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Communication on the potential of applied PV in the European Union: Rooftops, reservoirs, roads (R^3)

Georgia Kakoulaki*, Nigel Taylor, Sandor Szabo, Robert Kenny, Anatoli Chatzipanagi, and Arnulf Jäger-Waldau

European Commission, Joint Research Centre (JRC), Ispra, Italy

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Abstract. Photovoltaics (PV) is a cost-competitive and scalable technology for electricity generation that plays a crucial role to accelerate the European energy transition and achieve carbon neutrality. Large-scale installation of rooftop PV, as well as innovative PV applications such as floating PV coupled with hydropower and bifacial PV along roads and railways, offer multi-benefits, not least in reducing competition for land. In this study, we present a geospatial approach to assess the pan-European technical potential of these three applications, using publicly available datasets. The findings reveal that the PV total installed capacity could exceed 1 TW_p, which is far larger than the total PV capacity for 2030 in the EU Solar Energy Strategy (720 GW_p) and would be a significant contribution to the several TWs needed for the overall transition to net-zero by 2050. The evidence presented is a useful starting point for policy-setting at national and regional level, as well as for research and detailed analyses of location specific solutions.

Keywords: Photovoltaics / floating / bifacial / rooftop / EU solar strategy / R^3

1 Introduction

Photovoltaics (PV) has gained recognition as a highly successful and competitive energy source and numerous studies and institutions state that it is a key technology for decarbonisation [1,2]. In the EU, the 2022 Solar Energy Strategy sets a target to bring online 385 GW_p by 2025 and 720 GW_p of PV installed capacity by 2030. The strategy highlights the need to exploit innovative forms of deployment for multiple use of space. It also includes a proposed EU Rooftop Initiative, and the introduction of a gradual obligation to install solar PV in diverse types of buildings, with a goal of installing 51–58 GW_p by 2030 [3,4]. Furthermore, the European Parliament and Council have recently increased the binding target for the share of renewables in the final energy consumption to 42.5% by 2030 [5]. The total PV power capacity in EU reached 211 GW_p in 2022, representing a 23% increase compared to the previous year [6] at 41 GW_p. For 2023 this growth is continuing with reports that new installations will be 58 GW_p. [7,8] (implying an installation rate of approximately 60 GW_p per year) [9,10]. This growth is expected to continue and even increase, to reach several TWs of PV installations by 2050 [11].

The pursuit of carbon neutrality presents also challenges, including the fact that increased demand for renewable energy electricity can raise competition for land and increase associated acquisition or access costs. Furthermore, it is imperative to ensure that the impact on the environment and biodiversity is minimized and mitigated, in line with EU policies on biodiversity and nature.

PV installations on rooftops and applications such as floating PV (FPV) coupled with hydropower, as well as PV installations along transport infrastructure (roads and railways) can offer promising solutions to address these challenges associated with expanding renewable energy capacity. These implementations (hereafter R^3) present a viable option to maximise the use of existing infrastructure without occupying additional land. Most importantly, they reduce the competition for land resources and contribute to local energy production and decentralization, while reducing transmission losses and enhancing energy resilience at the same time.

In this work we present an estimation of the technical potential for the installed capacity and electricity generation of these R^3 PV applications at EU and national level, using advanced geospatial techniques. Additional technical potentials exist for PV installations on facades, on agricultural land (agrivoltaics) [12] and on degraded land (like coal region in transition [13]) but these are not part of this investigation.

* e-mail: georgia.kakoulaki@ec.europa.eu

In this study we focus on the R^3 forms of PV deployment i.e., the multiple use of buildings and man-made infrastructure, where the unique scalability and flexibility of PV technology allow installations without significant additional environmental or biodiversity impacts.

By highlighting the pan-European potential for such PV deployment forms, this research offers insights to policymakers, energy planners, and stakeholders. It aims to stimulate further research and innovation into design and formulation of effective projects that will need to reflect local conditions and promote planning policies that favour the adoption and integration of PV energy systems in our man-made environment and to be a significant part of the energy transitions in the EU and indeed worldwide.

