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High-resolution large-scale onshore wind energy assessments: A review of potential definitions, methodologies and future research needs

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ABSTRACT

The rapid uptake of renewable energy technologies in recent decades has increased the demand of energy researchers, policymakers and energy planners for reliable data on the spatial distribution of their costs and potentials. For onshore wind energy this has resulted in an active research field devoted to analysing these resources for regions, countries or globally. A particular thread of this research attempts to go beyond purely technical or spatial restrictions and determine the realistic, feasible or actual potential for wind energy. Motivated by these developments, this paper reviews methods and assumptions for analysing geographical, technical, economic and, finally, feasible onshore wind potentials. We address each of these potentials in turn, including aspects related to land eligibility criteria, energy meteorology, and technical developments of wind turbine characteristics such as power density, specific rotor power and spacing aspects. Economic aspects of potential assessments are central to future deployment and are discussed on a turbine and system level covering levelized costs depending on locations, and the system integration costs which are often overlooked in such analyses. Non-technical approaches include scenicness assessments of the landscape, constraints due to regulation or public opposition, expert and stakeholder workshops, willingness to pay/accept elicitations and socioeconomic cost-benefit studies. For each of these different potential estimations, the state of the art is critically discussed, with an attempt to derive best practice recommendations and highlight avenues for future research.

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Contents

1. Introduction

Renewable energy has become an important player in global energy and development policy, representing 62% of new power generation capacity from 2009 to 2018 [1]. The most significant non-hydropower renewable technology is onshore wind energy, which has grown from 13% to 24% of the renewable energy capacity over this period [2]. To ensure climate protection and sustainable development, renewable energy capacities including wind must grow four times faster than this from now to 2030 [1].

Achieving such growth requires an accurate assessment of the potential available to achieve this objective in a cost-efficient and socially acceptable way. In this context, resource assessments for renewable energy have become an active field of research, driven by the worldwide push towards more sustainable energy systems. The significant attention devoted to this area in research over the past decades has led to substantial methodological improvements and more reliable resource estimates. This includes improvements in atmospheric modelling and data availability, land use mapping with open-source data, as well as understanding of techno-economic turbine characteristics. One additional area which has seen particular methodological focus is improving the ways in which such studies account for non-technical (e.g., social) constraints for renewable resources like onshore wind (e.g. Refs. [3–6]).

Using a manual internet search and by screening 880 articles[1] and 88 reviews[2] in the Scopus database, we were able to identify and examine several previously published reviews on onshore wind energy. These include bibliometric analyses of general trends in this research area [7] or, for example, of specific factors that influence the economics of wind energy projects [8]. Other studies focus on the history of wind turbines [9] and global developments of wind energy diffusion in recent years [10]. A large stream of research deals with the forecasting of wind power generation or meteorological aspects, such as wind speeds, and has already resulted in many reviews [11–15]. Further reviews deal with onshore wind related to markets [16], environmental impacts [17], or detailed technical resource assessments of individual wind turbines in specific locations [18,19] such as urban environments [20]. Reviews of onshore wind potentials have mostly examined studies on specific aspects, such as the system integration of wind turbines, e.g., in electricity grid analyses [21] or energy system planning models [22]. There are also review studies that address onshore wind potential assessments in general, but usually only in a short section and mainly with a focus on the geographical potential [11,23,24]. Others have reviewed methods and tools for onshore wind potential assessments in the context of the broader spectrum of renewable resources, whilst focussing mainly on the technical aspects [25].

In summary, there is no review of best practices in identifying different (geographical, technical, economic) onshore wind potentials in large regions consisting of multiple countries or continents. At the lower end of the geographical scale, this review excludes detailed studies of wind park layout and planning (e.g. Refs. [26–28]) as such detailed analysis are not feasible at large scale. In addition, we similarly exclude sub-national or national resource assessments (e.g. Refs. [29–40]) that can be considered case studies and are therefore simply an application of standard state of the art methods reviewed here. The exception is when such studies employ a novel method, in which case they are considered with respect to these particular characteristics. Furthermore, the present review also considers non-technical, social aspects of onshore wind energy planning. Finally, the scope is limited to

[1] Search query on 12/15/2020: *TITLE ("onshore wind" OR "wind power" OR "wind energy" AND (evaluat* OR assess* OR analy* OR pot* OR plan* OR simul* OR optimi* OR model*)) AND TITLE-ABS-KEY (wind AND (power OR generation OR energy) AND (evaluat* OR assess* OR analy* OR pot* OR plan* OR simul* OR optimi* OR model*) AND (potential OR locat*) AND (generation OR cost OR lcoe OR econom*)) AND SRCTYPE (j) AND (LIMIT-TO (DOCTYPE, "ar")).*

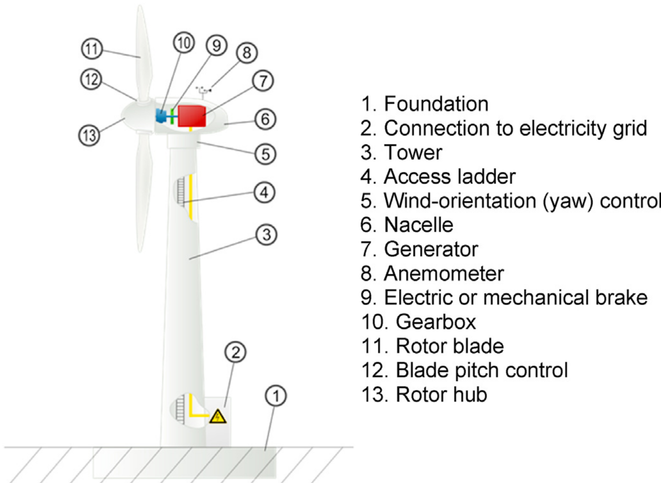

Fig. 1. Horizontal Axis Wind Turbine (HAWT) with three-bladed design and a description of the components [155].

Horizontal Axis Wind Turbines (HAWTs), as shown in Fig. 1, which are by far the most widespread due to higher aerodynamic efficiencies and lower costs than alternatives [41].

In the field of resource assessments for renewable energies, it is common to distinguish between different degrees of potential. Hence Hoogwijk et al. [42] distinguish four categories of potentials (cf. Table 1):

- The *theoretical or physical potential* refers to the total energy content of the wind within a specific region.
- The *geographical potential* equals the total area available for wind turbine installation accounting for technical, ecological and social constraints, such as minimum distances to infrastructure, protected areas or settlements.
- The *technical potential* corresponds to the wind power generated within the geographical potential. It considers constraints such as wind turbine characteristics, wind farm array losses and electrical conversion losses.
- The *economic potential* is the subset of the technical potential which satisfies criteria of economic profitability, which may differ between social welfare and private firm's profit-maximizing perspectives respectively. The economic potential strongly depends on prevailing energy-political and market frameworks.
- The above taxonomy can be extended further to consider that fraction of the technical potential considered practically achievable or desirable. So, for example, Jäger et al. [3] define the *feasible potential* as “the actual achievable economic potential, whilst accounting for market, organizational and social barriers, which mean that in practice the economic potential is not realized.”

