mechanical equipment	It was assumed that older electro-mechanical equipment would be replaced with modern equivalents, replacing turbines, casing, draught tubes and vanes. This can lead to an increase in weighted efficiency of between 4% and 6%, depending on the configuration and turbines type, that were considered in the calculations. When it was not possible to estimate the turbine type (because the head was unknown), a Francis turbine was assumed, as it is the most used type in the EU. This strategy in principle makes it possible to increase the current available power (which is lower than the originally installed power, owing to ageing) to its original value, while improving energy generation thanks to more flexible equipment. Therefore, this strategy has to be interpreted as additional energy generation only, as it does not increase the installed power capacity with respect to that declared at the commissioning phase. In some cases, this strategy could also increase the new power to a bigger value (for example, by installing larger turbines, or more turbines, if the discharge or head increases), but that is not considered in this study.	4%–6%, depending on the configuration and turbine type	Quaranta et al. (2021); Quaranta and Muntean (2023)
Modernisation	Energy gain from retrofitting of waterways and penstocks	Waterways and penstocks were assumed to be retrofitted and replaced with new ones with reduced head losses and friction, and assumed to be implemented in reservoir-type hydropower plants (those corresponding to higher heads) and to power plants with heads above 50 m, entailing additional energy generation of 5%. The aim is to restore them by bringing their performance up to the original, so no increase in capacity is envisaged.	5% (if reservoir-type)	Quaranta et al. (2021); Quaranta and Muntean (2023)

STRATEGY	VARIABLE	DESCRIPTION	FORMULA/PARAMETER	REFERENCE
Hydropower in water utilities	Available power of WDNs	The available power of a WDN is computed following the procedure in Quaranta et al. (2022a), which improved the model of Mitrovic et al. (2021). Here the calculations were further improved accounting for the network length as in formula (a) in the next column. — For Spain, Portugal and Ireland, the power potentials of 0.09, 0.31 and 0.41 kW every 1 000 people were considered, respectively (as found in Mitrovic et al., 2021). — For the other Member States, the following procedure was considered: → if the elevation range of the area is above 700 m, the potential of 2.89 kW per 1 000 people was considered, as for Scotland (Mitrovic at al., 2021); → otherwise, the potential (kW per 1 000 people) was calculated by 0.029 K, where K expresses the length (in metres) of WDN per person in each Member State. The available power of WWTPs is computed from the equation in Mitrovic et al. (2021) and as a function of the population served (in millions) as in formula (b).	$P_{cw}\left[\frac{kW}{kp}\right] = \begin{cases} 0.29k \ if \ e < 700m \ a.s.l \\ 2.89 \ if \ e > 700m \ a.s.l \\ 0.09 \ if \ c = ES \\ 0.31 \ if \ c = PT \\ 0.41 \ if \ c = IE \end{cases}$ (a) where P_{cw} is the power capacity for every 1 000 people (expressed as kW/kp), *k* expresses the length (in metres) of WDN per person in each Member State, and *c* is the country-specific factor. The other parameters, as found in Mitrovic et al. (2021), already include an efficiency rate reduction of 50 %).	Quaranta et al. (2022); Mitrovic et al. (2021); EurEau (2021)
Hydropower in water utilities	Available power of WWTPs	The available power of WWTPs is computed from the equation in Mitrovic et al. (2021) and as a function of the population served (in millions) as in formula (b).	$Pww[kW] = 44.2\,Mp$ (b) where *Pww* is the power potential (expressed as kW) and *Mp* is the population served (in millions).	Quaranta et al. (2022); Mitrovic et al. (2021)
Historical mill restoration	Available power of watermills (gap-filling strategy)	If head (*H*) and flow (*Q*) are known, the power (*P*) (in kW) could be estimated as in formula (c). When all of *P, Q* and *H* were known, the estimated power was compared with the reported one, and the lowest was taken, for cautionary reasons. The average power is 47 kW. If not known, *H, Q* and *P* were assigned considering the average values of watermills in the same river, and the same formula (c) was applied. When neither of the procedures above was applicable, the average power from mills in the same country was used.	$P = 9.81\ QH\eta\ (b)$ (c) where *Q* is the flow (m3/s), *H* is the head (m) and η is the efficiency, assumed η = 0.65	Quaranta et al. (2022)

Table A4.2. Current energy generation of the EU hydropower fleet and its modernisation potential.

