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Photovoltaic and wind energy potential in Europe – A systematic review

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ABSTRACT

In a context of increased renewable energy development, a growing number of studies are seeking to determine its potential. Their results provide a crucial input to long-term energy planning studies, dispatch simulations and energy policy design. This study conducts a systematic literature review of photovoltaic and wind energy potential in Europe to identify good practice in the calculation of such potential and compares the values obtained in the literature. The potential values are very heterogeneous, and the reasons for these differences are analyzed. 74% of these values exceed the capacities planned in energy transition long-term scenarios, confirming that such scenarios generally take into account studies of potential. This hides disparities, depending on the country and the technology: in general, wind power is more constrained than photovoltaics, and in particular several estimates for offshore wind power potential in Germany are lower than the capacities envisioned in some energy transition scenarios. Because the technical criteria are not limiting, some studies assessing potentials include other – political or aesthetic – criteria to give plausible development values for the potential. Assessments of renewable potential should be more explicit and cautious in their treatment of these criteria because the latter are linked to political will, hence their relevance to quantify a "potential", as opposed to a politically plausible scenario, is debatable.

1. Introduction

Since the Paris Agreement, many countries have begun setting renewable energy targets in order to reduce greenhouse gas emissions. At the same time, the European Commission has taken the lead of renewable energy targets by publishing the ambitious plan "A Clean Planet for All" [1], which is to be included in national strategies by each European Union member country. More recently, the European Commission set a target of 300 GW of offshore wind power by 2050 [2].

The costs of renewables have decreased significantly, which will help to achieve these targets. In fact, [3] report that since 2015, the costs of photovoltaics have decreased by 60%, those of offshore wind by 32% and those of onshore wind by 23%. [4] study the costs of renewables in the G20 countries and explain that renewable Levelized Costs of Energy[1] (LCOE) are already lower than conventional alternatives LCOE in several of these countries. Following this trend, renewable development scenarios continue to project a decline in renewable costs by 2030 or 2050 ([5–7]). However, the comparison of LCOE alone is not sufficient and it is necessary to consider the full system costs, including balancing and network.

With the costs of renewable technologies becoming more and more acceptable, many studies have addressed the issue of variability of renewable electricity and therefore the need for storage. [8–10] simulate systems with a high proportion of renewables (above 80%) and calculate the storage requirements and costs. They conclude that storage technologies will be able to cope with increased variability due to renewable generation sources. [11] go on to tackle more of the criticisms of renewables such as the need for transmission and distribution grid and ancillary services. On transmission grids, in particular, [11] explain that there are no technical problems with grid expansion but socio-economic issues: normally, grid development costs are a fairly small part of power system costs but can increase if public acceptance problems make it necessary to put power lines underground.

The issue of renewable installation potential therefore remains, not only the technical potential of the different technologies, but also the potential regarding the needs, willingness, or in the other sense, reluctance of the relevant populations. Population density is specifically

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[1] The LCOE is calculated as the ratio between all the discounted costs (investment, operation and maintenance, fuel) over the expected lifetime of an electricity generating plant divided by a discounted sum of the actual electricity amounts delivered.

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Abbreviations

AT	Austria
BE	Belgium
BG	Bulgaria
BIPV	Building-integrated photovoltaic
CH	Switzerland
CLC	Corine Land Cover
CPM	Capacity potential method
C + EPM	Capacity and energy potential method
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
EPM	Energy potential method
EROI	Energy Return On Investment
ES	Spain
EU27	27 countries of European Union
EEZ	Exclusive economic zone
FI	Finland
FR	France
GDP	Gross domestic product
GIS	Geographic Information System
GMPV	Ground-mounted photovoltaic
GR	Greece
HR	Croatia
HU	Hungary
IE	Ireland
IEA	International Energy Agency
IT	Italy
IUCN	International Union for Conservation of Nature
LCOE	Levelized Cost Of Energy
LT	Lithuania
LU	Luxembourg
LV	Latvia
MT	Malta
NA	not applicable
NL	the Netherlands
NO	Norway
OfW	Offshore Wind
OnW	Onshore Wind
PL	Poland
PT	Portugal
PV	Photovoltaic
RO	Romania
SE	Sweden
SI	Slovenia
SK	Slovakia
UNEP-WCMC	United Nations Environment Programme World Conservation Monitoring Centre
UK	United Kingdom
WDPA	World Database on Protected Areas
WoS	Web of Science

noteworthy in this type of analysis. This is particularly relevant in Europe compared to North America. According to the World Bank[2], the population density in 2020 was 112 inhabitants/km^2 in the European Union compared to 20 inhabitants/km^2 in North America. This relation between population density and the issue of renewable potential is due on the one hand to the consumption associated with this population (Europe has a high energy consumption per capita), and therefore to the current or future energy production needs of this population, and on the other hand to the remaining space on the territory to install these technologies.

In order to support – or question – these political decisions on renewable capacity targets, numerous studies of renewable energy potential are being conducted. These studies are a prerequisite for renewable energy development since development objectives must remain feasible and therefore must be set to be lower than the maximum potentials determined by these studies. However, the studies produce very different results. For ground-based photovoltaic, for example, [12] show a result of 86 TW in Europe[3], while [13] give 788 GW, i.e., more than 100 times less. These studies are 3 years apart ([12] is from 2017 while [13] is from 2014), so one could think that the difference in potential would be partly explained by technological progress. However, the potential here is in capacity (GW or TW) and not in energy (TWh/year), so the efficiency of the PV panels in harvesting the solar energy without too much loss does not matter. There could also be a higher installation density due to technological progress, but in this case [12] give a density of 133 MW/km^2 while [13] give a density of 151 MW/km^2.

By providing information about the feasibility of renewable energy development, studies of potential can thus excessively restrict it, or vice versa. There is therefore a need for some analysis on the wide variations between these published results, first to understand the discrepancies between the studies, and then to determine whether the renewable energy development scenarios are compatible with the potential.

Hence the aim of this study is to identify good practice in the calculation of such renewable energy potential and to compare the values obtained in the literature and the hypotheses that led to these values. This study focuses on wind power and photovoltaics (PV), which are the two technologies with the largest development targets in Europe. Actually, hydroelectricity is the most important renewable energy in Europe today, but its potential is already largely exploited ([14,15]).

This work is based on a systematic literature review of wind and photovoltaic potential studies in Europe, which to the author's knowledge had never been done. Its objective is to analyze these results concerning potential values and the methods used to obtain them. It distinguishes between onshore and offshore wind energy, and between ground-mounted (GMPV) and building-integrated (BIPV) photovoltaic energy. The potential values obtained in the literature show a great disparity between countries and technologies, which will be analyzed. However, these highly contrasting potential values are almost always higher than the values predicted by the development studies.

This paper has 4 remaining sections. Section 2 defines the terms of the study, describes the systematic literature review conducted and the most commonly used methods. Section 3 presents the results obtained by the different studies. Section 4 discusses the findings of the study and Section 5 concludes with the key findings and recommendations.

2. Material and methods

2.1. Definitions and choice of capacity potential over energy potential

2.1.1. Different types of potential for renewables

The potential for a given energy technology is defined as the amount of energy available from that technology in a defined geographical area. It can also be quantified in terms of installable capacity. The literature distinguishes different types of potential (e.g. technical, economic, etc.), but these terms do not always have the same meaning. Even the *technical*

[2] https://data.worldbank.org/indicator/EN.POP.DNST?locations=XU-EU.

[3] EU27 + Switzerland + Norway + United Kingdom.

potential, often used to represent the potential that accounts for energy losses[4] is not consistent between studies. For example, when calculating *technical potential* for onshore wind, [16] consider geographical constraints (excluding altitudes >2000 m, biodiversity reserves, urban areas, etc.), while [12] multiply the areal power density by the lower of two values, which are the "maximum allowable land area for wind power" and surface area that has an adequate capacity factor. Similarly, *economic potential* can have different meanings: [17] include in this potential all "social costs and benefits" whereas [18] account for "capital cost, production cost, electricity prices, and salient policies", yet with "land, political, and social/environmental constraints". On the other hand, sometimes different words can have very similar meanings: for example, *realistic potential* in [19] and *practical potential* in [18].

The different types of potential are therefore defined in order to avoid ambiguity. Fig. 1 shows the different types of potential and their interrelations.

The *theoretical potential* is the upper bound potential. No conversion loss is accounted for. This potential is basically how much the wind blows or how much the sun shines.

The *technological potential* is the *theoretical potential*, with the conversion loss added. It is the amount of energy and capacity one would get if it were technically possible and acceptable to install wind turbines or PV panels on every part of the planet.

The *technical potential* accounts for both conversion losses and exclusion of certain areas for technical reasons. For example, it is not technically possible to install wind turbines or PV panels on land that is too steep. These are "hard" exclusions: unless there is unforeseen technological progress, it will never be possible to install renewable technologies on the excluded areas.

The *environmental potential, social potential,* and *economic potential* have no additional hard constraints. They take into account soft constraints that may be likened to a slider, requiring a decision on where to place the cursor.

For example, for the *environmental potential*, Natura 2000[5] areas could be excluded, although there are already renewable energy facilities installed in Natura 2000 areas[6]. The *economic potential* accounts for all system costs (investment, generation, transmission and distribution, flexibility) and is based on a full power system assessment. From this full cost analysis, a threshold must be determined according to the maximum acceptable cost. An assessment of stakeholder costs alone would lead to levelized cost of energy (LCOE) arbitration and miss some system effects (e.g. additional costs related to balancing). The *social potential* considers social constraints, which are mainly conflicting uses, for example the exclusion of cities, grassland or military zones for the installation of renewables. These conflicting use constraints can be translated into legislation (for example, Article L553-1 of the French environment code forbids the installation of wind turbines within 500 m of residential zones).

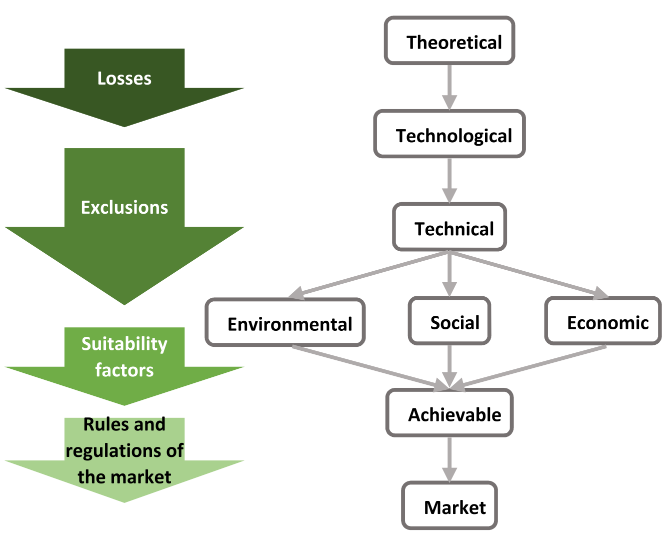

Fig. 1. Different types of potential and their interrelations.