Table 1 summarises how the above potentials are defined and relates them to examples to energy policy. Whilst theoretical/physical and geographical potentials are generally irrelevant for energy policy, technical, economic and feasible potentials are highly policy-relevant. On the one hand, these potentials are influenced by the laws, targets, and incentives at regional, national and international levels; on the other hand, these potentials and their dynamics arguably have a strong impact on policymaking, especially but not only in terms of the feasible potentials.

In this paper, we follow the same categorization of potentials, although we also highlight that this is an oversimplification, in particular the difference between geographical and feasible potential is vague. In the discussion in sections 5 and 6, we address these conceptual challenges in more detail. With the above framework of potentials as a structure, this paper provides an overview of recent developments in the field of resource assessment for onshore wind. In doing so, it discusses the state of the art in each of these areas and provides impetus for further research. Section 2 provides an overview of the geographical potential, especially the different land eligibility criteria employed in the literature on onshore wind energy. Section 3 then focuses on the technical aspects of onshore wind potentials, including the meteorological challenges and datasets, the technical characteristics of wind turbines, the issue of extreme wind speeds, and the spacing of wind turbines in wind parks. Subsequently, section 4 discusses economic aspects of onshore wind assessments, including the definition of the economic potential, the economic characteristics of turbines, various economic potential estimates for onshore wind, and the question of system/integration costs. Section 5 then turns to the so-called feasible potentials, reviewing the literature addressing those aspects not falling within a solely technical and/or economic framework, e.g., public acceptance, noise etc. Finally, section 6 critically assesses the methodological approaches presented in the preceding sections and presents some outlooks for further research.

2. Geographical onshore wind potential

The geographical potential of wind energy is mostly defined as specific geographical areas available to install wind turbines (e.g. Refs. [3,43–46]), as shown in Fig. 4 (1, top). Other names for this type of wind energy potential in literature are practical potential [47], preliminary area definition [48], environmental factor [49], generally suitable sites [6] or suitable construction area [50]. Some studies include the geographical potential in part or fully into the technical potential (e.g. Refs. [29,30,44]), while others do not even cover this step at all [31]. Other studies further divide the

Table 1
Overview of different potential definitions and examples of their policy relevance.

Potential term	Definition	Policy relevance
Theoretical or physical potential	Total energy content of wind, e.g. globally.	Generally irrelevant
Geographical potential	… the geographical area available for wind turbines, e.g. globally.	Generally irrelevant
Technical potential	Electricity that can be generated from wind turbines within the geographical potential, over a given period of time (e.g. a long-term average or an hourly time series over a specific year), and with a given turbine technology (e.g. current, future).	Wind industry R&D, innovation and market dynamics
Economic potential	Subset of the technical potential that can be realized economically.	Energy-political frameworks
Feasible potential	Subset of the economic potential after accounting for non-technical and non-economic constraints.	Public acceptance, market barriers, inertia/resistance

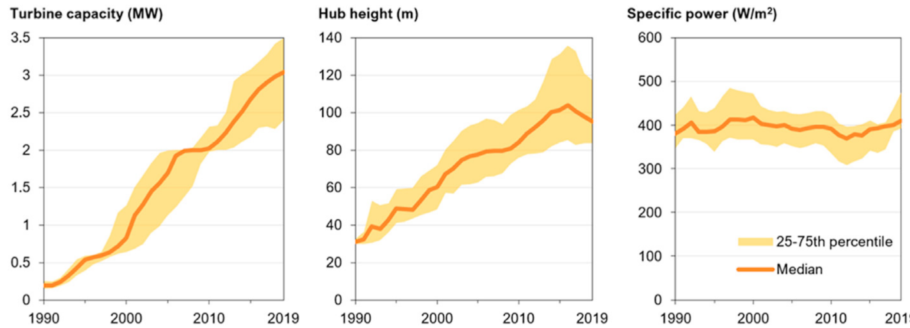

Fig. 2. Evolution of Europe's onshore wind turbines over the last three decades. Each panel shows the average specifications of new turbines installed in each year using data from Refs. [80,81]. Shaded areas represent half of all new turbines installed, covering the 25th to 75th percentiles.

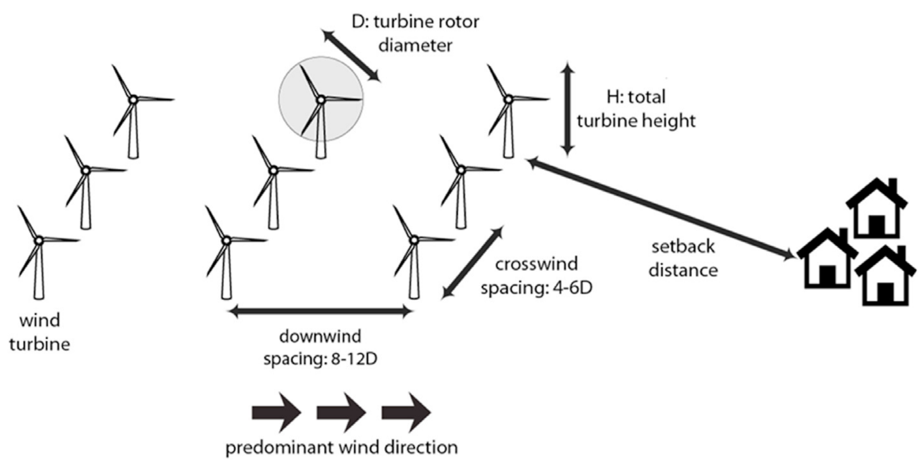

Fig. 3. Schematic of wind farm layout showing typical spacing and setback distances (for typical setback distances, see Table 3).

geographical potential, e.g. into geophysical suitability as well as technical and environmental permission [44]. In most studies, determining the geographical potential is one of the first steps in analysing the wind energy potential. However, this step can also be carried out after determining the technical potential (e.g. Ref. [47]) (see Fig. 4).

This section provides an overview and justification of the constraints applied to determine the geographical potential and ranges of buffer/offset distances in literature are given (section 2.1). Subsequently, approaches to process the set of constraints and often used databases are listed with their main characteristics (2.2).