Note: The additional power capacity is only from wasted energy recovery.

Source: Authors' own elaboration.

MEMBER STATE	ESTIMATED CURRENT PRODUCTION (TWh/year)	ADDITIONAL ENERGY POTENTIAL (TWh/year)	ADDITIONAL CAPACITY POTENTIAL (GW)
AT	40.2	4.8	0.13
BE	1.5	0.2	0.01
BG	5.0	0.7	0.03
CY	2.4	0.3	0.04
CZ	—	—	—
DE	—	—	—
DK	27.5	2.9	0.10
EE	—	—	—
EL	1.1	0.1	0.01
ES	5.1	0.7	0.04
FI	36.3	4.9	0.21
FR	66.5	8.6	0.35
HR	7.0	0.9	0.02
HU	45.9	5.4	0.21
IE	3.2	0.4	0.04
IT	0.8	0.1	0.01
LT	1.7	0.2	0.01
LU	0.2	0.0	0.00
LV	—	—	—
MT	—	—	—
NL	3.4	0.4	0.02
PL	16.1	2.0	0.08
PT	19.0	2.6	0.09
RO	4.5	0.6	0.02
SE	6.5	0.8	0.04
SI	12.6	1.5	0.05
SK	69.5	9.4	0.25
EU-27	**376.0**	**47.6**	**1.76**

Table A4.3. Potential additional energy production from modernisation in EU rural municipalities (sorted by greatest production gains).

Note: only countries with hydropower production are reported.

Source: Authors' own elaboration

MEMBER STATE	NUMBER OF RURAL MUNICIPALITIES	PRODUCTION GAINS (GWh/year)
SE	53	7053
FR	380	6678
ES	217	4282
IT	206	3930
AT	92	3465
DE	311	1898
PT	109	1849
RO	68	1214
FI	44	833
EL	21	650
HR	16	640
SK	11	532
SI	12	450
PL	29	298
BG	10	261
CZ	30	255
LU	3	208
BE	8	175
IE	5	105
LV	3	102
LT	1	55
HU	5	23
EU-27	**1634**	**34955**

MEMBER STATE	CITIES		TOWNS AND SUBURBS		RURAL AREAS	
	Number	GWh/year	GWh/year	GWh/year	GWh/year	GWh/year
ES	1	90.6	7	1 007.5	79	15 680.6
EL		—		—	14	3 254.9
RO	6	1387	9	730.3	34	2 287.9
PT		—	3	2 971.1	21	1 999.7
FR	1	43.3	1	8	37	1 581.6
SE		—	5	43 971.8	15	1 069
BG	1	312.3	3	330.8	5	845.7
CZ		—		—	8	768.4
PL	1	666.6		—	7	740.5
HR		—	1	106.6	2	385.6
IT		—		—	14	357.2
SK		—		—	4	322.7
AT		—	1	220.6	9	150.4
IE		—		—	2	46.8
BE		—	1	8.1	1	28.5
SI		—		—	2	25.7
LU		—		—	1	6.6
FI		—	4	—	6	—
LT	1	396.3		—		—
EU-27	11	**2 896.0**	35	**49 354.8**	261	**29 551.8**
Total EU-27						**81 803.00**

Table A4.4. Potential: energy generation from FPV and number of municipalities by degree of urbanisation (sorted by highest rural production).

Note: Only countries with hydropower production are reported.

Source: Authors' calculations.

Table A4.5. Potential energy generation from water distribution networks and wastewater treatment plants in EU-27 and by Member State.

Source: Authors' calculations.