2 Methodology

The geospatial assessment presented here draws from previous work carried out by the authors of the Joint Research Centre, European Commission. The work on rooftop PV follows the work from [14], the floating PV coupled with hydropower builds on the work from [15] and the application of PV along roads and rails follows the work [16] (under review). The PV energy yield for the different technologies and module configurations was estimated with the online open access tool Photovoltaic Geographical Information System (PVGIS) developed at the Joint Research Centre (JRC) [17]. The PV yield is based on hourly solar irradiation data (2005–2020) and the system losses are assumed uniformly at 14% for the rooftop and floating PV application. For the PV application along transport infrastructure, we used 22% of module efficiency. Crystalline silicon PV modules were used in all the three PV applications as the most used technology. Moreover, the potential carbon intensity reduction was estimated if R^3 would be deployed. All the examined scenarios are conservative estimates and we considered factors like geography, protected areas, environmental constraints and land use limitations.

2.1 Rooftop PV potential in the EU

The estimation of the rooftop PV potential in EU follows the work of [14]. In this work freely accessible statistical and satellite image layers were used to firstly estimate the available rooftop footprint area and then derive the technical potential for rooftop PV electricity production with a spatial resolution of 100 m ×100 m across the EU. The estimation of the net available rooftop area was based on the author's previous work [18] where approximately half of the roofs in the EU were considered suitable for PV rooftop installations. Accounting the need of space between the modules' racks and self-shading, the suitable area was reduced to 26% of each building density pixel assuming a direct equivalence between building area and rooftop area [14]. The excluded 74% includes rooftop areas with unfavourable orientation and/or inclination, other uses such as air-conditioning units and chimneys, shading from other constructions, walkways for maintenance etc. The resulted suitable rooftop area is equal to 7 150 km^2, representing 0.17% of the total EU land area. The total estimated technical installed capacity is equal to 580 GW_p and the potential electricity generation equal to 680 TWh/yr. These values are conservative and by only increasing the PV module energy conversion efficiency since that study (in 2018 a value of 18% was assumed, whereas in 2002 the average efficiency was 22%, so the installed capacity and generation would increase by 22%) the PV installed capacity and electricity generation will be higher.

2.2 Floating PV potential in the EU

The estimated technical installed capacity and the potential electricity generation of floating PV deployed on 337 existing hydropower reservoirs, at specific geographic locations in EU under several area coverage scenarios was presented in [15]. The optimal FPV surface cover is highly site specific. A 10% reservoir surface coverage scenario was selected as an optimal trade-off value between environmental impact, evaporation reduction, investment costs and feasibility in the European context [19–21]. Hydropower plants defined as hydropower-based dam and hydro pump storage with an installed capacity larger than 5 MW were selected. Reservoirs with electricity and water supply as main use were selected as the grid connection already exists and the installation cost can be reduced. Reservoirs located in Natura 2000 protected areas, were excluded as an approach to reduce potential environmental impacts. The total reservoir area for the selected scenario is equal to 1 608 km^2 and the existing hydropower installed capacity for the studied hydropower plants is equal to 48.73 GW_p with a corresponding electricity generation up to 94.4 TWh/yr.

2.3 PV along roads and rails in the EU

The technical installed capacity and potential electricity generation of vertical PV modules (bifacial or monofacial) along roads and rails was estimated following [16]. Open-access data of the transport network, including roads [22] and railways [23] from various sources were used. The data were harmonised to ensure consistency and accuracy for the used input data in the geospatial-based simulation models. The transport network was segmented into 500 m sections, and the mean direction of each segment was calculated. The segment directions were then classified using 8-point cardinal directions (N, NE, E, SE, S, SW, W, NW).

An idealised vertical structure of 4 m height was assumed (as a typical noise barrier on highways has a height of 4.2 m [24,25]). The first metre from the ground was either used as a base for the PV systems or left empty to reduce the impact of soiling, shading and stone damage. Crystalline silicon modules with dimensions 1 m × 2 m (area of 2 m^2), a 22% efficiency and a nominal module peak power at Standard Test Conditions (STC) of 440 W_p was assumed. The PV yield was estimated for each segment's midpoint for both roads and railways. The inner-city part of the road sections was excluded due to the limited availability of space and land use reasons.