2.1. Criteria

The availability of specific areas for wind turbines is most often derived from a set of primarily geographical criteria. Set definition and the utilisation of criteria to determine geographic suitability differ in literature. In most cases these criteria are used as strict exclusion criteria with or without buffer distances (e.g. Refs. [3,44,46]) or combined into indicators like a suitability factor (e.g. Refs. [6,32,42]), which adds a quality criterion to the geographical potential beyond the mere binary exclusion of areas.

Table 2 gives an overview of typical criteria and the range of buffers applied to the geographical potential. These criteria can be categorised into different types like physical or technical constraints (e.g., *slope*, *altitude* and *water bodies)*, exclusion criteria in the context of the built environment (e.g., *settlements* or *roads*) and related legislation, and environmental constraints to protect flora and fauna. While some criteria like *settlements, protected areas, roads* and *railways* occur in several studies, others like *agricultural area* [45], *power plants* [44], *firing areas* [43], *glaciers* [33,55] and *tropical forests* [42] are applied only infrequently; the latter three result mainly from different characteristics of the studied regions. In addition, the criterium *forests* is handled differently in literature ranging from full exclusion (e.g. Refs. [34,35,45,47,50]) to allowing some shares to be suitable for wind turbines (sometimes dependant on the respective scenario), e.g. Refs. [32,42,47,55]. Furthermore, the listed criteria and their respective buffer distances are divided into sub-criteria in several studies depending on the availability of databases and their underlying level of detail and definition of categories like settlement types (e.g. Refs. [32,36,46]).

Apart from studies explicitly focussing on urban areas, there is a general consensus about excluding settlements and in most cases employing offset distances [37], see Table 3 and Fig. 3. Distances between dwellings and wind power installations are ensured mainly in two ways. First, immission control regulations enforce levels of noise and visual impacts to be below well-defined thresholds. Whether a turbine can be built in a certain location thus depends on the characteristics of the planned turbine and is decided on a case-by-case basis. Hence, some studies (e.g. Refs. [6,38,49]) list noise as dependent on distance from the wind turbine as a criterium in their geographical potential. Second, distances can be ensured by enforced setbacks, which in most cases are standardised but, in some cases, depend on the height of the wind turbine (Table 3 and Fig. 3). Setback distances are usually much larger than necessary for immission control and therefore exclude larger areas from wind power installations. The amount of excluded area depends not only on the setback distance, but also on

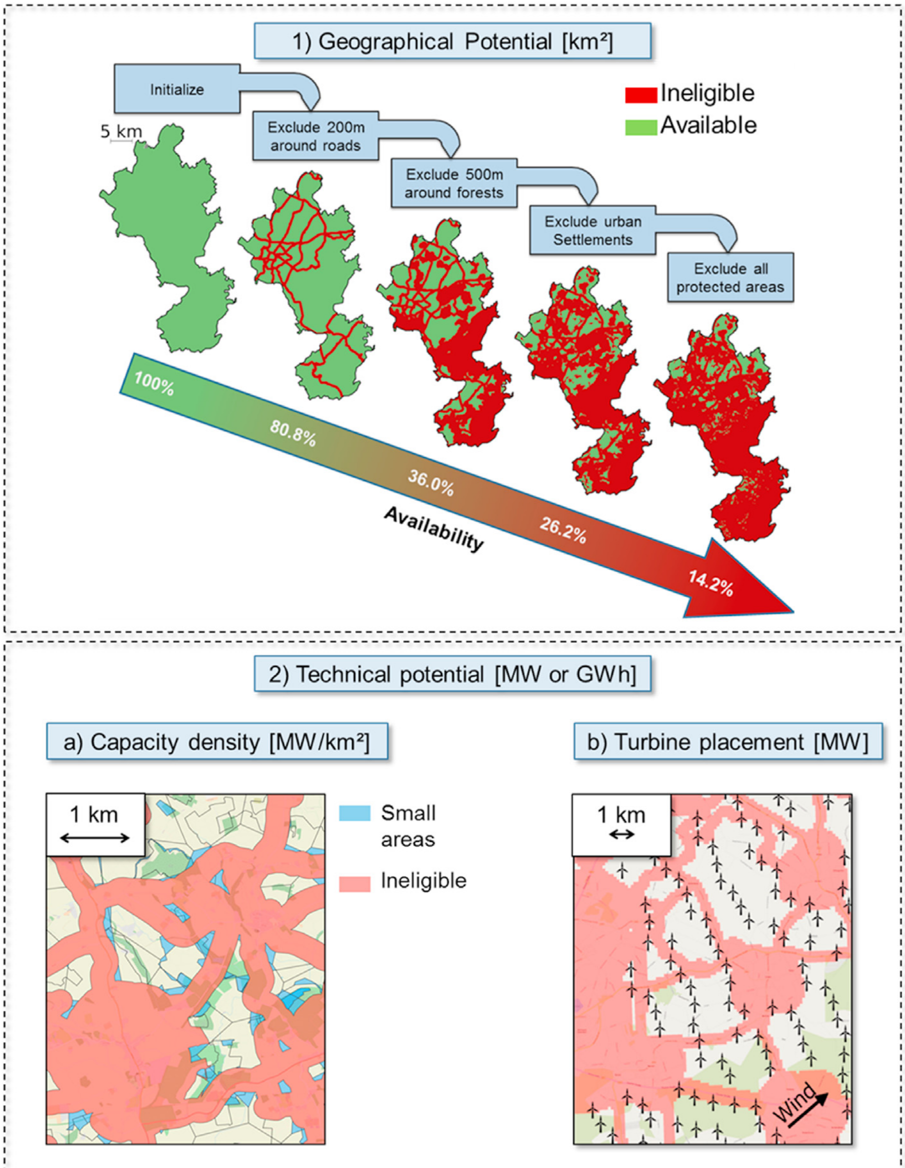

Fig. 4. Stepwise elimination of unsuitable areas to determine the geographical potential (1, top) and the two main approaches to capacity estimation based on a capacity density (2a) and turbine placing (2b). Figures adapted from Ryberg et al. [51] with permission.

Table 2
Overview of criteria applied to derive the geographical potential of onshore wind energy.