Of course, these three potentials (*environmental potential, social potential,* and *economic potential*) are not mutually exclusive: it could be decided that rooftop PV would be placed neither on historical monuments (which would be a social constraint) nor on north-facing roofs (which would be an economic constraint), and therefore a *socio-economic potential* could be calculated.

This literature review classifies each study according to its type of potential. For instance, the results of a study that applies a single social exclusion criterion would be considered a *social potential*; it would exclude areas for social reasons only on the basis of that single criterion. The social cursor mentioned above would have been placed low on the scale. The type and number of constraints to be taken into account in these three types of potentials differ greatly between studies and can lead to misunderstandings. The consideration of social constraints is one of the causes of disagreement in the controversy between Enevoldsen et al. ([20,21]) and McKenna et al. ([22]). While McKenna et al. consider that Enevoldsen et al. have only taken into account technical constraints and therefore that the potential they obtain is only technical, Enevoldsen et al. respond that they have taken into account the proximity of wind farm development to critical landscape elements – residential areas, protected areas, and existing wind farms – which are key factors in social opposition, and therefore that their potential is indeed socio-technical.

The *achievable potential* is a more realistic value: a suitability factor is applied to all exclusion zones and may vary depending on the type of zone. For example, if agricultural areas and forests are not excluded, each of these zones can have their own suitability factor. Suitability factors are often used to compensate for imprecise exclusion information. For example, there would be no need to exclude agricultural land in its entirety (because some renewables are already installed in these areas) but of course, the whole agricultural land resource would not be entirely covered with renewables.

The *market potential* involves profitability constraints, given the electricity industry's rules and regulations. Contrary to *economic potential*, it takes legislation into account. Usually, for this type of potential, researchers use the LCOE, which relates to the current regulation mode (volume-paid productions, regardless of when it is produced) and current costs (which may change in the future) and is a market criterion only because there is a feed-in tariff at a certain level.

Although there is often a notion of time horizon, there is generally no notion of achievable potential at a deadline (maximum installable capacity per year)[7].

2.1.2. Link between potential and time horizon and choice of capacity potential

These different potentials can be expressed in terms of capacity (GW) or energy (TWh/year). In the following, the comparison between

[4] For example the fact that it is not possible to install wind turbines on every square meter of available land: the installation density reflects the need to separate one wind turbine from another by a distance equivalent to several times the rotor diameter, thus minimizing the wake effect.

[5] Natura 2000 is a network of protected areas in Europe, which includes the most valuable and threatened species and habitats (https://ec.europa.eu/environment/nature/natura2000/index_en.htm).

[6] For example Arga wind farm, see [75].

[7] On the contrary, [12] even include a minimum multiplicative factor with respect to the installed capacity in 2015.

potentials focuses on potentials in terms of capacity (hereafter referred to as *capacity potentials*) instead of potentials in terms of energy (hereafter referred to as *energy potentials*) because it reduces dependency on the time horizon, thus providing a more reliable comparison of the results. For example, technological characteristics such as the conversion losses of PV are dependent on the time horizon but only influence the calculation of the *energy potential* and not the *capacity potential*.

Using the *capacity potential* does not entirely eliminate the impact of the time horizon. For example, the time horizon will still determine the nominal capacity of the PV panels.

However, it should be noted that the *capacity potential* has the limitation compared to the *energy potential* that it is not directly comparable to consumption. It is therefore less obvious to use in practice for a policymaker who wants to decarbonize the consumption of his country[8].

2.2. Database description

To analyze the methods used and the results obtained for potentials in the literature, a multiple-key-word search on article titles was performed.

- First, a geographical key word, related to the geographical scope, which is the European Union, plus Switzerland, Norway and the United Kingdom. The word “global” was added in order to avoid missing articles.
- Second, a technology key word, as the focus was on PV and wind technologies.
- Third, a word characterizing the search for potential values.

The resulting equation is shown in Table 1.

The search was carried out in December 2020, and the results were limited to the period between 2005 and 2020.

The search was done on 3 search engines: Web of Science, Scopus and Google Scholar. On Web of Science, it yielded 358 results. On Scopus, the search on the title gave only one result (and moreover incoherent) so it was done on the set of title, abstract and keywords. It gave 626 results. Finally, on Google Scholar, the query is limited by a rather small number of characters. Therefore, only the last two keyword columns were included and the search returned 176 results.

The focus was on national and international studies, discarding subnational papers. Studies that were not related to potential were excluded, as well as studies that did not define it as described within the scope of this study: many studies focus on evaluating wind speed or irradiation at different geographical and temporal scales, which is outside our scope. The majority of the articles were in English. Articles in other languages (Polish, Korean, which were included because their title was in English) were still examined but were ultimately out of the scope and therefore excluded.

These searches yielded 35 relevant articles (32 were peer-reviewed and 3 were grey literature). Elsewhere, other relevant sources were found: 9 peer-reviewed articles and 11 grey literature documents. Some of these other sources were chosen because they appeared to be pioneering, even if they sometimes slightly predated the start of the search window (2004) or were sub-national. Other sources were missed in the searches. In total, 55 sources were deemed relevant. Grey literature studies were included because they sometimes have a similar or even greater influence than peer-reviewed studies. For example, [23] was cited 449 times according to Google Scholar, [24] 49 times, and [25] 37 times.

Fig. 2 shows changes in the cumulative number of studies by technology. A study is referenced for a technology when it calculates a potential for that technology, and therefore studies are counted several times if they evaluate several technologies.

Table 1
Web of Science search equation.

Geographical key word	AND	Technology key word	AND	Potential key word
(EU OR Europe* OR Global OR Austria* OR Belgian OR Belgium OR Britain OR British OR Bulgaria* OR Croatia* OR Cypriot OR Cyprus OR Czech OR Danish OR Denmark OR Dutch OR English OR Estonia* OR Finland OR Finnish OR France OR French OR German OR Germany OR Greece OR Greek OR Hungary OR Hungarian OR Ireland OR Irish OR Italian OR Italy OR Latvia* OR Lithuania* OR Luxembourg OR Luxembourger OR Luxembourgish OR Malta OR Maltese OR Netherlands OR Norway OR Norwegian OR Poland OR Polish OR Portugal OR Portuguese OR Romania* OR Slovak OR Slovakia OR Slovenia OR Slovene OR Slovenian OR Spain OR Spanish OR Sweden OR Swedish OR Swiss OR Switzerland OR United Kingdom)		(Renewable electricity OR Wind OR Solar OR PV OR Photovoltaic*)		(Potential OR Available OR Resource)

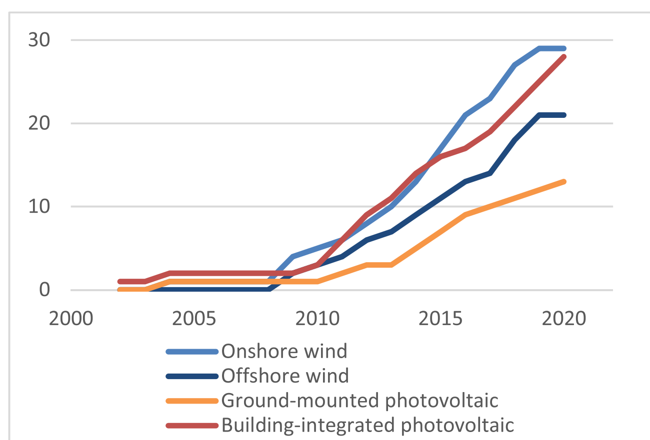

Fig. 2. Cumulative number of potential studies per technology over time.

There has been a clear increase in the number of studies of potential in recent years. Studies relating to onshore wind show the greatest increase, with 29 studies referenced, while there are only 13 for ground-based PV. The number of studies relating to onshore and offshore wind increased very early, before the 2010’s, and at the beginning of this trend, offshore wind grew as fast as onshore wind. However, from 2013 onwards, the growth in onshore wind accelerated compared to offshore wind. PV-related studies greatly increased in recent years, especially since 2013, probably due to the dramatic decrease in PV costs[9]. BIPV

[8] Thanks to an anonymous reviewer for suggesting the addition of this idea.

[9] See Fig. 2.1 in [76].

appears to be generating more interest than GMPV, despite its higher cost, probably because of its high acceptability.

The remainder of this study aims to compare the methods estimating the potential of wind and PV and explain the differences in results. Sensitivity analyses in the referenced studies were not considered but only the main scenarios. If the studies presented several hypotheses or results corresponding to several time horizons, the longest-term were used. When the so-called "economic" potential was the optimal potential to satisfy the demand, this value was not included because it constituted a scenario for the development of renewables and not a potential as defined in this work.

Table A-1 in *Supplementary information* lists the referenced sources with their origin (Web of Science or elsewhere), geographical coverage, type of literature (grey or peer-reviewed), technology assessed (onshore or offshore wind, ground-mounted or building-integrated photovoltaic), methodology used, and type of potential identified (technical, economic etc.).

As explained above, *capacity potential* is more reliable than *energy potential* with respect to time horizon dependency. The results are therefore compared in terms of *capacity potential*. For several studies, the results were only given in energy volume. All the relevant authors were contacted to request their results in GW or other information, such as the installation density or precisions on the exclusions performed.

All 55 studies are discussed in the "Methods used in the literature" section whereas only those that had appropriate data (45 studies) are compared in the "Results" section.

2.3. Methods used in the literature

2.3.1. General method steps

The simplest method adopted in the literature (referred to in the following as the *capacity potential method*) is first presented.

Wind and PV capacity potential assessment methods tend to follow two basic steps. The first step consists of estimating the eligible surface area (in km^2). This step is further broken down into two phases, the exclusion phase (exclusion of areas that are not eligible for technical, economic, social or environmental reasons) and the suitability phase (use of suitability factors to compensate for the incomplete nature of the exclusion criteria)[10]. After this initial estimation of the eligible area, the second step uses an installation density assumption to estimate the capacity potential (in GW)[11].

Depending on the exclusions made and the suitability phase, the capacity potential can be a potential of all the types defined in Section 2.1.1 above (technical, socio-economic, achievable, etc.). However, the distinction between *technological potential* and *theoretical potential* is irrelevant when speaking in terms of capacity potential, since losses are not taken into account.

Besides this general method, some studies provide innovative methods for calculating the eligible area or the density.

[26] use a participatory evaluation to determine the eligible area. It involves a lot of different stakeholders (public authorities, wind farm developers, environmental groups, etc.) who had to state their preferences on a number of criteria such as topographical restrictions, distance to settlements or suitability of protected areas to host wind turbines.