MEMBER STATE	ENERGY FROM WDN (GWh/year)	ENERGY FROM WWTP (GWh/year)
AT	64.9	3.1
BE	27.8	1.6
BG	89.4	4.0
CZ	20.1	1.5
DK	14.7	0.8
DE	153.3	12.0
EE	1.7	0.2
IE	17.2	0.7
EL	46.9	2.6
ES	163.7	11.4
FR	247.5	10.0
HR	42.6	1.7
IT	335.2	17.1
CY	1.3	0.1
LV	4.0	0.3
LT	5.8	0.4
LU	1.5	0.1
HU	17.1	1.3
MT	0.6	0.1
NL	30.6	2.4
PL	84.5	5.5
PT	30.5	1.5
RO	53.2	4.0
SI	22.1	0.9
SK	15.2	1.1
FI	28.0	0.8
SE	23.2	1.5
EU-27	**1 542.4**	**86.5**

MEMBER STATE	NUMBER OF RURAL MUNICIPALITIES	ENERGY FROM WDN (GWh/year)	ENERGY FROM WWTP (GWh/year)
FR	30 677	79.81	3.47
IT	5 084	73.36	3.64
DE	8 367	33.49	2.69
AT	1 712	29.18	1.35
PL	1 878	28.11	1.98
ES	6 797	21.97	1.53
RO	2 740	21.05	1.47
EL	5 891	15.75	0.88
BG	169	13.47	0.67
CZ	5 698	10.07	0.52
HR	450	9.05	0.36
SI	166	8.78	0.36
PT	2 183	7.58	0.38
IE	2 798	7.43	0.29
FI	243	7.29	0.21
SE	146	5.41	0.35
SK	2 612	5.06	0.39
HU	2 824	4.55	0.41
DK	46	4.36	0.26
BE	213	3.71	0.21
NL	80	2.91	0.24
LT	42	2.23	0.16
LV	94	1.27	0.09
EE	62	0.90	0.07
LU	72	0.47	0.03
CY	370	0.26	0.02
MT	6	0.02	0.00
EU-27	**81 420**	**397.54**	**22.02**

Table A4.6. Potential energy generation from water distribution networks and wastewater treatment plants in EU rural municipalities (sorted by greatest total production).

Note: Only countries with mills suitable for restoration are reported.

Source: Authors' calculations.

Table A4.7. Potential energy generation and available power from restorable historical watermills in the EU-27 and its Member States.

Source: Authors' calculations.

MEMBER STATE	NUMBER OF MILLS	AVAILABLE POWER (MW)	POTENTIAL ENERGY (GWh/year)
AT	769	51.30	256.52
BE	836	28.24	141.20
BG	11	0.02	0.10
CY	0	0.00	0.00
CZ	32	0.28	1.39
DE	4 157	74.53	372.63
DK	1	0.03	0.17
EE	197	1.69	8.46
EL	2 337	37.53	187.67
ES	176	22.47	112.35
FI	293	4.09	20.47
FR	6 763	229.91	1 149.56
HR	7	0.24	1.21
HU	22	0.76	3.81
IE	43	1.49	7.44
IT	1 507	86.03	430.16
LT	93	4.15	20.75
LU	20	0.69	3.46
LV	113	4.89	24.44
MT	2	0.01	0.03
NL	105	0.30	1.52
PL	426	7.44	37.22
PT	124	4.29	21.47
RO	30	1.04	5.19
SE	909	82.87	414.33
SI	420	14.54	72.72
SK	0	0.00	0.00
EU-27	**19 393**	**658.85**	**3 294.27**