Criteria	Excludes	References
Slope	Values above 1–30°	[6,32,33,36,44–46,55]
Altitude	Values above 2–3.5 km	[35,42,44–47,55]
Water bodies	Distances below 0–1 km	[3,33–35,38,44–46,50,55]
Settlements	Distances below 0–3 km	[3,5,6,30,32–36,38,42–44,46,49,50,55]
Roads	Distances below 60–500 m	[3,5,30,32–36,43–46,50]
Power Plants	Distances below 1 km	[44]
Airports	Distances below 1–6 km	[3,5,32,33,35,36,38,43–46,49]
Transmission lines	Distances below 60–250 m	[3,5,33,44,46,49]
Railways	Distances below 60–500 m	[3,5,32,33,35,36,43–46,49,50]
Protected areas	Distances below 0–2 km	[5,30,32–36,38,42–47,49,55,56]
Forests	Distances below 500 m	[34,35,45,50]
Tropical forests	Distances below 0 m	[42]
Glaciers	Distances below 0 m	[33,55]
Firing areas	Distances below 0 m	[43]
Sandy areas	Distances below 0 m	[46]
National borders	Distances below 3–50 km	[43]
Mining areas	Distances below 0–3 km	[3,46,50]

Table 3
Minimum setback distances to settlements applied in a selection of European countries. Most values are for 2017/2018 and are subject to change. Sources: [57–59].

Country	Distance
Belgium	
Flanders	>3x rotor diameter
Wallonia	400 m, or 4x total height
Brussels	Not permitted
Austria	
Lower Austria	1,200 m
Upper Austria	800 m
Burgenland	1,000 m
Styria	1,000 m
Croatia	350 m, <45 dBA
Denmark	4 x total height
Estonia	1,000–2,000 m
Finland	1,000–2,000 m
France	500 m
Germany	In most states 400-1,100 m. Regional differences, up to 10x tower
Greece	500–1500 m
Ireland	500 m
Italy	200 m from single dwellings; 6x tip height from towns (~700 m)
Latvia	500 m
Lithuania	<45 dB night time noise, shadow coverage <30 h/year
Netherlands	4x hub height
Poland	10x total height
Portugal	~ 400 m (noise regulation)
Romania	500 m
Spain	500–1,000 m
Sweden	1,000 m to urban areas; 500 m to single houses
UK	
England	Local regulations, from 700 m to 10x total height; some cases 2,000 m
Wales	500 m recommended
Scotland	Local recommendation 2,000 m
Northern Ireland	10x rotor diameter to occupied property & minimum distance 500 m recommended

the definition of settlements. In Germany, for example, the available area for wind power installations at a setback distance of 1 km is reduced by more than 30% when setbacks are considered not only for pure settlement areas but also for areas of mixed-use [39]. Immission control thresholds vary between countries and setback distances are often defined on the subnational level; sometimes as low as the municipal level.

Wind resource assessments whose geographical scale is multinational therefore have to include a plethora of different regulations, which is considered a challenging task. While most studies with sufficiently high geographical resolution consider setback distances to settlements, these setback distances are only rarely based on existing, actual regulation in the assessed regions of multi-national studies and instead are generic assumptions such as a uniform distance (e.g. 600 m) or a multiple of the tower height [4,5,40,57,60]. Whether the magnitude of setback distances has a large impact on study results likely depends on the settlement structure. For Germany, which has a high population density, the magnitude of setback distances can have a large impact on wind potentials, with the technical potential with a 1000 m setback being just 1/3 of the potential with a 600 m setback [61]. Table 3 gives an overview of minimum setback distance for selected European countries and shows the large variation in these regulations between countries.

Even while several studies (e.g. Refs. [33,34,42,45,46,62]) include wind speeds in their set of criteria for the geographical potential, we classify this as belonging to the technical potential (cf. section 3). However, if the size of the covered area might result in computational challenges, excluding areas below a specific minimum wind speed can be a good way to overcome this computational barrier.

The arguments for selecting specific criteria and their buffer for the geographical potential range from technical, economic to societal and legal aspects. For example, the fall in wind power due to a reduction in air density is used to explain the exclusion of high altitude locations (e.g. Refs. [32,42,44,55]). Other examples are regional planning catalogues and existing legislations, which build the basis for buffer distances [5,32] or biodiversity and natural health, which are used as an argument to exclude protected areas [45]. A distinct argumentation is particularly important for criteria which either exclude large areas or whose overlap with other criteria is small. While the impact of criteria varies geographically, Ryberg et al. [63] show that forests, habitats, slopes, and settlements are most impactful and mining areas and airports are least impactful for studies in Europe. However, a quantification of the impacts on the results probably cannot be derived for all criteria, and, therefore, some studies have started to incorporate surveys [64]. However, this issue seems to be more related to the feasible potential addressed in section 5.

Most often, the set of criteria and their buffers are chosen once. Only some studies include further scenarios to explore the impact of different settings or future developments in the context of sensitivity analysis (e.g. Refs. [6,34,43,46,47]). Such scenarios typically add or remove restrictions and vary buffer zones to non-eligible areas or vary suitability factors. Hence, up to now most approaches for the geographical potential are more or less static.

2.2. Approaches and databases

Several studies (e.g. Refs. [34,44]) utilize only the previously selected criteria or combine them with an additional buffer distance to exclude further non-suitable areas. Hence, those studies interpret the criteria as distinction between eligible or non-eligible areas. In contrast, another type of study applies suitability factors (e.g. Refs. [32,42,47,55]). Suitability factors are used for different purposes like to address uncertainty in the database due to a lack in level of detail [55] or to combine different level of details in databases [32]. These suitability factors typically range between 0 and 1 and are most often translated as the fraction of land eligible for wind turbines in a specific geographical category or grid cell (e.g. Refs. [42,46]). Besides suitability factors, applying fuzzy sets to define an acceptable level in terms of selected criteria, which are then combined into an integrated satisfaction degree via a multi-criteria decision making approach, is another approach in literature [38]. A combination of approaches, considering some criteria as pure exclusion criteria and others via suitability factors or as fuzzy sets, exists in literature as well (e.g. Refs. [38,47]). Moreover, another study combines exclusion zones, economic viability and social acceptability into a suitability score [5]. However, we consider this type of score to belong more to the feasible potential types discussed in sections 5 and 6.

Even if the regional scope of studies on wind energy potential differ, some databases are frequently used due to their global or continental scope and their open availability (Table 4). These databases are most often complemented with further national or regional databases including both open and closed data. These regional data can range from landuse data [3,6] to military air traffic lanes [65]. Furthermore, natural protected areas are also often defined by regional datasets [30]. The utilized databases can bear different spatial resolutions ranging from around 100 m^2 to several km^2, whereby the lowest spatial resolution typically determines the level of detail of the wind energy potential analysis, with some studies combining several databases (e.g. Refs. [3,43]). Nonetheless, only rarely a validation or uncertainty analysis is performed, implying that a dedicated analysis on the impact of using different types of databases is still missing.