For other studies, the installation density is the result of optimization. [27] optimize the placement of wind turbines based on the energy return on investment (EROI). A ranking of the most productive locations is then obtained. The authors suggest setting an EROI threshold in order to obtain a potential. This adds an economic factor[12], but it is not specified in Table A-1 in *Supplementary information* that the potential is economic, because the values used in the *Results* chapter do not include this EROI threshold. [28] select, for any wind site, the turbine type (capacity, hub height, foundation, and rotor diameter) that minimizes the LCOE. The resulting potential, while not correcting for economic criteria per se, was labeled as an *economic potential* in Table A-1 in *Supplementary information* because the LCOE is minimized locally. [29,30] adopt the same principle and choose the turbine design that minimizes the LCOE at each location, depending on wind conditions and surface roughness. The results of these studies have been considered as *economic potentials* in *Supplementary information*, although there is no exclusion for this criterion.

Lastly, an interesting approach, developed by [31] in a follow-up study to [32] and by [16], is the quantity-price curve of the potential. These studies plot the capacity factor and/or the average LCOE as a function of the exploited potential. This method is stakeholder-centered since it considers the LCOE, but by adopting a systemic approach, one could then consider plotting the total system cost as a function of the exploited potential.

2.3.2. Exclusions

Table 2 summarizes all the exclusions applied in the different sources. The columns show the four different types of exclusion (technical, economic, social and environmental). The rows show the different technologies and the cells of the table show the exclusions made by the referenced studies.

Conflicts of use are considered here as soft constraints (social exclusions), whereas some studies considered them to be technical constraints. This implies that a forest and a fishing area would not necessarily remain a forest and a fishing area for example, and therefore it would be possible (soft constraint) to install wind turbines or ground-mounted PV panels on them.

Some criteria have no obvious classification. For example, "elevation and slopes" is included among the technical criteria but the constraint actually depends on the degree of altitude and slope: for a really high altitude or a really steep slope, it will indeed be technically impossible to install wind turbines or PV panels but for a more moderate altitude or slope, it will only be more complicated and therefore more expensive, and the criterion will be economic. The same reasoning applies to "depth" for offshore wind turbines.

For BIPV, except for some very local studies ([33–35]), exclusions are not made explicitly as is the case for other technologies. For wind and GMPV, there are databases that allow the exclusion of certain areas (for example, the exclusion of residential areas). For BIPV, on the other hand, the estimation of building areas is difficult (see Section 2.3.5) and therefore the estimation of shaded areas or areas with HVAC equipment is often done via availability factors rather than explicitly, even if new image analysis methods are being developed.

2.3.3. Suitability factors

Suitability factors are used to mitigate the fact that all exclusions cannot be accommodated and to take into account reluctance. Indeed, the non-excluded areas have owners, goals, projects, are home to fauna and flora and are part of a landscape. Suitability factors are usually dependent on land-use categories: different values are applied to forests, grassland, agricultural areas etc. In the absence of suitability factors, renewable energy potential values are almost always unrealistic.

Suitability factors are by nature imprecise but can be varied to obtain the potential depending on acceptability. [36] do this, for example, by

[10] The exclusion phase can be understood as part of the suitability phase, with suitability factors of 0%.

[11] Instead of step 2, an overlaying of the eligible surface area with the amount of power per unit area (kWh/m^2) (calculated from the wind speed or solar irradiance) gives an energy potential. This method will be referred to as the *energy potential method*. Finally, the combination of the two methods will be called *capacity and energy potential method*.

[12] EROI is an energy factor, but introducing an EROI threshold is similar to including a capacity factor (also an energy factor) threshold, which directly impacts the economic evaluation of the system.

Table 2
Exclusions applied in referenced studies and proportion of studies that apply each exclusion (e.g., 14 of the 29 studies that concern onshore wind apply the "Wetlands and areas covered by water" exclusion).

	Technical exclusions	Economic exclusions	Social exclusions (conflicting uses)	Environmental exclusions
Onshore wind	Wetlands and areas covered by water **(14/29)** Elevation **(15/29)** Slope **(16/29)** Snowy areas/Glaciers **(8/29)** Rocky areas **(1/29)**	Capacity factor **(12/29)** Distance to roads and to power transmission lines **(1/29)**	Urban areas, dwellings, roads, railways, airports, ports, other built areas **(25/29)** Air and military corridors, buffers around military and weather radars **(1/29)** Landfill and construction zones **(1/29)** Power transmission lines (+ buffer around) **(2/29)** Forests **(8/29)** Beaches and burnt areas **(2/29)** Distance to dwellings and historical landmarks **(11/29)** Buffer around roads and rails **(6/29)**	Natura 2000 **(7/29)** CDDA **(4/29)** WDPA **(8/29)** Bioreserves **(2/29)** Bird habitat **(1/29)** Fauna-Flora Habitat **(1/29)** IUCN **(2/29)** Other protected zones (not specified) (sometimes with buffer) **(3/29)**
Offshore wind	Depth **(17/21)** Areas around seismic faults **(1/21)**	Capacity factor **(9/21)** Distance to shore **(17/21)**	Oil & Gas extraction (with buffer) **(4/21)** Sand extraction **(1/21)** Shipping routes (sometimes with buffer) **(6/21)** Fishing areas **(3/21)** Military zones **(2/21)** Cables and pipelines (with buffer) **(6/21)** Telegeography **(1/21)** Protected wrecks, anchorage areas, aggregate dredging, existing wind farms **(1/21)**	IUCN **(5/21)** WDPA (by UNEP-WCMC) (sometimes with buffer) **(4/21)** Nature conservation, maritime wildlife **(1/21)** CDDA **(1/21)** Bird Habitat (+buffer) **(2/21)** WMHS **(1/21)**
Ground-mounted PV	Wetlands and areas covered by water **(11/13)** Elevation **(2/13)** Slopes **(6/13)** Glaciers **(7/13)** Rocky areas **(5/13)**	Capacity factor **(4/13)** Distance to roads, railways, power transmission lines **(1/13)**	Urban areas **(12/13)** Agricultural land, distance to dwellings **(1/13)** Grasslands **(3/13)** Roads, railways, ports, airports **(6/13)** Beaches **(5/13)** Forests **(12/13)**	WDPA **(4/13)** CDDA **(1/13)** Natura 2000 **(3/13)** Biological reserves **(3/13)** Unadapted geomorphology (DSMW) **(1/13)** "Environmentally sensitive areas" **(1/13)**
Building-Integrated PV	– NA	Capacity factor **(2/28)** Pitch of the roof least exposed to sunlight **(1/28)** North-facing roofs **(1/28)** East, North and West-facing façades **(1/28)**	Remarkable buildings (historical for example) **(9/28)** Areas dedicated to installation of thermal solar panels **(4/28)** Cities with >100 historical monuments **(1/28)** Commercial and industrial roofs **(2/28)** Roof area reserved for fire access, low structural quality of buildings **(1/28)** Chimneys **(6/28)** Shaded areas **(13/28)** Windows **(1/28)** Too small available areas **(2/28)** Security distances to the edges **(3/28)** HVAC, elevators, terraces **(11/28)**	– NA

varying this factor between 1% and 25%.

Suitability factors are often based on previous studies. For example, many studies[13] refer to the suitability factors identified in [16], which itself refer to several other sources, including [37]. An attempt to determine the origin of the latter's figures was not successful. In the same way, Bergamasco and Asinari are also pioneers in their assessment of available roof surface since their two studies[14] are used as a basis for [19,38]. [25]'s suitability factors are also used to determine those of [19,27,38].

Some suitability factors are calculated more explicitly. [32] use installed capacity of onshore wind and ground-based PV per municipality in 2012. Using an installation density assumption (8 W/m^2 for onshore wind and 60 W/m^2 for ground-mounted PV), the ratios of renewable technology to municipal area are determined. The suitability factors are set to the median value of those ratios: 12% for onshore wind and 1% for ground-mounted PV. It should be noted that if this study had been performed at the regional (or other administrative division) level, the results would have been very different: since there are municipalities in which no renewable energy is yet installed, the installed capacity per unit area per region is significantly lower than the capacity per unit area installed per municipality. This calls these suitability factors into question, even though they are calculated more explicitly than those mentioned above.

As another example, [38] estimate social acceptance on the basis of an opinion poll. They finds that 61% of people are "very favorable" to installing solar panels on their own roof, which they consider to be a conservative value of social acceptance and apply it to their result for *technical potential*, considering that this value would stand for the suitability factor.

[39] begin by estimating suitability factors for several criteria (solar radiation, topographic parameters, population, transportation network and electricity grid). For example, they use the literature to identify three slope values that correspond to suitable, poorly suitable, and unviable land, and normalizes these features (0 for poorly suitable to 100 for very suitable). They then calculate a weighted average of all the factors (equal weights, except for solar radiation) to obtain a total suitability factor.

For offshore wind, [40] also evaluate several suitability indices (wind resources, wind device structural survivability, accessibility and distance to consumer centers). For example, a threshold value of structural survivability is set and associated with a suitability index of 20%, then a linear relationship is established to derive suitability indices based on structural survivability. Finally, a formula (the quotient of the minimum over the maximum of the suitability indices) gives the total

[13] [18,27,77–79] (indirectly, through [80]), [30,81].
[14] [33,54].

suitability factor.

[41] assign scores to numerous criteria (wind speed, distance from road network, distance from electricity grid, slope of terrain, distance from urban areas, distance from places of interest, distance from natural environments, land cover type, landscape architecture) and then weight these criteria based on a survey of regional wind energy experts.

Overall, suitability factors cannot be precisely determined and are expected to vary with the time horizon of the renewable potential, either upwards (people would become increasingly convinced by renewables and would want to install more of them) or downwards (people would get tired of these technologies), but they are necessary to provide a realistic value of the potential.

2.3.4. Installation density

The installation density, expressed in MW/km^2, is, to some extent, an economic factor: it is the result of a tradeoff between the maximization of the installed capacity and the minimization of the wake effect in the case of onshore and offshore wind, and mutual shading in the case of PV. [42] highlight this compromise with figures: existing wind farms have installation densities between 10% and 50% of the installation density specified in technical studies[15].

Onshore and offshore wind turbines may be arranged either in a rectangle or a circle which gives different installation density hypotheses. For photovoltaics, installation density can be confusing because it can have different meanings. Table 3 summarizes these different types of installation density and the following will detail the photovoltaics density types.