MEMBER STATE	NUMBER OF RURAL MUNICIPALITIES	NUMBER OF MILLS	AVAILABLE POWER (MW)	POTENTIAL ENERGY (GWh/year)
FR	3 039	5 739	188.1	940.5
AT	261	713	47.6	237.8
DE	1 316	2 507	46.1	230.5
IT	492	828	45	224.8
SE	107	458	40.8	203.9
EL	968	2 247	34.1	170.3
BE	143	474	17.7	88.3
ES	41	113	14.4	72.1
SI	103	308	10.7	53.3
PL	245	331	4.9	24.7
LV	47	102	4.5	22.7
FI	110	215	3.2	16.1
LT	28	72	2.7	13.7
PT	30	49	1.7	8.5
EE	40	185	1.6	8.0
IE	33	36	1.1	5.7
RO	9	20	0.7	3.5
LU	11	17	0.6	2.9
HU	9	11	0.4	1.9
HR	3	7	0.2	1.2
CZ	23	29	0.2	1.1
NL	10	34	0.1	0.5
DK	1	1	0.0	0.2
BG	6	6	0.0	0.1
EU-27	**7 075**	**14 502**	**466.5**	**2 332.3**

Table A4.8. Potential energy generation and available power from watermills restoration in EU rural municipalities (sorted by highest production).

Source: Authors' calculations.

5

Annex 5
Data sources

Table A5.1. Description of the datasets used in the analysis.

NAME	PROVIDER	DESCRIPTION	URL	TEMPORAL RESOLUTION	SPATIAL RESOLUTION
Wiki-Solar	WolfeWare Ltd	The Wiki-Solar dataset contains a list of utility-scale solar projects with relevant attributes associated, such as capacity (MW alternating current), status, coordinates, emissions and land use, for each existing solar PV installation until the beginning of 2023. Almost 5 000 solar plants were identified in the EU-27 from this database.	*https://www.wiki-solar.org*	2023	Point locations, EU-27
Harmonised global datasets of wind and solar farms	OpenStreet-Map	Using OpenStreetMap infrastructure data, a publicly available, spatial, harmonised dataset describing global solar PV was used from Dunnett et al. (2020). These data are available in vector format and include metadata describing whether the location is urban or beside/on a water body, as well as the panel area. Almost 17 000 solar plants were selected for this analysis, covering the EU-27.	*https://www.nature.com/articles/s41597-020-0469-8*	2023	Point locations, EU-27
2018 LUISA base map and land-use/cover map	JRC, Unit B3	The land-use data in this analysis are based on the 2018 LUISA base map, which is a high spatial (100 m) and thematic (41 classes) resolution map produced in 2020 by the JRC. It is constructed by refining the original thematic and spatial detail of Corine Land Cover 2018 using a geospatial data fusion approach (Pigaiani et al., 2021). Four main land-use groups can usually be defined: built-up areas (urban residential, industrial and commercial, and green urban areas); agricultural land (arable land, mixed crops and livestock, pasture / livestock grazing, and permanent crops); forest and natural areas (broadleaved and/or coniferous trees, transitional woodland-shrub, moors and heathland, sclerophyllous vegetation, and natural grassland); and finally other land uses (water bodies, infrastructures, dump and construction sites, etc.).	*https://publications.jrc.ec.europa.eu/repository/handle/JRC124621* and *https://observatory.rural-vision.europa.eu/*	2018	Grid (100 m)