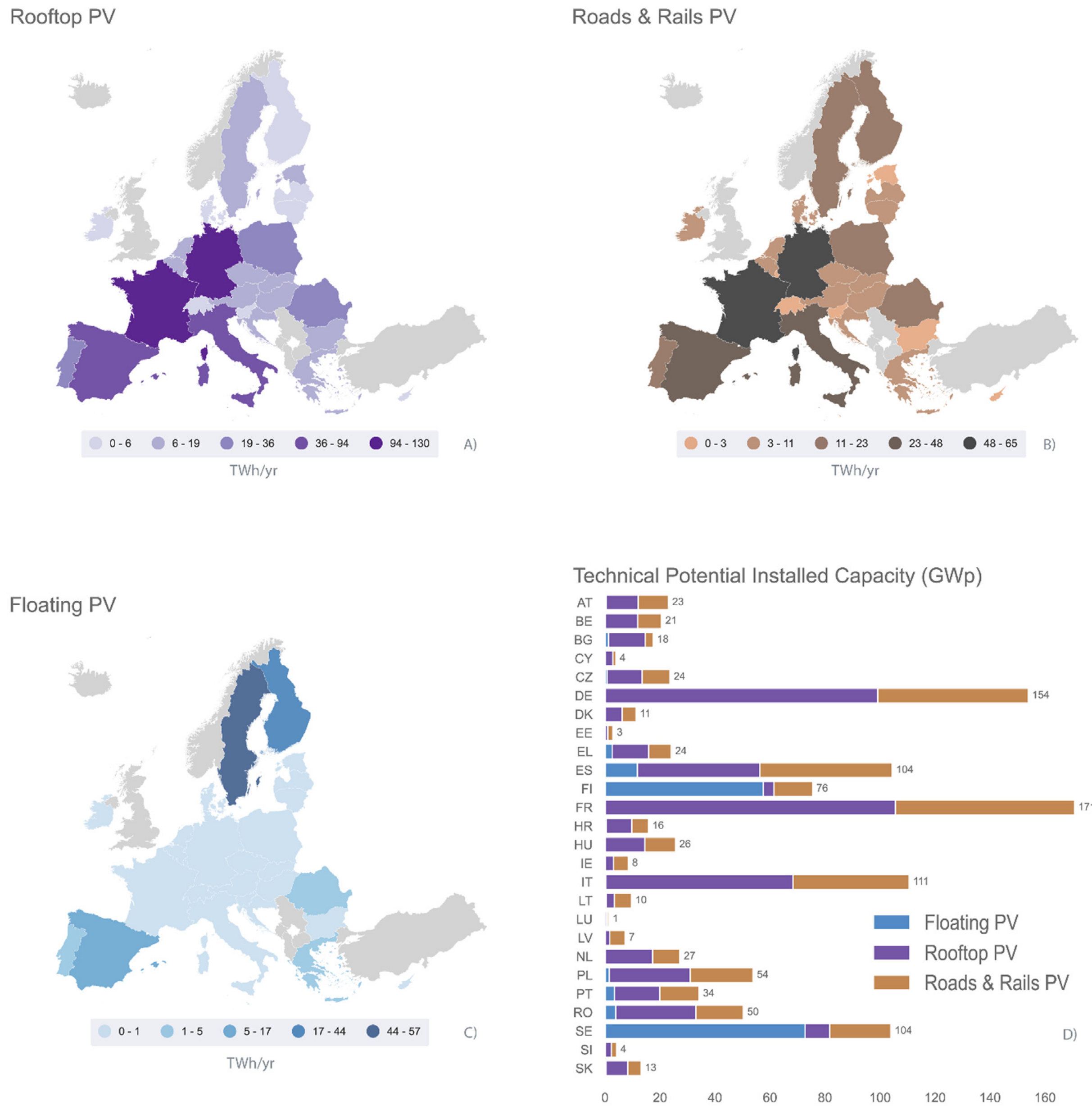

Fig. 1. The potential electricity generation per PV application, A) Rooftop B) vertical bifacial PV along roads and rails C) floating PV on hydropower reservoirs and D) bar chart with the cumulative technical installed capacity of the pre-mentioned PV applications.

3 Estimated potential of R^3

The total electricity generation potential for each considered PV application at national level is presented in Figure 1 (A, B, C) with choropleth maps. The five countries with the highest electricity generation potential are France, Germany, Italy, Spain, and Sweden, contributing 716 TWh/yr out of the EU total of 1 208 TWh/yr, or 60%. The biggest share of this electricity generation potential comes from the rooftop PV followed by the PV installed along the roads and railways. In Finland and Sweden, the highest share of electricity generation potential comes from floating PV, reflecting their substantial hydropower reservoir areas in those countries.