In terms of the accuracy of the employed geospatial databases, some studies use sources such as Open Street Map (OSM) to consider existing buildings. Whilst this open-source data is widely available, it differs greatly in its coverage. The OSM database is constructed with user-volunteered input, which naturally calls into question its completeness. For example, Barrington-Leigh et al. [66] assessed OSM's completeness of roads on average globally, concluding that roughly 80% of all roads are accurately represented in the database, a coverage which varies by country. In most European countries, the estimated road completeness is well above the global average, often around 99% complete, with the exceptions of Turkey (79%), Albania (75%), and, most notably, Russia (47%). Nevertheless, the OSM's completeness of roads seems to increase for developing countries like Iran especially for cities irrelevant of their size in accordance to Minaei [67]. Additionally, Herfort et al. [68] emphasize that developed countries were and are in the focus of mapping activities within OSM, which also holds true for countries in which Non-Governmental Organisations (NGOs) are active. In addition, Hecht et al. [69] estimated the completeness of buildings in several regions of Germany, and found significant discrepancies from known building locations. In the federal state of North Rhine-Westphalia buildings completeness was found to be 25%, while in the state of Saxony it was only 15%. For example, much more recently, Broveli and Zamboni [70] evaluated OSM building completeness in Lombardy Italy and found the dataset to be 57% complete. Li et al. [71] identified 13 missing built-up areas in Mozambique's OSM data with a new approach combining social and remote sensing, which achieved an overall accuracy of more than 90% showing room for improving OSM's completeness. Another promising dataset in this context is the World Settlement Footprint, which has global coverage at 10 m resolution and to our knowledge has not yet been employed for global onshore wind potential analyses [72].

3. Technical onshore wind energy potential

This section discusses the technical potential of onshore wind generation, beginning with the meteorology (section 3.1) and wind turbine technical characteristics (3.2), followed by a discussion of the influence of extreme wind events on wind power potential (3.3) and wind turbine spacing in parks (3. iv). These aspects culminate in the technical potential, as defined in Table 1. Selected international studies are summarized in terms of technical and economic potentials for onshore wind in Table 7. The technical potentials in this table, based on about 20 cited studies, range from 96 to 580 PWh globally (up to 717 PWh including offshore) or 0.4–77 PWh for Europe. The latter is shown for selected studies in Fig. 5 and the economic potentials are discussed in section 4.3.

3.1. Meteorological wind power potential

Broadly, there are two types of wind resource assessment that

Table 4
Overview of global and continental databases utilized in determining the geographical potential.

Dataset	Classes	Openly Available	Spatial Resolution	Regional coverage
Corine land cover [92]	44	Yes	100 m linear phenomena 25 ha areal phenomena	Continental
ESA Land Cover Climate Change Initiative [93]	22 (compatible with GlobCover)	Yes	300 m globally higher resolution Africa	Global includes yearly maps
Natura 2000 [94]	Sites designated under Birds Directive and Habitats Directive	Yes	Varying	Continental
EU's Common Database on Designated Areas [95]	Individually for each area	In most parts	Varying	Continental
World Database on Protected Areas [96]	Individually for each area	Yes	Varying	Global
Global 30 Arc Secon Elevation project [97]	Elevation	Yes	Lateral resolution ~1 km at equator	Global
GlobCover land cover dataset [98]	22	Yes	300 m	Global
Digital chart of the world [99]	Country border	Yes	–	Global
Geographical information system for the analysis of biodiversity data [100]	Biodiversity	Limited	–	Global
Moderate Resolution Imaging Spectroradiometer (MODIS) [101]	5 different land cover classification schemes, primary land cover scheme with 17 classes defined by the IGBP	Yes	≥500 m	Global
USGS HYDRO 1k elevation dataset [102]	Stream lines, basins,	Yes	1 km	Global
Open Street Maps Project [103]	28 primary features with various subfeatures	Yes	Varying	Global
NASA. SRTM 90m Digital Elevation Data [104]	Elevation	Yes	90 m at the equator	Global
Google Earth [105]	Various	Varying	Varying	Global

Table 5
Overview of meteorological datasets' coverage and resolution. Coverage and resolution information is approximate and based on the given example datasets; other datasets exist which may sit outside the given ranges.

Type of data source	Example datasets	Coverage		Resolution	
		Spatial	Temporal	Spatial	Temporal
Observations	HadISD [106], Tall Tower Database [107]	Global (irregular)	Historical, 20–50 years (irregular)	Site-specific	5min-1hr
Global reanalyses	MERRA-2 [114], ERA5 [113], JRA-55 [191] CFSR [192]	Global	Historical, 40–70 years	30–60 km	1–6 h
Long-term global reanalysis	20CRv3 [124], CERA20C [125]	Global	Historical, 100–150 years	ca. 100 km	3 h
Regional reanalyses	COSMO-REA2 [131], COSMO-REA6 [193] BARRA-R [133]	Regional	Historical, 7–22 years	2–12 km	1hr
Wind-focused reanalysis	NEWA [122], DOWA [132]	Regional	Historical, 11–30 years	2.5–3 km	0.5–1 h
Wind atlases	NEWA [132], GWA [137]	National to global	Historical average	200-50m	N/A
Climate models	CMIP5 [142,143], CMIP6 [142], EUROCORDEX [143]	Global or regional	Historical and future, 80–250 years	Ca. 10 km –300 km	Hourly to monthly

Table 6
Overview of HAWT economic characteristics from selected studies. The specific year of currencies is indicated, if known from the source.