Photovoltaic installation density has different meanings: first, it can refer to the module density itself and apply to both ground-mounted and building-integrated photovoltaic systems. For BIPV, the module density can be expressed per unit of roof/façade area or per unit of ground area, which can be tricky. For a PV module installed on a sloping roof, its footprint on the ground is smaller than its footprint on the roof because of the cosine of the angle between the ground and the roof, often around 30°. For GMPV, there is a second type of installation density, which is the density of the photovoltaic utility. As explained in [12,43], the density of the photovoltaic utility takes into account the roads that surround the modules in a photovoltaic farm and the need for sufficient spacing between the modules to limit mutual shading. As with wind power, layout choices can impact both installation density and yield. For example, installing photovoltaic panels oriented east-west rather than south reduces mutual shading, allowing more compact installations and smoothing the production curve ([44]). The Cestas solar power plant has made this choice ([45]).

It is very important to clarify this difference in installation density type. Indeed, according to [19], there is a ratio of 1–4 between the typical installation density of solar farms and that of panels. [42] find the same order of magnitude but explain that the installation density of PV farms has increased over time: it has tripled in Germany in 20 years ([46]), due to increasing module efficiency and optimized installation design for more economic land use.

Installation density is a relatively more reliable parameter than suitability factors, especially because it is based on technical specifications. However, the values used in the literature are very scattered, which will be discussed in *3.2 Scatter of values*.

Table 3
Installation density types.

	Onshore and offshore wind	Ground-mounted photovoltaic	Building-integrated photovoltaic
Arrangement pattern	Rectangle or circle	–	–
Installation density type	–	Module density or utility density	Module density per unit of roof/façade area or per unit of ground area

2.3.5. Building-integrated photovoltaic: difficult evaluation of the available surface

For BIPV, evaluating the available roof surface is particularly difficult and leads to a greater variety of methods.

These methods can be grouped into two types. The methods that appeared first are those based on rules of thumb or national statistics, from which they sometimes extrapolate. More recently, methods based on geographical information systems (GIS) have been developed. They are sometimes complemented by machine learning algorithms. Table 4 lists the BIPV studies grouped by type of method and provides some details of these methods' implementation.

3. Results

The results were compared in terms of potential per unit area, obtained by dividing the potential in MW by the area of the country[16] in km^2 (except for offshore wind where it is divided by the area of the Exclusive Economic Zone (EEZ) in km^2). This should not be confused with the installation density assumption, which has the same unit (MW/km^2).

In the remainder of this study, Hungary is excluded from the offshore wind analyses because it has no EEZ and only one study ([43]) calculates its potential, considering that Hungary could install wind turbines on Lake Balaton. [56]'s values for 100% suitability were also excluded because they are much higher than any other GMPV value and distort the results. All other GMPV studies give achievable potentials. This is probably due to the fact that GMPV has a high density per unit area (higher than wind) and is installed mainly on agricultural land, which represent large proportions of the countries (around half of the area). Therefore, not introducing suitability factors tends to result in extremely large and unrealistic potentials, which is why studies are more likely to provide the achievable potential.

3.1. Comparison with renewables development scenarios for the five biggest countries

For the five countries with the greatest electricity consumption[17] (Germany (DE), France (FR), United Kingdom (UK), Italy (IT), Spain (ES)) and for Europe as a whole, the differences between the potential values and the values proposed by the renewable energy development studies were studied. These five countries together account for 60% of European consumption and individually at least 8% of European consumption. They also happen to be the European countries with the highest installed wind and photovoltaic capacity.

The renewable energy development studies included are detailed in Table 5.

Fig. 3 shows potential per unit area values (MW/km^2) obtained by studies of potential and capacities planned in renewable energy development studies as well as the currently installed capacity. These values are given for each technology and for each of the five countries as well as

[15] The author refers to a study [30] which gives the installation density of 60 large wind power plants from 10 manufacturers with a spacing of 10 rotor diameters in the main wind direction and 5 rotor diameters in the transverse direction.

[16] EEZ surface area data were obtained from http://www.seaaroundus.org/data/#/eez.Surface area data were obtained from https://data.worldbank.org/indicator/AG.SRF.TOTL.K2; year 2012 was chosen.

[17] World Bank Data from 2014: https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC.

Table 4
Building-integrated photovoltaic method types.

	Study	Details of the method
Rules of thumb/ national statistics	IEA (2002) [47]	Rules of thumb for determining the available façade and roof area in relation to the area occupied by the building on the ground
	Hoogwijk (2004) [23]	Based on IEA (2002) [47] data, determines a formula for calculating the roof area per person, correlated to the GDP
	Mainzer et al. (2014) [48]	Relies on available German statistical data on the number of buildings by type and municipality, the type of inhabitant and the roof pitch
	RE-Shaping (2011) [49] and e-Highway (2014) [13]	Uses IEA (2002) [47] data, but RE-Shaping (2011) [49] adds another 50% factor in order to take into account the potential installation of thermal solar panels
	Defaix et al. (2012) [50]	Uses IEA (2002) [47] data as well but adds a hypothesis on the number of floors per dwelling type to take into account multi-story buildings
	Jacobson et al. (2017) [12]	Roof area per country is calculated by a formula from the floor area, an overhang multiplier, a slope multiplier and the number of stories. The floor area and the number of stories are derived from GDP/capita, density, urbanization, with parking areas calculated separately. Overhang and slope multipliers take into account latitude.
	Dupont et al. (2020) [51]	Uses Jacobson et al. (2017) [12]
	Fina et al. (2020) [52]	Uses empirical statistical data from Germany for Austria, considering that the two building stocks are similar
Geographical information system (GIS)	Izquierdo et al. (2011) [53]	GIS sampling method, using a Spanish cadaster database and satellite images
	Bergamasco & Asinari (2011a) [54]	GIS with polygons characterizing buildings
	Bergamasco & Asinari (2011b) [33]	Later improvement of the previous method with ortho-images
	Deloitte (2018) [55]	Database of the buildings in each municipality and digital elevation map of the Netherlands
	Zappa & van den Broek (2018) [43]	Roof area from Corine Land Cover' (CLC) urban categories multiplied by the fraction of these categories covered by buildings using building footprint data from the United Kingdom and the Netherlands
	Ruiz et al. (2019) [56]	Relies on CLC: for residential PV, artificial areas and continuous and discontinuous urban fabric are considered whereas for industrial PV, industrial, commercial and transport areas are considered
	Petrichenko et al. (2019) [57]	Derives roof-to-floor area factors from GIS analysis
	Bódis et al. (2019) [58]	Uses earth satellite observation data and machine learning, corrects data overestimation using other sources, such as CLC
	Gomez-Exposito et al. (2020) [59]	Assesses available rooftop surface with cartographical data from the national geographical database, using GIS
	Assouline et al. (2017) [34]	Uses the Support Vector Machines (SVM) method, associated with GIS
	Assouline et al. (2018) [35]	Uses another Machine Learning method, Random Forests, to evaluate the potential of PV on rooftops

Table 5
Renewable energy development studies and current installed capacity included in the analysis.

Studies	Time horizon	Onshore wind	Offshore wind	Photovoltaics
European Wind Energy Association (2015) [60] – three scenarios	2030	X	X	
WindEurope (2017) [61] – three scenarios	2030	X	X	
HeatRoadmap (2017) [62] – three scenarios	2050	X	X	X
European Commission (2013) [63] – reference scenario	2050			X
WindEurope (2019) [64]	2050		X	
European Commission (2018) [65] – nine scenarios	2050	X	X	X
IRENA (2020) [66]	Current installed capacity (2019)	X	X	X

for Europe. They are plotted on a logarithmic scale for improved legibility.

For PV, separate renewable energy development studies for GMPV and BIPV could not be found. Only sources that give potentials for both types of PV were therefore included. Fig. 4 shows indicators for each country and each technology: Fig. 4a) shows the percentage of potential studies that are higher than all development studies, while Fig. 4b) shows the percentage of development studies that are lower than all potential studies.

The potential values are very disparate and on average, for each country and each technology, 74% of the potential values are above all development values. This average, however, hides significant differences. The potentials are more constraining for onshore and offshore wind: for these technologies, only two thirds of the potential studies are above all development values. The most marked case is offshore wind power in Germany, where only 14% of the potential values are above the maximum development value. On the contrary, PV seems to be less constraining: for France, Spain and the UK, the potential is never binding for development. Looking at the data country by country, Spain and the UK are the least constrained by potentials: about 85% of potentials are above the maximum development value. On the contrary, the situation is much more critical for Germany, where only 46% of potential studies are above development studies. The same conclusions can be found in Fig. 4b): the development prospects for PV are much less limited by potential studies than the prospects for wind power and Germany is the country for which the development of renewable energies are the most restricted by potential studies.

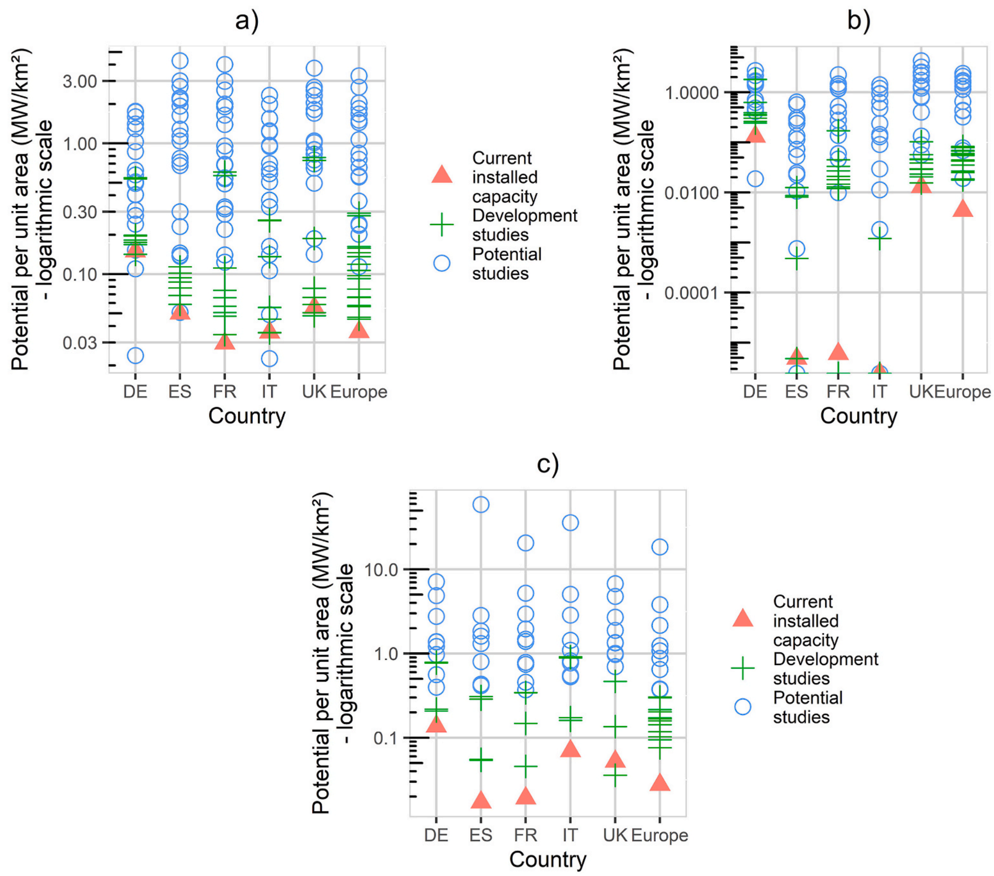

Fig. 3. Wind and PV potentials compared to capacities planned in development studies.
The current installed capacity refers to year 2019 (a) Onshore wind potential vs capacities planned in development studies, (b) Offshore wind potential vs capacities planned in development studies, (c) Photovoltaic potential vs capacities planned in development studies.