Figure 1, presents the overall technical potential installed capacity for R^3 across different countries. France, Germany, Italy, and Sweden exhibit a technical installed capacity exceeding 100 GW_p, with Spain and Finland closely following (104 GW_p). Rooftop PV has the highest share of the potential installed capacity in France, Germany, and Italy but also in other smaller countries. Romania and Poland trail behind with over 50 GW_p, wherein rooftop PV and transport PV applications contribute equally to their respective capacities.

Figure 2, illustrates the potential percentage of the 2022 electricity consumption covered by R^3. Also, each country is labelled with the corresponding potential carbon intensity reduction expressed in percentage. The map color-coding ranges from light yellow, indicating countries

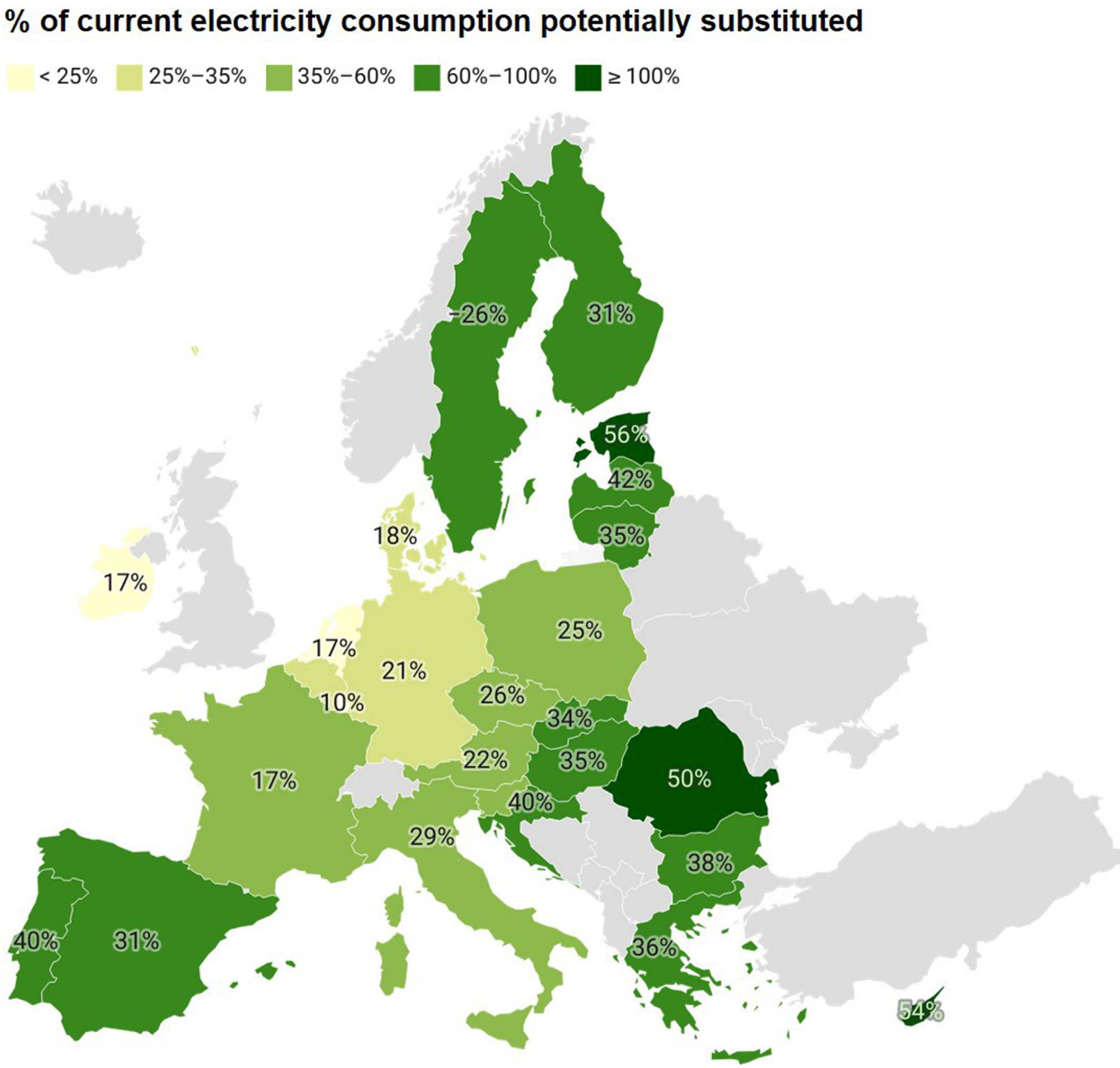

Fig. 2. Choropleth map showing to what extent the full use of the R^3 deployment options could substitute what is currently (2022) consumed. The labels represent the corresponding percentage reduction in carbon intensity per country.