	Total capex per kW	Turbine only per kW	Operation and Maintenance (O&M) cost	WACC	Year (reported year, if given, otherwise source year)	Region
IRENA [73]	$\$_{2019}$1473		0.0060–0.0200 $\$_{2019}$/kWh	7.5% (real, OECD countries and China) 10% (real, rest of the world)	2019	Global average
US DoE [74]	$\$_{2018}$1470	$\$_{2018}$700-900	29 $\$_{2018}$/kW/a (2010–2017)		2018	United States
Gass et al. [75]	€1700	€1400	€0.0018/kW/a	7%	2013	Austria
European Environment Agency [54]	€1000		4% of capex per year[a] (40.0 €/kW/a)	7.8% (private, presumed real) 4% (public)	2005	Europe
European Environment Agency [54]	€720		4% of capex per year[a] (28.8 €/kW/a)	7.8% (private) 4% (public)	2020	Europe
European Environment Agency [54]	€576		4% of capex per year[a] (23.0 €/kW/a)	7.8% (private) 4% (public)	2030	Europe
IRENA [76].	$800-1350				2030	Global average
IRENA [76].	$650-1000				2050	Global average
NREL [77]	$\$_{2018}$1470	$\$_{2018}$1011	44 $\$_{2018}$/kW 0.012 $\$_{2018}$/kWh	5.0% (real)	2018	United States
NREL [77]	$\$_{2018}$1065		34.3 $\$_{2018}$/kW	5.0% (real)	2030 Low Innovation	United States
NREL [77]	$\$_{2018}$929		39.0 $\$_{2018}$/kW	5.0% (real)	2030 Median Innovation	United States
NREL [77]	$\$_{2018}$795		43.6 $\$_{2018}$/kW	5.0% (real)	2030 High Innovation	United States
NREL [78]	$\$_{2020}$1436	$\$_{2020}$991	43 $\$_{2019}$/kW/a 0.012 $\$_{2019}$/kWh	6.3% (nominal) 3.7% (real)	2019	United States
Danish Energy Agency and Energinet [79]	€$_{2015}$1330	€$_{2015}$890	34.1 €$_{2015}$/kW/a 0.012 €$_{2015}$/kWh		2015	Denmark
Danish Energy Agency and Energinet [79]	€$_{2015}$1120	€$_{2015}$710	18.7 €$_{2015}$/kW/a 0.006 €$_{2015}$/kWh		2020	Denmark
Danish Energy Agency and Energinet [79]	€$_{2015}$1040	€$_{2015}$640	16.8 €$_{2015}$/kW/a 0.005 €$_{2015}$/kWh		2030	Denmark
Danish Energy Agency and Energinet [79]	€$_{2015}$980	€$_{2015}$590	15.5 €$_{2015}$/kW/a 0.004 €$_{2015}$/kWh		2040	Denmark
Danish Energy Agency and Energinet [79]	€$_{2015}$960	€$_{2015}$580	15.1 €$_{2015}$/kW/a 0.004 €$_{2015}$/kWh		2050	Denmark

[a] This assumes a 20 year lifetime and that the 4% are applicable per year, which is not stated in the source.

lead to two types of data requirements. First, there are static or climatological wind potential assessments, requiring a wind atlas with wind speeds and/or power densities. Second, there are models of time-resolved renewable generation variability for use in energy system modelling (e.g., Refs. [82–84]), requiring appropriate input data such as from wind masts or meteorological reanalyses. These two types of assessment can also be combined: for example, static products like the Global Wind Atlas can be used to bias-correct reanalysis-based time series [85–89]. Wind speeds increase with altitude through the lower atmosphere, which is typically modelled by a logarithmic or power-law relationship [90]. For example, capacity factors increase by 16–34% when moving from 50 to 100 m above ground; and a further 8–15% when moving from 100 to 150 m, averaged across several sites in Europe [91]. We now discuss

Table 7
Overview of selected multi-country studies with technical and (in some cases) economic potentials[a].

Source	Focus	Available area [M.km^2]	Assumed turbine size [MW]	Power density [MW/km^2]	Technical potential [PWh/a]	Generation costs	Economic potential definition	Economic potential [PWh/a]
Hoogwijk et al. [42]	Worldwide onshore wind, several potentials	11.00	1.00	4.00	96.00	≥0.05 US$/kWh	1) ≤ 0.07 US$/kWh 2) ≤ 0.06 US$/kWh	1) 14.00 2) 7.00
Archer and Jacobson [233]	Worldwide analysis, onshore and offshore wind potential	n.a.	1.50	6.00	627.00	0.03–0.04 US$/kWh	n.a.	n.a.
EEA [54]	European analysis, onshore and offshore wind for the EU27	5.40	2.00	10.00	41.00	1) 2020: 0.05–0.07 €/kWh 2) 2030: 0.04–0.06 €/kWh	≤0.06 €/kWh1) 2020 2) 2030	1) 8.90 2) 25.10
Resch et al. [234]	European analysis, Several renewable technologies, potentials and costs for the EU27	n.a.	2.00	n.a.	0.40	0.05–0.10 €/kWh	n.a.	n.a.
Lu et al. [235]	Worldwide analysis, onshore and offshore wind potential	n.a.	2.50	8.93	690	n.a.	n.a.	n.a.
Held [236]	European analysis, Several renewable technologies for the EU27, considering social acceptance: here onshore wind in 2050	n.a.	2.00	3.00	1.96	0.05–0.13 €/kWh	n.a	n.a.
Scholz [237]	European and MENA countries analysis (40 regions), potential and costs for renewable energy technologies	n.a.	2.00–5.50	10.40	9.00	0.04–0.20 €/kWh	n.a.	n.a.
Jacobson and Archer [238]	Worldwide analysis, onshore and offshore wind potentials	n.a.	5.00	11.36	72 TW	n.a.	n.a.	n.a.
Zhou et al. [47]	Worldwide analysis, onshore wind potentials and costs	n.a.	1.50	5.00	400	n.a.	<0.09 US$/kWh	119.5
Stetter [239]	Worldwide analysis, several renewable technologies	n.a.	1.95–5.50	10.40	684–717	0.06–0.08 €/kWh	n.a.	n.a.
Mentis et al. [240]	African onshore wind, several potentials	5.40–8.20	2.00	5.00	31.00	n.a.	n.a.	n.a.
McKenna et al. [53]	European analysis, onshore wind potentials and costs	0.74	3.00	8.3–18.6	20.00	0.06–0.5 €/kWh	n.a.	n.a.
Silva-Herran et al. [64]	Worldwide analysis, onshore wind potentials and costs	n.a.	2.00	2.00–9.00	n.a.	n.a.	1) < 0.14 US$/kWh 2) < 0.10 US$/kWh	1) 110 2) 29
Bosch et al. [55]	Worldwide analysis, onshore wind potentials	41.74	1.50	1.12	580.00	n.a.	n.a.	n.a.
Eurek et al. [241]	Worldwide analysis, onshore and offshore wind potentials	59.67	3.50	5.00	557.00	n.a.	n.a.	n.a.
Dalla-Longa et al. [57]	European analysis, onshore wind potentials and costs	n.a.	n.a.	n.a.	5.0–11.7	n.a.	n.a.	n.a.
Enevoldsen et al. [52]	European analysis, onshore wind potentials	2.71	4.50	10.70	76.52	n.a.	n.a.	n.a.
Ryberg et al. [51]	European analysis, onshore wind potentials 2050	1.35	3.10–5.00	9.90	34.30	0.03–0.10 €/kWh	1) ≤ 0.04 €/kWh 2) ≤ 0.06 €/kWh	1) 4.62 2) 22.08

[a] *Includes studies with at least two countries, one whole continent or a global scope, based on the following search query on February 14, 2021: TITLE ("onshore wind" OR "wind power" OR "wind energy" AND (evaluat* OR assess* OR analy* OR pot* OR plan* OR simul* OR optimi* OR model*)) AND TITLE-ABS-KEY (wind AND (power OR generation OR energy) AND (evaluat* OR assess* OR analy* OR pot* OR plan* OR simul* OR optimi* OR model*) AND (potential OR locat*) AND (generation OR cost OR lcoe OR econom*) AND (glob* OR euro* OR africa* OR america* OR australia* OR asia* OR world*)) AND SRCTYPE (j) AND (LIMIT-TO (DOCTYPE, "ar")).*

five key sources of meteorological data in turn, which are summarized in Table 5.