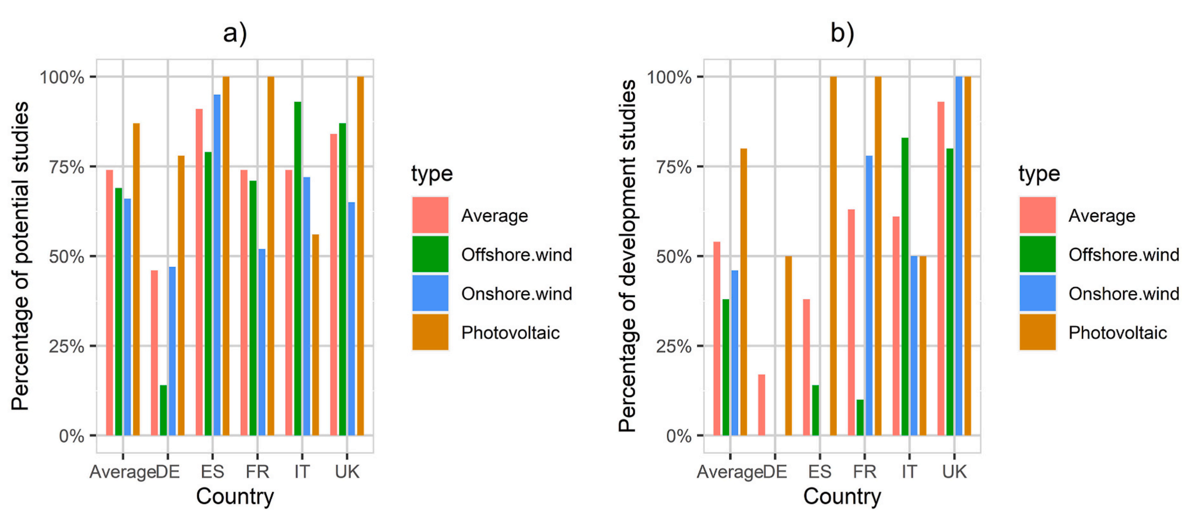

Fig. 4. Percentage of (a) potential studies that are higher than all development studies, (b) development studies that are lower than all potential studies.

Table 6
First quartile, median and third quartile of potential per country and per technology – related to current installed capacity.

First quartile, median, third quartile of the potential per country	Onshore wind (GW)	Offshore wind (GW)	Ground-mounted photovoltaic (GW)	Building-integrated photovoltaic (GW)	Current installed capacity (2019) in wind and PV (GW)	Total wind and PV potential divided by current installed capacity
DE	105	37	100	99	110	3
	182	**80**	**398**	**195**		**8**
	415	83	797	252		14
UK	179	461	147	75	38	23
	260	**1029**	**334**	**127**		**46**
	525	1944	545	167		84
ES	144	24	165	55	34	11
	557	**97**	**661**	**87**		**41**
	1106	278	934	142		72
IT	61	24	86	71	32	8
	183	**103**	**312**	**102**		**22**
	350	462	728	190		54
FR	174	65	141	77	27	17
	375	**134**	**744**	**120**		**51**
	906	397	1372	255		109
NL	16	51	11	19	11	9
	28	**77**	**35**	**25**		**15**
	55	148	96	46		31
SE	128	128	59	12	10	33
	160	**187**	**95**	**23**		**47**
	479	394	117	39		103
BE	5	2	8	11	8	3
	14	**5**	**42**	**16**		**10**
	20	6	77	26		16
DK	25	87	17	7	7	19
	50	**161**	**56**	**14**		**40**
	103	255	138	19		74
PL	122	19	88	46	7	39
	206	**78**	**401**	**48**		**105**
	546	91	802	123		223
GR	27	11	49	13	6	17
	87	**130**	**113**	**18**		**58**
	258	356	280	33		155
PT	36	5	22	12	6	13
	89	**58**	**84**	**17**		**41**
	116	113	118	32		63
AT	14	NA	30	10	5	11
	39		**50**	**19**		**22**
	58		127	35		44
IE	56	65	27	6	4	39
	112	**577**	**121**	**9**		**205**
	239	808	215	15		319
RO	44	11	85	20	4	40
	176	**39**	**357**	**27**		**150**
	368	83	713	59		306
CH	4	NA	12	8	3	8
	21		**22**	**16**		**20**
	40		33	32		35
NO	195	536	33	4	3	256
	375	**1756**	**42**	**8**		**727**
	737	2649	119	21		1175
BG	16	3	30	9	2	29
	60	**12**	**103**	**10**		**93**
	163	40	281	24		254
CZ	27	NA	26	13	2	33
	74		**99**	**16**		**95**
	109		198	28		168
FI	35	49	14	7	2	53
	69	**120**	**17**	**10**		**108**
	282	194	59	25		280
HU	8	0	32	12	2	26
	92	**0**	**162**	**15**		**135**
	166	0	297	31		247
HR	10	2	11	5	1	28
	32	**27**	**45**	**7**		**111**
	70	61	89	18		238
LT	30	4	16	4	1	54
	58	**14**	**90**	**4**		**166**
	143	18	179	12		352
SK	13	NA	12	6	0	62
	28		**53**	**7**		**176**
	47		107	18		344

(*continued on next page*)

Table 6 (*continued*)

First quartile, median, third quartile of the potential per country	Onshore wind (GW)	Offshore wind (GW)	Ground-mounted photovoltaic (GW)	Building-integrated photovoltaic (GW)	Current installed capacity (2019) in wind and PV (GW)	Total wind and PV potential divided by current installed capacity
EE	16	15	7	2	0	100
	29	**53**	**26**	**2**		**275**
	63	85	52	4		510
CY	2	0	9	1	0	42
	6	**3**	**14**	**2**		**87**
	16	65	20	5		368
LU	0	NA	1	1	0	7
	2		**5**	**1**		**28**
	2		9	1		42
SI	1	0	3	2	0	26
	6	**0**	**8**	**3**		**74**
	11	0	31	5		204
MT	0	2	0	0	0	13
	0	**41**	**0**	**1**		**280**
	0	76	1	1		520
LV	25	27	11	3	0	660
	51	**63**	**46**	**3**		**1630**
	96	97	91	7		2910
Total	1518	1628	1252	610	325	15
	3421	**4844**	**4535**	**952**		**42**
	7489	8703	8625	1665		81

Table 6 gives the median values of the potential per country[18], as well as the first and third quartiles in capacity (GW) for each technology. It finally gives the total wind and PV potential (first quartile, median and third quartile) divided by the current installed capacity (2019). In total, in Europe, the median of the wind and photovoltaic potential represents 42 times the current installed capacity. However, the first quartile of potential amounts to only 15 times the installed capacity while the third quartile equals 81 times the installed capacity. This hides differences per country: Germany has the lowest development potential compared to its installed capacity since the latter is already very large, whereas Latvia can multiply its current installed capacity by a median of 1630, since its current installed capacity is very low. The differences between countries will be discussed in Section 3.3.

3.2. Scatter of values

Table 7 shows the average potential both per unit area and as a percentage of the country's surface area (or EEZ), as well as the interquartile range and standard deviation for each technology. The average potential per unit area for onshore and offshore wind are very similar. As the installation density per surface area is much higher for PV than for wind, the average potential per unit area for GMPV is higher. For installation of BIPV, the eligible surface area is very limited compared to the surface area of the country, resulting in a much smaller average potential per unit area. Indicators such as interquartile range and standard deviation show that the values are extremely scattered, especially for GMPV.

To give an idea, the installed wind and PV capacity per unit area at the end of 2019 according to [66] are given in Table 7. However, these two types of values (potential and installed capacity) are calculated differently: the installed capacity per unit area is simply a division of the installed capacity by the surface area of Europe, whereas the average potential per unit area is the average of all the values obtained in the potential studies, therefore all countries do not necessarily have the same weight according to the number of studies that have estimated their potential.

For BIPV, studies usually give the installation density relative to the roof/façade, so the percentage of the country's surface area occupied by this technology could not be calculated.

Table 8 gives some statistics on the installation density data used by the referenced studies. Some studies have several installation density options or different installation densities depending on the country (when the installation density results from an optimization, for example in [27]), but these statistics are based on the average value for each study. For BIPV, as mentioned above, studies give either the installation density relative to the ground or the installation density relative to the roof/façade, but rarely both. Table 8 shows installation density statistics relative to the roof/façade, which has more values.

The interquartile range and standard deviation show that the installation density values are quite scattered, contrary to what might have been expected, as they are often derived from technologies' technical characteristics. However, they are the result of a trade-off between power per unit area and load factor (due to wake effect or reciprocal shading), and are therefore project-specific. For this reason, wind turbine manufacturers do not generally give installation densities. Manufacturers' installation densities for PV panels can be found: they represent the power per unit area of a panel. They are shown in Table 8 for comparison with BIPV installation density but not with that of GMPV, which includes all the rest of the utility installation. The average BIPV installation density relative to the roof/façade is 172 MW/km^2. This seems slightly higher than the values given by the manufacturers ([67]), but this can be justified by the long-term view taken by studies of potential.

The fact that the installation density assumptions are widely disparate is discussed for wind technology in [68]. The analyses generally rely on the values of existing plants, but while the installed capacity is fairly clear, the plant surface area is not. [68] explain that the measurement of plant area is generally incorrect (counting space outside the wind farm boundaries, space between clusters of turbines, and overlap space that results from the assumption of a large, fixed area around each turbine) and obtain a historical installation average of 19.8 MW/km^2 for onshore wind, which is 1.6–13 times the density that it references in the literature.

After testing the type of potential obtained (technical, social …), it turned out that this criterion could not explain the wide variation in potential values. This is probably because the study is qualified as being

[18] The following abbreviations are used hereafter: AT (Austria), BE (Belgium), BG (Bulgaria), CH (Switzerland), CY (Cyprus), CZ (Czech Republic), DE (Germany), DK (Denmark), EE (Estonia), ES (Spain), FI (Finland), FR (France), GR (Greece), HR (Croatia), HU (Hungary), IE (Ireland), IT (Italy), LT (Lithuania), LU (Luxembourg), LV (Latvia), MT (Malta), NL (the Netherlands), NO (Norway), PL (Poland), PT (Portugal), RO (Romania), SE (Sweden), SI (Slovenia), SK (Slovakia), UK (the United Kingdom).