with a small potential of substitution to dark green, indicating those with high potential of substitution. France and Germany could reduce their current (2022) carbon intensity between 17% and 21% with R^3 installations. Poland and Italy, the largest emitters of carbon dioxide, can benefit from the installation of R^3 with a potential reduction of carbon intensity up to 29%. Smaller countries with lower R^3 technical potential installed capacity such as Estonia, Greece, Latvia, and Lithuania can reach a CO_2 reduction of over 35%.

In Figure 3, the x-axis presents the potential electricity consumption coverage by R^3 (ratio of the technical potential electricity generation from R^3 per country (TWh) to the total final electricity consumption per country), while the y-axis shows the total final electricity consumption (TWh/yr) in 2022 per country [26]. It is observed that several small countries such as Cyprus, Estonia, could produce more electricity than their current total final consumption if deploying R^3, followed Latvia and Portugal. In the case of Romania, the country could potentially replace its entire 2022 electricity consumption with electricity generated by R^3, and even surpass it by 25%.

Eleven EU countries could deliver between 50% to 100% of their 2022 electricity consumption (Bulgaria, Croatia, Greece, Finland, Hungary, Slovakia and Sweden) if they make full use of R^3 applications. France and Germany have the largest total final electricity consumption in the EU, but they have the potential to substitute their current consumption by more than 30% with R^3. Italy