NAME	PROVIDER	DESCRIPTION	URL	TEMPORAL RESOLUTION	SPATIAL RESOLUTION
2018 LUISA population	JRC, Unit B3	2018 LUISA population and projections (up to 2050) for the EU-27 at 100 m resolution are starting points for simulation within the LUISA territorial modelling platform (Pigaiani et al., 2021; Jacobs-Crisioni et al., 2017; Perpiña Castillo et al., 2021).	*https://publications.jrc.ec.europa.eu/repository/handle/JRC124621* and *https://observatory.rural-vision.europa.eu/*	2018	Grid (100 m), EU-27
Gross electricity production	Eurostat	The dataset provides reported values of annual gross electricity production from non-combustible fuels at the country level, broken down by fuel and plant type (online data code NRG_IND_PEHNF).	*https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_pehnf/*	2022 (reference year used)	Country data, EU-27 + other countries
Electricity production capacities	Eurostat	The dataset provides reported values of annual electricity production capacities for renewables at the country level, broken down by fuel and plant type (online data code NRG_INF_EPCRW).	*https://ec.europa.eu/eurostat/databrowser/view/nrg_inf_epcrw/*	2021 (reference year used)	Country data, EU-27 + other countries
Energy production	IRENA	The IRENA Renewable Energy Statistics provides comprehensive, reliable data on annual renewable energy capacity and actual power generation worldwide.	*https://www.irena.org/publications/2022/Jul/Renewable-Energy-Statistics-2022*	2021 (reference year used)	Country data, EU-27 + other countries
Energy production	ENTSO-E	The datasets represent the future state of the power systems of the ENTSO-E members, used for long-term planning. The available datasets describe the energy sector in Europe by providing a realistic representation of the European power system.	*https://www.ent-soe.eu/data/map/* and *https://transparency.entsoe.eu/*	Time series from 2014 to 2023	Country data, EU-27 + other countries
Topography	Copernicus	EU-DEM (Digital Elevation Model) represents the first surface as illuminated by sensors. It is a hybrid product based on Shuttle Radar Topography Mission and Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Map data and generated as a contiguous dataset divided into 1° tiles and projected to European Terrestrial Reference System Lambert Azimuthal Equal Area by the JRC. Slope and aspect were derived from the digital surface model as a GeoTIFF grid of 25 m resolution (Copernicus, 2023).	*https://spacedata.copernicus.eu/en/web/guest/collections/copernicus-digital-elevation-model*	2000–2016	Grid (25 m), EU-27
Rooftop PV	JRC, Unit C2	The study developed a pan-European spatial analysis tool to quantify the PV electricity potential of existing buildings' rooftops to a high level of accuracy. This is complemented by a measure of financial viability (cost analysis).	*https://doi.org/10.1016/j.rser.2019.109309*	2019	Grid (100 m), EU-27

NAME	PROVIDER	DESCRIPTION	URL	TEMPORAL RESOLUTION	SPATIAL RESOLUTION
Enspreso	JRC, Unit C7 and Energy and Industry Geography Lab	Energy Systems Potential Renewable Energy Sources (Enspreso) is an EU-28 wide, open dataset for energy models on renewable energy potentials, at the national (NUTS 0) and regional (NUTS 2) levels for 2010–2050. Technical potentials are provided for wind, solar and biomass, based on coherent geographic information system-based land-restriction scenarios (Ruiz et al., 2019).	*https://data.jrc.ec.europa.eu/collection/id-00138*	2019	NUTS 0, NUTS 2, EU-27
Restor Hydro	Restor Hydro project (European Small Hydropower Association)	The Restor Hydro project identified and mapped most relevant historical hydropower sites (weirs and mills) in Europe that are suitable for refurbishment.	*https://eref-europe.org/restor-hydro-database/*	2012	Point locations, EU-27
JRC Hydro-power database	JRC, Unit D7	The dataset is an output of the Water–Energy–Food–Ecosystems Nexus project. It has been created for power system modelling purposes and collects basic information on European hydropower plants.	*https://data.jrc.ec.europa.eu/dataset/52b00441-d3e0-44e0-8281-fda86a63546d*	2019	Point locations, EU-27
JRC Open Power Plants Database	JRC, Unit D7	The JRC Open Power Plants Database is a dataset of European power plants (Hidalgo Gonzalez et al., 2019).	*https://data.jrc.ec.europa.eu/dataset/9810feeb-f062-49cd-8e76-8d8cfd488a-059810feeb-f062-49cd-8e76-8d8cf-d488a05*	2019	Point locations, EU-27
Global Hydropower Database	Wenhua Wan's public data (figshare)	The Global Hydropower Database is a collation of available hydropower plant information, distributed across 134 countries worldwide (Wan et al., 2021). The global hydropower database (GHD) is freely available for non-commercial use.	*https://figshare.com/articles/dataset/Global_Hydropower_Database_GHD_/11283758/3*	2020	Point locations, global
Renewables go-to areas for wind and solar installations	JRC, Energy and Industry Geography Lab	'Renewables go-to areas' are specific locations where the rapid deployment of new installations to produce energy from wind and solar is not expected to have significant environmental impacts. This requires the exclusion of the following relevant layers: Natura 2000 sites, nationally designated protected areas, ecologically or biologically marine areas, bird areas, biodiversity areas, peatlands, etc. (European Commission, 2022c).	*https://energy-industry-geolab.jrc.ec.europa.eu/* and *https://joint-research-centre.ec.europa.eu/scientific-tools-databases/energy-and-industry-geography-lab/acceleration-areas-renewables_en*	2022	Raster and vectorial layers, EU-27