Table 7
Descriptive statistics of the potential per unit area and percentage of the country's surface area values obtained in the systematic literature review[a].
The second largest value was chosen here because the largest was 114%, which is clearly due to a mismatch between the EEZ assumption chosen by the study and the one used here.

	Onshore wind		Offshore wind		Ground-mounted photovoltaic		Building-Integrated photovoltaic	
	Potential per unit area (MW/km^2)	Percentage of country's surface area (%)	Potential per unit area (MW/km^2)	Percentage of country's surface area (%)	Potential per unit area (MW/km^2)	Percentage of country's surface area (%)	Potential per unit area (MW/km^2)	Percentage of country's surface area (%)
Average	1.02	16.19	1.12	25.36	2.97	2.60	0.33	NA
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.01	NA
Maximum	7.02	79.85	5.46	93.24[a]	72.89	54.80	5.17	NA
Interquartile range	1.24	19.59	1.65	41.29	2.22	1.68	0.36	NA
Standard deviation	1.10	15.19	1.15	25.35	8.70	6.52	0.50	NA
Installed capacity in 2019	*0.04*	*NA*	*0.005*	*NA*	*0.03 (both ground-mounted and building-integrated PV)*	*NA*	*0.03 (both ground-mounted and building-integrated PV)*	*NA*

Table 8
Descriptive statistics of the installation density used in the systematic literature reviewFor BIPV, the density is per km^2 of panel, whereas for other technologies, it is per km^2 of land (or sea for offshore wind).

Installation density (MW/km^2)	Onshore wind	Offshore wind	Ground-mounted photovoltaic	Building-Integrated photovoltaic
Average	7.58	7.24	96.78	171.95
Minimum	1.85	0.95	30.00	41.05
Maximum	19.93	16.20	185.00	239.34
Interquartile range	4.37	6.13	110.00	31.82
Standard deviation	3.66	4.90	58.93	59.05
Manufacturer data	-	-	-	*150 (monocrystalline), 168 (polycrystalline), 96 (thin film)*

of a certain type (e.g. "environmental"), as long as it uses one restriction for this criterion. There is therefore no difference made between a study that has strict restrictions for a certain criterion and one that does not. The tests on the method used (*capacity potential method*, *energy potential method* …) were not conclusive either, probably because the studies are mostly of the *capacity and energy potential method* type.

3.3. Potential per country

To explain the differences in results, the potentials were first compared by country and their differences were analyzed. Fig. 5 shows the potential per unit area per country for each technology. Europe is also represented (average per country weighted by their contribution to the European surface area). For ground-mounted PV, the average is well above the median in all countries and sometimes even above the maximum displayed (the graph is zoomed in and 5 values are hidden, they are detailed in the figure legend). This is due to [12]'s values, which are well above the others and the fact that there are fewer studies than for other technologies, which gives more weight to [12].

The values are particularly scattered for GMPV, because of [12]'s values. Without the [12] study, the scatter of values for GMPV is comparable to the other technologies, although BIPV values remain more concentrated. For the other three technologies, there appears to be less scatter (see *Supplementary information* for further discussion on this). Besides the scatter of the results, it can be noted that the sorted list of the countries is quite different across technologies. The potential is indeed dependent on certain characteristics of the countries (e.g. percentage of agricultural land for onshore wind or GMPV) which will be discussed below.

The graphs in Fig. 6 are plots of the median of each distribution of technology potential per unit area by country as a function of other variables. Several plotting tests of the potential per unit area were done as a function of the percentage area of agricultural and forest land, population density, surface area of the country (or EEZ surface for offshore wind), rate of protected areas, altitude and latitude[19]. These factors have been chosen because they are decisive in the calculation of the potential. The percentages of agricultural, forest and protected areas are used in the calculation to increase or decrease the eligible area. Altitude and latitude can be determining factors in the calculation of the load factor and can therefore intervene in economic exclusions when selecting areas with the best load factor. The surface area (of the country or its EEZ) does not seem, at first glance, to be a determining factor of the potential per unit area, since it is normalized by it, but it is finally an important factor for offshore wind energy, as will be discussed later on. Finally, population density can operate in two directions. The higher the population density, the more buildings there are, which is favorable for the development of BIPV, but unfavorable for the development of onshore wind and GMPV. On the other hand, above a certain population density, in cities, people no longer live in single-story houses but in high-rise buildings, which do not reduce the surface area eligible for the installation of GMPV and onshore wind nor significantly increase the surface area eligible for the installation of BIPV. Only the graphs for which the regression line had the highest R^2 for each technology are presented in Fig. 6.

The onshore wind potential per country is best explained by indicators on available surface area and especially by the proportion of agricultural land in the national surface area: the potential increases when the agricultural area increases. Fig. 6a) shows the onshore wind potential per unit area per country as a function of the agricultural area ratio: the higher the proportion of agricultural area, the higher the onshore wind potential per unit area. Some countries do not follow this rule because the percentage of agricultural land is obviously not the only

[19] EEZ surface areas were collected on http://www.seaaroundus.org/data/#/eezLatitude data were collected on https://developers.google.com/public-data/docs/canonical/countries_csvIUCN protected area data were collected on https://www.protectedplanet.net/en/search-areas?geo_type=countryAgricultural land percentage data were collected on https://data.worldbank.org/indicator/AG.LND.AGRI.ZSForest land percentage data were collected on https://data.worldbank.org/indicator/AG.LND.FRST.ZSAltitude data were collected on https://www.pdx.edu/econ/country-geography-dataSurface area data were collected on https://data.worldbank.org/indicator/AG.SRF.TOTL.K2 with year 2012 chosenPopulation density data were collected on https://data.worldbank.org/indicator/EN.POP.DNST.

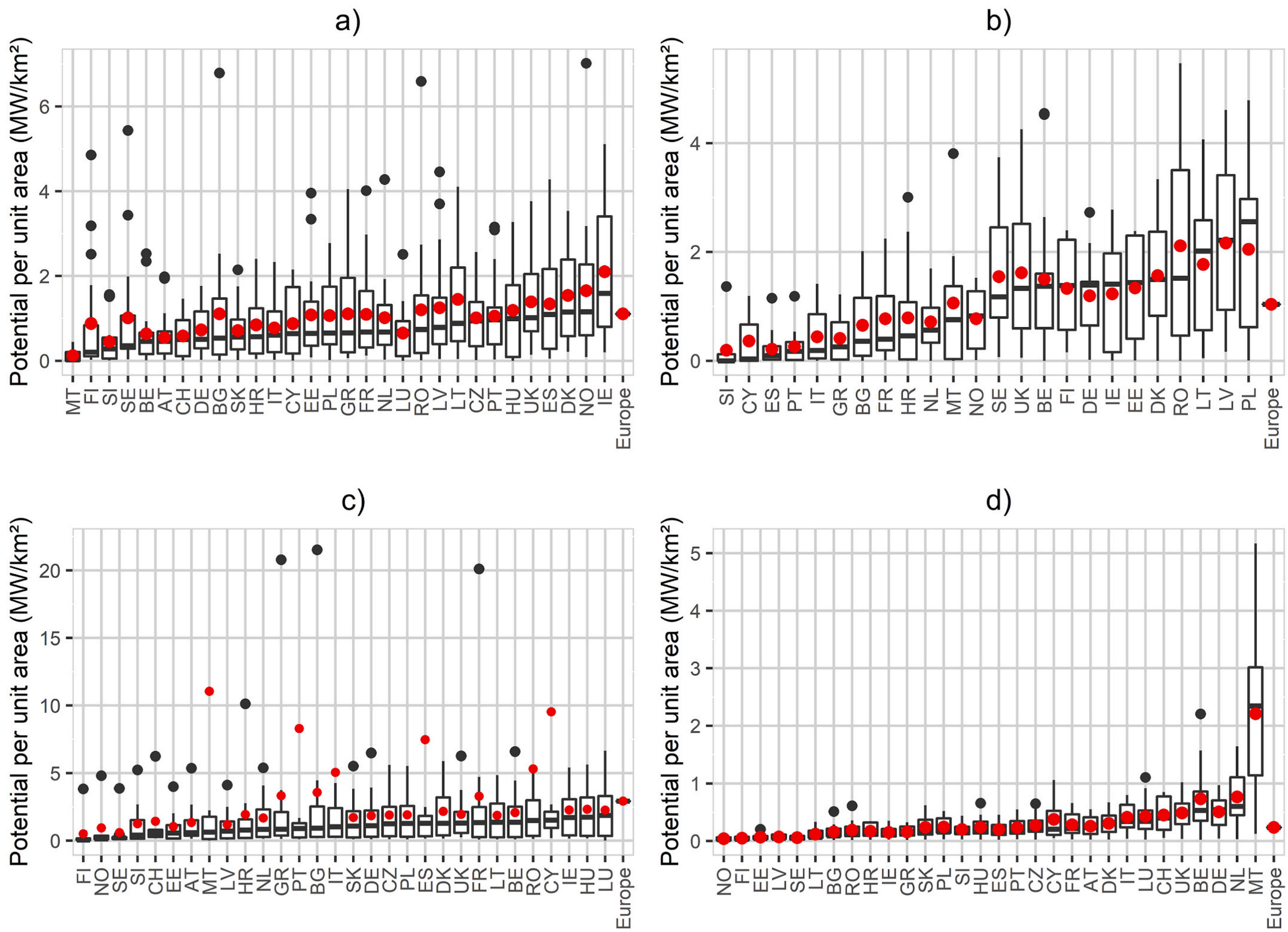

Fig. 5. Potential per unit area per country ranked by increasing median - for each technology, a) Onshore wind, b) Offshore wind, c) Ground-mounted photovoltaic, d) Building-integrated photovoltaic.
The red dots are the average values for each country. The ground-mounted photovoltaic graph is zoomed in for better display: the hidden values are all from the [12] study and are 73 MW/km^2 for MT, 69 MW/km^2 for PT, 59 MW/km^2 for CY and ES, 35 MW/km^2 for IT and 34 MW/km^2 for RO.

factor determining onshore wind potential: for example, Malta has a percentage of agricultural land comparable to the other countries but the lowest potential because it has the highest population density.