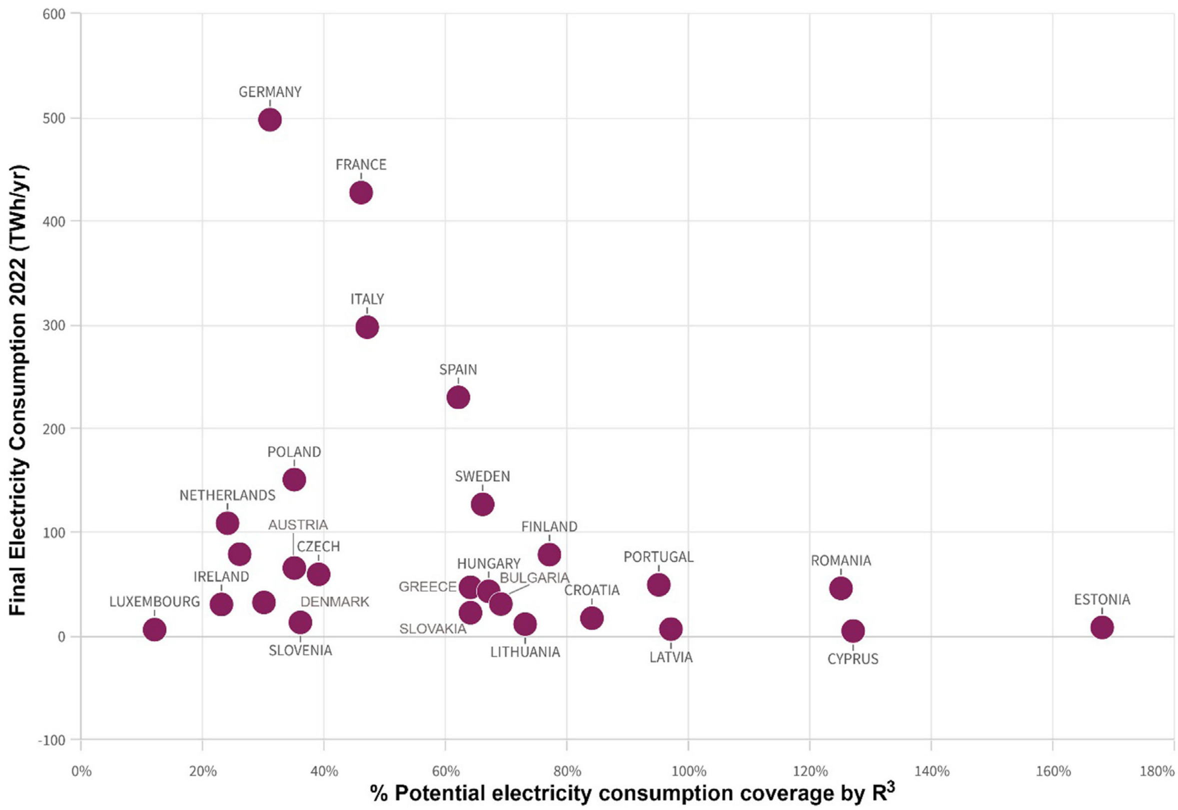

Fig. 3. Scatter plot of the ratio of the technical potential electricity generation from R^3 per country (TWh/yr) to the total final electricity consumption per country versus the total final electricity consumption (TWh/yr) in 2022 (EUROSTAT) per country.

with the third largest total final consumption could replace the current electricity production with R^3 PV deployment up to 47%.

In Figure 4, the potential per capita consumption if installing R^3 is compared to the consumption per capita in 2022 [27]. For example, Austria has a per capita consumption of 8 000 kWh of which 33% can be potentially substituted by electricity generated by R^3 PV applications The installation of R^3 in countries such as Cyprus, Estonia, Latvia, and Romania reveal the potential to not only substitute the current consumption but also provide additional electricity for other purposes. Furthermore, most of the countries could substitute more than 25% of their current electricity consumption with green electricity derived from R^3 installations. Moreover, the installation of R^3 can potentially replace the current EU electricity average consumption per capita by up to 44%. Countries like Austria, Belgium, France, and Spain whose consumption per capita is higher than the EU average, can potentially replace between 25% and 43% of it with R^3 applications.

4 Conclusions

The present work estimated the potential technical installed capacity and electricity generation of three PV applications: rooftop PV, floating PV on hydropower reservoirs and PV installed along roads and rails and how the 1 TW_p of PV installations can not only be reached but in fact surpassed. This in itself would be more than the EU Solar Energy Strategy target of 720 GW_p by 2030, and would make a significant contribution to the several TWs needed for achieving net-zero by 2050.

The total technical installed capacity potential amounts to 1 120 GW_p, of which 560 GW_p can be delivered by rooftop PV, 403 GW_p, by vertical bifacial PV along roads and rails and 157 GW_p by floating PV on reservoirs. Moreover, the deployment of R^3 can increase the total installed capacity of solar PV to 1 331 GW_p, six times more than the current 2022 installed capacity of 211 GW_p. The cumulative total potential of electricity generation is equal to 1 208 TWh/yr, representing 48% of the total electricity consumption in 2022 (2 495 TWh/yr, [26]). The rooftop PV application contributes to the total electricity generation with 680 TWh/yr (or 26% of the total final consumption of 2022), the floating PV on reservoirs 137 TWh/yr (or 6% of the total final consumption of 2022) and the vertical bifacial PV along roads and rails with 391 TWh/yr (or 16% of the total final consumption of 2022). As a consequence, the total electricity generation (the currently generated 196 TWh/yr plus the potentially generated by R^3) could reach 1 404 TWh/yr, representing 56% of the current electricity consumption.

Overall, the implementation of R^3 technology has the potential to significantly expand the contribution of solar PV to the continental electricity generation and decrease the reliance on fossil fuel energy sources. Local and regional