Observations. Many wind speed observations are available from weather stations and masts, for example, via the UK Hadley Center HadISD database [106] and the Tall Tower Database [107]. Station measurements can be affected by relocation, device updates, measurement error, and changes in the local topography [108]. Using station measurements for large-scale studies of wind potential thus requires dedicated quality control procedures of the underlying data [106,107]. Measurements are also spatially and temporally irregularly sampled. For example, 51% of the 222 masts higher than 10 m in the Tall Tower Database are in Iran, and none are found in South America or northern Africa [107]. There is scope to improve spatial coverage in future by including the growing number of deployed and long-running wind farms, assuming wind park operators are willing or forced to share their data. Due to their limited coverage and irregular sampling, observations can be of little use in large-scale wind power modelling efforts despite their undisputed value at specific locations or in statistical downscaling of modelled or reanalysis data. Winds derived from satellite measurements are available at 10-m and over the sea, so they cannot be used directly for wind resource assessment. Although, as with weather station measurements, there are methods to extrapolate these wind speeds to turbine operating height [109], they are still limited to offshore wind assessments.

Global reanalyses. Most large-scale studies and databases for

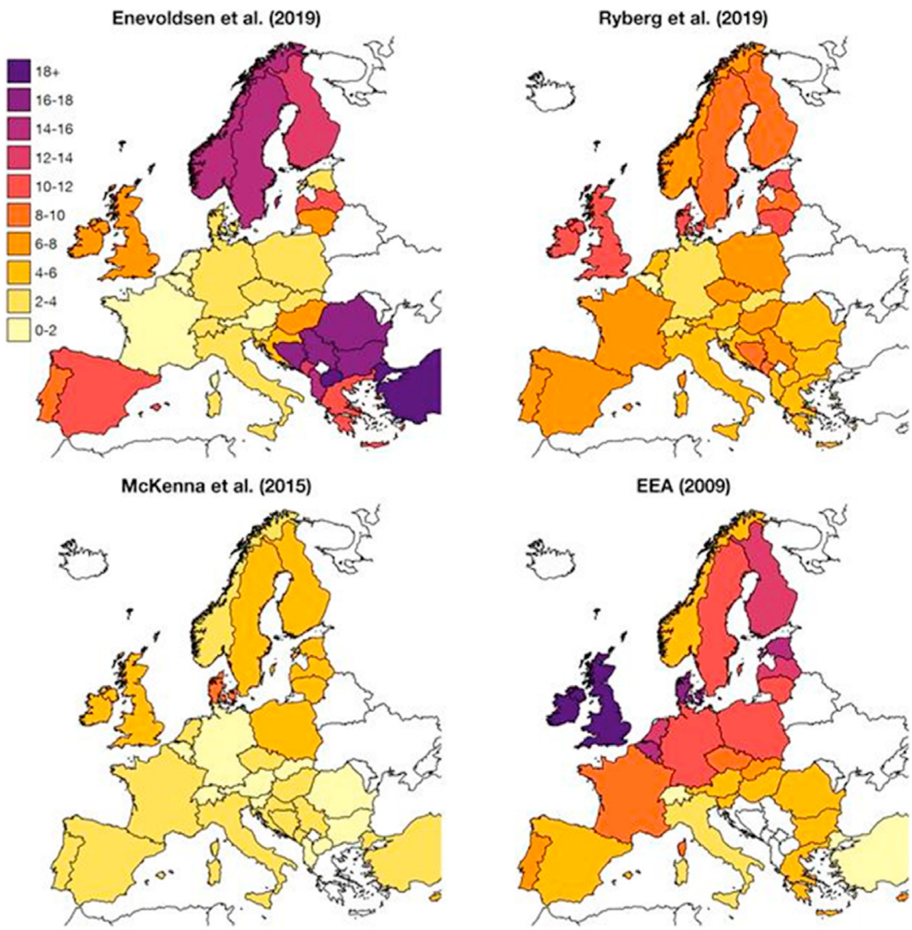

Fig. 5. Specific potential for onshore wind in selected European countries in GWh/km^{21} of total land area [51–54]. To our knowledge, these are the only studies to have assessed this potential at the national scale across Europe. The shown potentials are technical, with the exception of Enevoldsen et al. [52], which refers to a so-called 'socio-technical' potential.

wind power potentials rely on reanalyses (e.g., Refs. [87,110,111]). Reanalyses combine a numerical weather prediction model of the atmosphere with observations using a technique called data assimilation (e.g., Ref. [112]). They provide meteorological data on a global regular grid, with information considered representative for the entire grid cell. This differs from observational data which provides point-based information. The choice of a reanalysis-based product depends on modelling context, and which temporal and spatial scale needs representing. Well known reanalyses of the satellite era (1979 to today) are ERA5 [113] and MERRA2 [114]; ERA5 has also recently been extended back to around 1950 [115]. Several studies have been undertaken to assess the performance of reanalyses to capture wind speeds. Over flat terrain in Northern Germany and the Netherlands, global reanalysis results are relatively well correlated to measured data [116–119]. Temporal variability in general is underrepresented in reanalysis [116], which is confirmed by Cannon et al. [120] particularly for individual locations. Ramon et al. [121] find important discrepancies with regard to interannual variability and decadal trends in satellite-era reanalysis, yet report that ERA5 agrees reasonably well with tall tower measurements, except in areas of complex terrain where the subgrid orographic drag artificially lowers the simulated wind speeds [122,123]. In applications that require longer time series, centennial reanalyses like 20CRv3 [124] and CERA20C [125] are used to investigate long-term wind variability (e.g., Ref. [126]). However, there are documented deficiencies of these datasets, most notably strong wind speed trends in CERA20C that are likely spurious [127]. Another issue is that global reanalyses are relatively smooth and thus tend to exaggerate spatial correlations between neighbouring regions [85].