The pattern for offshore wind is the least pronounced, but the offshore wind potential per unit area is generally inversely proportional to a country's EEZ area (see Fig. 6b), which shows the offshore wind potential per unit area per country as a function of increasing EEZ area). This figure excludes Slovenia because its median was zero, which is not convenient in a logarithmic scale graph. Because it is more expensive and technically more difficult to install wind turbines far from the coast, a large EEZ area is not always advantageous for offshore wind potential per unit area. Countries with a smaller EEZ area often find it proportionally more accessible, which explains the decreasing pattern in Fig. 6. Of course, again, this rule is not absolute because having a small EEZ area does not necessarily mean that it is proportionally more accessible. Moreover, this is not the only criterion that determines potential. For example, it can be seen that Portugal has a lower potential per unit area than the United Kingdom, which is due, among other things, to the great depth of the sea in the Portuguese EEZ, while the depth of the EEZ in the United Kingdom is less inhibitory. The seas bordering the countries are represented by the colors on the graph. Countries facing the northern seas (North Sea, Baltic Sea and northern part of the Irish Sea) generally have a higher potential per unit area than countries facing the southern seas (Mediterranean, Black Sea, and the part of the Atlantic Ocean bordering France, Spain and Portugal). This can be explained by water depth, relatively low in the northern seas while being very high in their southern counterparts, making the installation of offshore wind turbines much more difficult.

Fig. 6c) shows ground-mounted PV as a function of agricultural surface area and Fig. 6d) shows BIPV as a function of population density. Of course, GMPV increases with agricultural area and BIPV increases with population density.

For offshore wind, the values of the potential per unit area with and without the possibility of installing floating wind turbines were compared (Fig. 7). It was assumed that studies which do not specify the type of turbines used (floating or fixed) but only exploit the sea to a depth of 50 m do not consider the possibility of installing floating turbines. The possibility of installing floating wind turbines is a determining factor in the calculation of the potential, which is approximately 5 times greater if this possibility is considered.

3.4. Change in potential over time

After comparing the potential between countries, the change in potential over time was assessed.

Fig. 8 shows change in potential per unit area for each technology compared to publication date. The graphs in this figure show both a single value per study (the average value of potential per unit area for

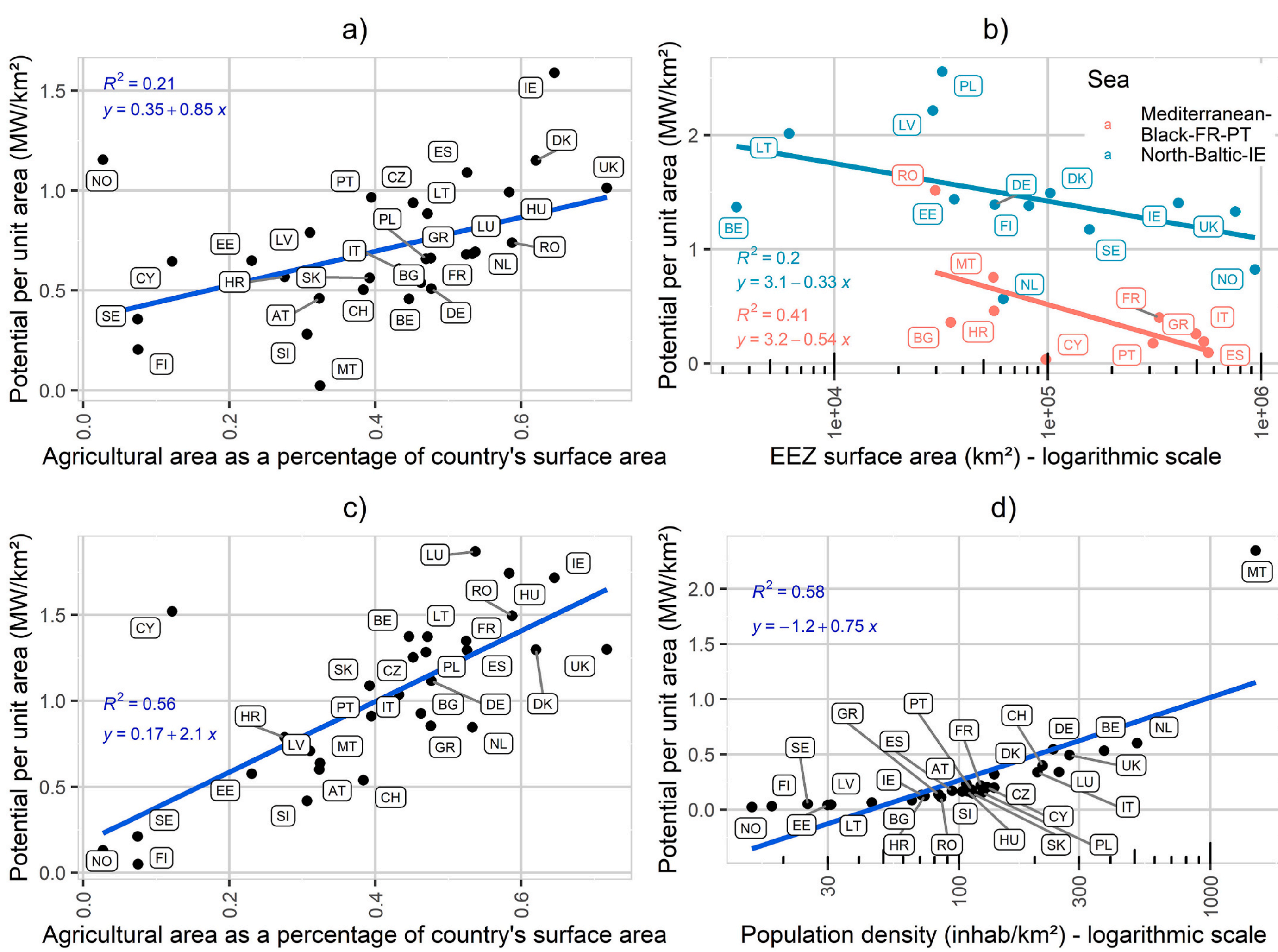

Fig. 6. Potential per unit area as a function of a) agricultural area for onshore wind, b) EEZ surface area for offshore wind, c) agricultural area for ground-mounted photovoltaic and d) population density for building-integrated photovoltaic.

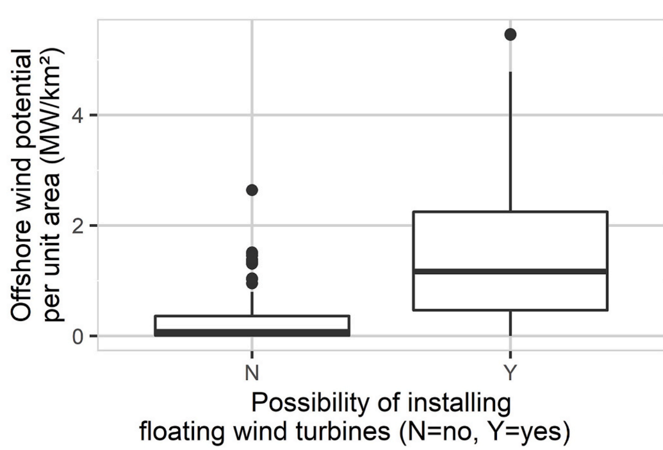

Fig. 7. Offshore wind potential per unit area with and without the possibility of installing floating wind turbines.

each study) and all the values obtained in each study. The regression line is shown only for the data series for which the slope is significant at the 90% confidence level. For the two series for which the line is plotted (onshore wind and GMPV – all values), the slope is even significant at the 99% confidence level. The trends are thus very significant, whereas for the other data series (offshore wind and BIPV), there is no particular trend. Studies carried out at the national level have a different color to those carried out at the European level but both contribute to the evaluation of the trend.

There is an upward trend in potential for onshore wind. To explain this increase, the change over time of the installation density was studied for all technologies but no trend was found. Since onshore wind installation density does not increase over time, the increase in potential may be due to lower exclusions applied to territories or to higher suitability factors.

For GMPV there are too few studies. The trend shown in the graph is due to the 2019 [56] study: there appears to be an increase in potential over time. On the other hand, when this study is excluded, a decreasing trend is shown with non-zero significance for a 7% risk. Therefore, no robust conclusion can be drawn regarding changes in GMPV potential over time.

3.5. Peer-reviewed vs grey literature

After assessing changes in potential as a function of publication year, the source of the values was studied, to find out if there is a difference between the articles from grey literature (12 documents) and peer-reviewed articles (33 articles).

For example, articles that are at the preprint stage are considered grey literature. On the contrary, the [69] study appears in a journal

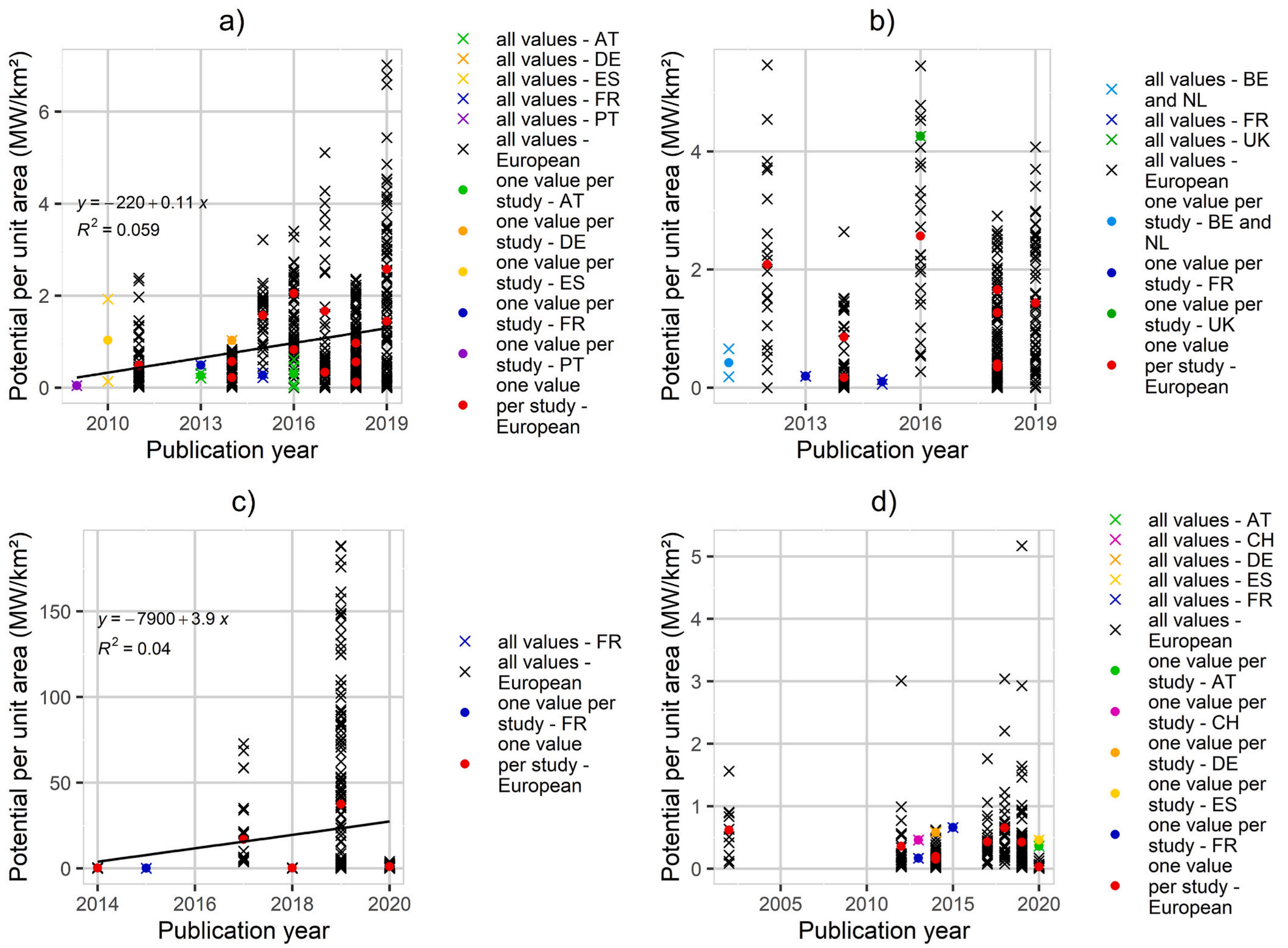

Fig. 8. Change in potential per unit area over time (by publication year) – a) onshore wind, b) offshore wind, c) ground-mounted PV, d) building-integrated PV.