NAME	PROVIDER	DESCRIPTION	URL	TEMPORAL RESOLUTION	SPATIAL RESOLUTION
High nature value (HNV) farmland	EEA	The concept of HNV farmland ties biodiversity to the continuation of farming on certain types of land and the maintenance of specific farming systems across the whole European territory. The map of HNV farmland, which holds special biodiversity value, can be useful for carrying out analyses on spatial and time trends (EEA, 2022).	*https://www.eea.europa.eu/data-and-maps/data/high-nature-value-farmland-1*	2000–2012	Grid (100 m), EU-27
Agricultural land abandonment	JRC, Unit B3	Agricultural abandonment processes, as a result of economic decisions on the use of land, is developed within an integrative, spatially dynamic land-use modelling framework, namely, the LUISA Territorial Modelling Platform (Perpiña Castillo et al., 2020). Current and future land-use trends and major drivers of land abandonment were included under the EU Territorial Reference Scenario 2017 (Jacobs-Crisioni et al., 217). A composite EU risk map of agricultural land abandonment is used in this analysis.	*https://doi.org/10.1016/j.envsoft.2020.104946* and *https://observatory.rural-vision.europa.eu/*	2012–2050	Grid (100 m), EU-27
Erosion	JRC, Unit B3	This is a map of soil erosion by water in the EU, at a resolution of 100 m. It uses data for 2010 and 2015 from a modified version of the JRC's RUSLE 2015 model. RUSLE 2015 considers inputs of rainfall, soil, topography, land use and management. The model can be used to predict the effect of a range of policy scenarios. All the input layers have been peer-reviewed and published as well (ESDAC, 2016).	Data available on request: *https://esdac.jrc.ec.europa.eu/*	2010 and 2016	Grid (100 m), EU-27
Agricultural suitability maps	JRC, Unit B3	Three suitability maps of arable, mixed-crops and pastures production systems were used to identify locations with the lowest agricultural productivity. Computed internally in the 2021 LUISA reference scenario, the suitability results are weighted composite maps based on a set of exploratory variables with values ranging from 0 to 1, at 100 m spatial resolution (Jacobs-Crisioni et al., 2017).	Data available on request	2018	Grid (100 m), EU-27
World wind farms	The Wind Power	This database is a register of wind farms around the world. The dataset used here covers Europe, with more than 21 000 onshore and offshore wind farms in the EU. It contains data on the site location and technical specifications of each project, including its installed capacity. Wind farms included in the version of the database used here date up to April 2023.	*https://www.thewindpower.net/*	2023	Point locations, global

NAME	PROVIDER	DESCRIPTION	URL	TEMPORAL RESOLUTION	SPATIAL RESOLUTION
Global Wind Atlas	DTU – Technical University of Denmark	The Global Wind Atlas is an open-source, web-based application mapping wind resources around the world, and provides raster data at 250 m horizontal resolution. It features different datasets on wind characteristics. The dataset used here are the CFs – IEC class 2.	*https://globalwindatlas.info/en/*	Based on modelling	Grid (250 m)
Transport infrastructures World wind farms	Tele Atlas (Multinet)	Distances to the closest road were obtained by shortest-path calculations using road network data from Tele Atalas MultiNet (Tele Atlas, 2020). A 100 m resolution map with distances from each location (cell) to the closest road was built for the EU-27.		2014	Vector layer, EU-27

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