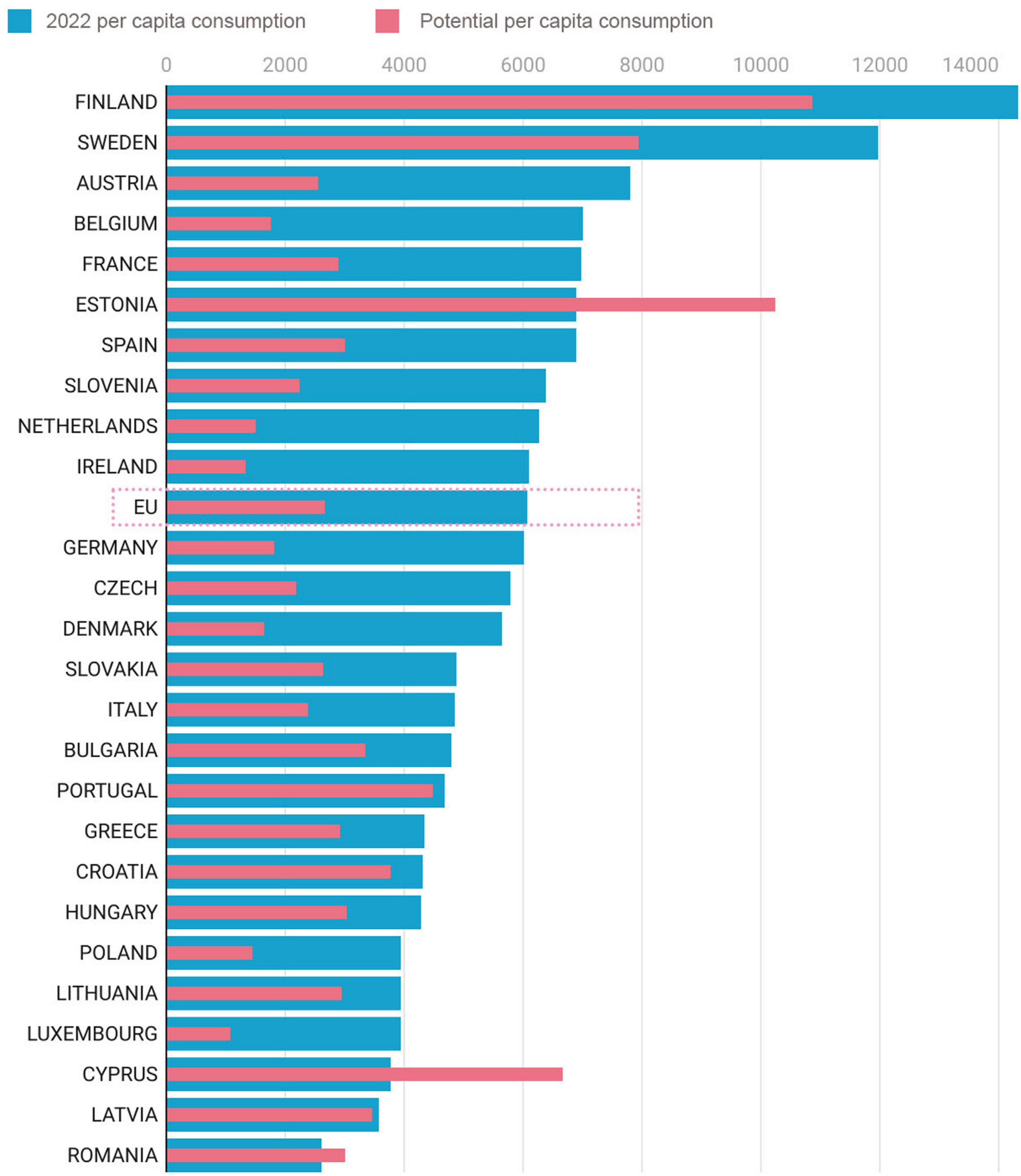

Fig. 4. Electricity consumption per capita (2022), and the potential per capita electricity consumption if R^3 is installed.

stakeholders will be in the best position to decide on which of the available options are the most suitable for the local conditions and can realise the low hanging options first and gradually extend the installation to the ones with more compromises. In some regions unutilised reservoirs, in some other roads in industrial areas or large roofs could be the starting points for PV deployment and, if extended further, can be proven effective in reaching the local climate goals. The results of this study present an opportunity for future research to address numerous factors that are crucial for the successful integration of renewable energy sources. These factors include anticipating and accommodating future increases in the overall electricity demand, ensuring proper grid maintenance, and effectively planning and expanding the infrastructure to accommodate the growing number of PV installations. By considering these factors, future studies can contribute to the development of strategies and policies that will ensure the sustainable and efficient utilization of renewable energy in the future.

Conflicts of interest

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

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Data availability statement

Data are available on request.

Author contribution statement

Conceptualization: G. K., S. S., N. T., A. JW., R.K. Methodology: G. K.; Data curation: G. K.; Visualization: G. K; Writing: G. K. Review & editing: G. K., A. C., N. T., S. S., R.K., A. JW.

Disclaimer

The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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