article as [56], so it was considered to be peer-reviewed. Likewise [38, 70], are counted as one single peer-reviewed study because they constitute the same study and [38] is peer-reviewed whereas [70] is classified as a grey literature study.

Fig. 9 shows boxplots of the potential per unit area (MW/km^2) for peer-reviewed and grey literature and for each technology. The comparison was also made for potentials as percentages of the country's surface area instead of potentials per unit area (MW/km^2), but the latter graph is not shown. The difference between grey and peer-reviewed literature is very similar in both cases, which shows that this difference is not due to the installation density (in MW/km^2) hypothesis. The graph is zoomed for better readability, but only a few values for offshore wind peer-reviewed literature are not visible on the graph.

Grey literature studies give lower estimations of potential than their peer-reviewed counterparts, mainly for onshore wind, offshore wind and ground-mounted PV. This trend is very pronounced for GMPV, as it is the technology for which there are the fewest studies and therefore each study has a greater influence on the trends. For example [56], with a density of 300 MW/km^2 (the highest density for GMPV) increase the average of the peer-reviewed literature values while [71], who use a density of 30 MW/km^2 (the lowest), decrease the average of the grey literature values.

4. Discussion

In Fig. 8, the only potential that actually increases over time is onshore wind. In Fig. 4, development studies make much more use of wind potential than PV potential. This corroborates the observation in Fig. 2, which showed strong interest in wind, particularly onshore.

In Fig. 3, the potential per unit area for onshore wind is much greater in France, Spain and the UK than in Italy and Germany. On the other hand, renewable energy development studies show Germany as having the greatest number of onshore wind installations per surface area. The offshore wind potential per unit area is much greater in France, Germany and the UK than in Italy and Spain, but again, renewable energy development studies show Germany as having the greatest number of offshore wind installations per surface area. This illustrates the fact that in the current context for which the potentials are generally not limiting, the prospects for the development of wind energy are not necessarily in the countries that have the most potential, but rather in the countries in which there is already clear development.

Hard constraints are not at all limiting for wind and PV energy potential values, so studies apply suitability factors in order to obtain more reasonable values. Even with these, the potentials obtained are not constraining for current development perspectives. Instead, alternative methods coupling potentials with other factors could be developed. Quantity-price curves with LCOE are already developed ([16,31]). It would be interesting to show these curves with potential as a function of total system cost rather than using LCOE. It would also be interesting to develop studies that would show potential at a very local scale in order to see grid constraints, or give a potential according to distance from dwellings, a determining factor for local opposition ([72]). This would make it possible to compare the different potentials, which would be more relevant.

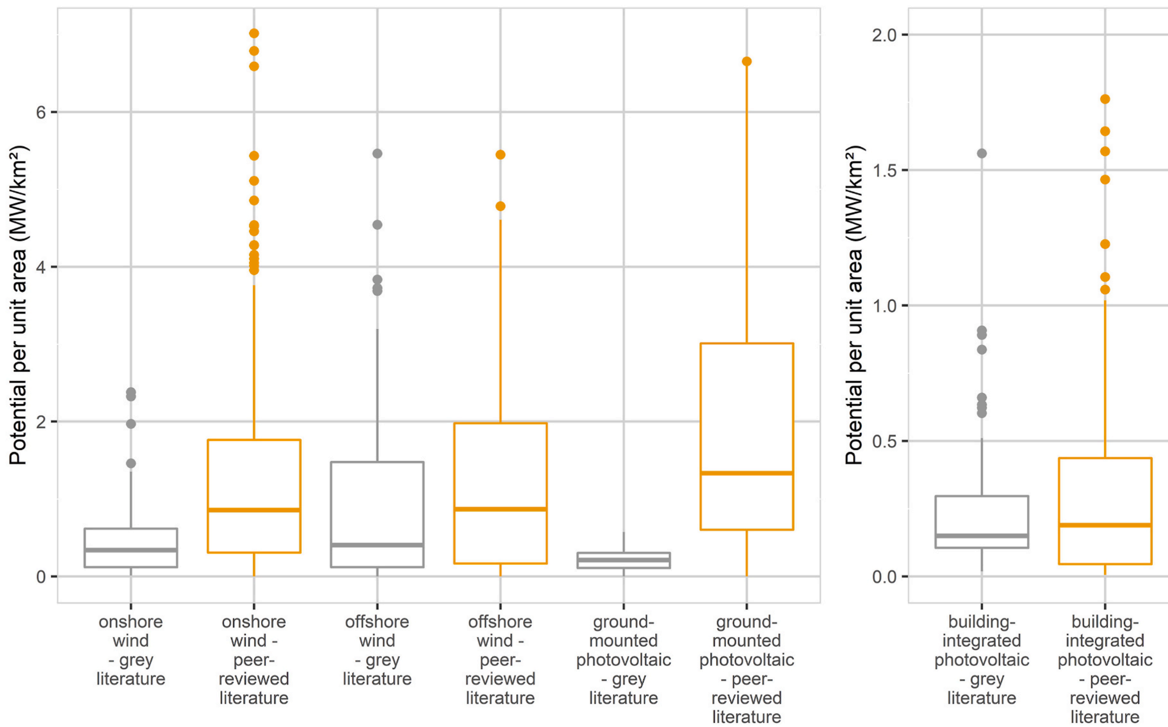

Fig. 9. Potential per unit area in grey and peer-reviewed literature.

It can be noticed that floating photovoltaic has not been discussed in this study, which is surprising because it seems to be an interesting technology. [73] for example explain the various interests that this technology can present, such as the easiness of panel cooling and the reduction of land occupancy. However, there do not seem to be any specific studies on its potential in Europe, since such studies would not have been excluded during the systematic research. In fact, out of the results obtained with the three search engines, only one study ([74]) focused on floating photovoltaics, and calculated its potential only on a dam reservoir under construction in Portugal (and therefore not on the whole country, which made it inconsistent with the purpose of this study). The floating photovoltaic potential is therefore a topic that should be developed in future research.

5. Conclusions

In this study, a systematic review of wind and PV energy potential studies was conducted. The methods used to assess potential were analyzed and the results obtained were compared. The referenced studies do not differ much in terms of their methods, but greatly in their results.

The methods consist of excluding certain areas that are not eligible for wind and PV energy installation, then excluding certain proportions of other areas that have softer constraints, and finally applying a technology installation density assumption. The problem is that the exclusion criteria most widely used in the potential studies do not give a limiting potential value for current development prospects. The studies therefore include, explicitly or not, political, aesthetic, social or economic constraints via suitability factors, in order to limit the potential. The problem is then to incorporate politics or social willingness, but without presenting it as such. The choice of developing nuclear energy rather than wind or photovoltaic energy may be political or social, but it is not due to limits on potential for renewables: there are political or social reasons why part of the potential will never be used.

In terms of results, the average potential values obtained, in installable capacity compared to the country's surface area, are, respectively, 1 MW/km^2 for wind (onshore and offshore), 3 MW/km^2 for ground-mounted PV and 0.3 MW/km^2 for building-integrated PV. However, these values are questionable, since the standard deviation is respectively 1 MW/km^2 for wind, 9 MW/km^2 for ground-mounted PV and 0.5 MW/km^2 for building-integrated PV. The average installation density assumption used in the referenced studies is 7 MW/km^2 for wind (with a standard deviation of 4 MW/km^2), 97 MW/km^2 for ground-mounted PV (with a standard deviation of 59 MW/km^2) and 172 MW/km^2 for building-integrated PV (with a standard deviation of 59 MW/km^2). On average, the percentage of the area (land or EEZ) available for each technology is 16% for onshore wind (standard deviation of 15%), 25% for offshore wind (standard deviation of 25%) and 2.6% for ground-mounted PV (standard deviation of 6.5%).

Studies of wind and PV energy potential were compared with those for its development. Results from studies of potential are mainly higher than the capacities planned in development studies (74% of the potential values exceed energy transition long-term scenarios capacities), with great disparities between countries and technologies. For example, wind potential constrains expected development of wind energy much more than is the case for PV.

To analyze the differences in terms of results, the potentials were first compared by country and found to differ according to the countries' intrinsic characteristics: agricultural area ratio, exclusive economic zone surface area, population density. Changes in potential per unit area for wind turbines and PV panels were then studied according to publication year. For PV and offshore wind, no clear trend can be deduced. However, estimates of onshore wind potential are clearly increasing over time, while after studying the installation density, the density hypothesis is not found to increase over time. Therefore, the upward trend in estimates of onshore wind potential is due to a reduction in spatial exclusions or higher suitability hypotheses. The fact that estimates of onshore wind potential increase with publication year, that onshore wind development studies predict high installed capacities compared to the potential, and that the number of studies concerning this technology is increasing significantly year after year seems to show some enthusiasm for onshore wind energy. Last, the origin of the studies (peer-reviewed or grey literature) was examined. It was found that peer-reviewed studies estimate higher results than grey literature studies.

The key findings are that only the exclusions of technically ineligible areas are restrictive. To this *technical potential* are added political, aesthetic, social or economic constraints which differ according to the studies and lead to varied but more realistic results, and which sometimes constrain the development objectives of renewables, but more often leave them unhindered.

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Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.113189.

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