Regional reanalyses. While ERA5 provides hourly data with ~30 km horizontal grid spacing, higher resolutions may be required to resolve wind patterns in complex terrain [128,129]. In fact, using global reanalyses can lead to a severe underestimation of wind energy technical potential [130]. Regional reanalyses provide higher resolution. COSMO-REA2, for example, has a horizontal resolution of 2 km, and can effectively resolve meteorological phenomena from a scale of ~14 km [131]. This is sufficient to resolve some mountainous weather patterns [130], while disagreement with observations remains large in particularly complex terrain [118,130]. Downscaling is computationally expensive, resulting in few regions of the world having high-resolution reanalyses. Although there are many reanalyses available for Europe [119,131,132] as well as BARRA-R in Australia [133], only single-year tests have been undertaken for China [134] and the North American NARR project [135] has effectively been superseded by the global reanalysis ERA5 in its spatial resolution (~32 km). Where high resolution is available, datasets have necessarily limited scopes; COSMO-REA2 only covers seven years and nine European countries. Since regional reanalyses are provided over a confined area, they rely on boundary data from a global reanalysis. As a consequence, potential large-scale issues in the global reanalysis can propagate to the regional reanalysis.

Wind atlas datasets. In contrast to current reanalyses that are not designed with a specific focus on wind energy, wind atlas projects like the New European Wind Atlas (NEWA) [122], the Dutch Offshore Wind Atlas (DOWA) [132], the Wind Atlas for South Africa (WASA) [136] and the Global Wind Atlas (GWA) [137] provide tailored, long-term mean wind energy information at a high spatial resolution. NEWA is based on a dynamical downscaling of ERA5 using the WRF model evaluated against mast measurements and exists as a mesoscale and microscale product [122,138]. The spatial grid spacing of the mesoscale NEWA is 3 km at seven different heights above ground level, and provides wind speed and power density averaged over 1989 to 2018. The NEWA microscale atlas is based on a second linearized downscaling to 50 m spatial resolution [122]. The GWA [137] version 3 (GWA3) was created with more than 2400 overlapping mesoscale tiles downscaled from the ERA5 reanalysis. The blended global mesoscale data is further downscaled to a spatial grid of 250 × 250 m that covers all land (except Antarctica) and 300 km offshore. The high-resolution details of the surface elevation and surface roughness are found to improve the long-term means when compared to observations [85,122]. However, higher resolution does not automatically mean higher quality [117].

Climate models. While reanalyses and observations are only available in hindsight, climate model projections can be used to investigate impacts of future climate change on wind power generation. Climate model simulations are fundamentally different from reanalyses and observations giving rise to different sources of uncertainty (e.g., Ref. [139]). Large ensembles of climate model simulations are available from the Climate Model Intercomparison Project (CMIP; [140,141]) and downscaled projections are available from the Coordinated Downscaling experiment (CORDEX) initiative [142,143]. These datasets have been used in different assessments related to future wind energy potentials (e.g., Refs. [144–152]). Pryor et al. [153] recently reviewed the literature on the subject.

3.2. Wind turbine technical characteristics

The next stage of the analysis for the technical potential involves wind turbines, which are discussed in this section. The focus here is on horizontal axis wind turbines (HAWT) that adopt the lift principle, due to their higher conversion efficiency, greater reliability and economies of scale allowing for cost effective multi-MW machines [41,154] (Fig. 1).

HAWTs are not simply uniform and homogenous machines. Instead, the choice of generator and rotor are designed for the specific conditions they will experience, and so different turbine types will have very different performance characteristics. Wind speeds can be converted to power output using empirical power curves, statistical approaches, or physical meta-models. Empirical power curves are typically provided by turbine manufacturers [156], for example, in Refs. [55,110,157,158], but these require appropriate smoothing to account for heterogeneity in wind speeds experienced at different turbines within a farm and at short timescales [159]. Statistical approaches take historical data for measured wind speed and power output, typically at a regional or national aggregation, to derive a relationship between the two which automatically accounts for smoothing and other factors (e.g. Ref. [120]). Hypothetical power curves can be derived using meta-models (e.g. Refs. [51,160]) based on turbine specifications such as the specific power. This can help with future-focused studies, as power curves for next-generation turbines typically only become available after they have been operational for some time.

Three key design factors which influence energy production are the turbine's capacity, its hub height (which influences the wind speeds experienced), and the ratio of generator capacity to blade length (which determines the specific power and thus the general shape of the power curve). Fig. 2 shows the evolution of these three parameters over the past three decades for onshore wind turbines in Europe. Turbine capacity has increased 16-fold since 1990, with a steady increase of 106 kW per year on average. The dominance of the 2 MW platform is visible from 2005 through to 2013, but since then 3 and 3.5 MW turbines have become commonplace. Similarly, hub height now averages 100 m, 2.5 times greater than in 1990. This has grown by 3 m per year, but has plateaued since 2015.

In addition, the cut-in and cut-out wind speeds determine the feasible range of operation for a given turbine and thereby also the lower and upper bounds of wind speeds for actual power generation. Other technical characteristics affect the shape of a wind turbine's power curve and thus its productivity, including storm control (for safety), noise reduction settings (sometimes required in built-up areas), the assumed size of a wind farm, and technical degradation over the turbine's lifetime [161].

The specific power of a turbine is arguably the most important feature in determining a turbine's output. The blade length (rotor diameter) determines the swept area and thus how much wind energy the turbine is exposed to. The generator capacity determines the maximum rate at which energy can be converted into electricity. Over the past 30 years, the specific power of European onshore turbines has remained nearly constant, averaging 394 ± 11 W/m^2 (see Fig. 2). The IEC categorises turbines by three wind speed classes, defined by the annual average wind speed they are suited for. For example, the Vestas V66/2000 (66m rotor diameter, 2000 kW generator) is a Class I turbine, suitable for sites with annual average wind speeds above 10 ms^{-1}. It has a specific power of 1.7 m^2/kW and would yield a capacity factor of 22.3% in central Scotland [91]. In comparison, the larger-bladed V80/2000 (Class II, 2.5 m^2/kW 398 Wm^{-2}) would yield 31.4%, and the V110/2000 (Class III, 4.8 m^2/kW 210 Wm^{-2}) would yield 47.9% in the same location. All are 2 MW turbines, but one produces twice as much energy as another. This simplified comparison overlooks the constraints on turbine spacing, however, as discussed in section 3.4 below.

3.3. Extreme winds and their impact on turbine design

As well as the general wind turbine characteristics discussed in the previous section, one specific and important characteristic is the ability to manage extreme wind conditions. For wind-farm planning, the expected extreme wind at hub height needs to be calculated to find suitable turbines that can harvest the most wind energy while also reducing the risk of damage from harsh wind conditions. For this reason, the fifty-year extreme wind at hub height is a design parameter specified in the IEC standard 61400-1 [156]. With climate change, and the resulting changes in frequency of extreme weather events, this may become an even more important issue than in the past.

There has been a gradual development of the methodologies for the extreme wind estimation. The earliest dataset of fifty-year wind was produced in line with general civil-engineering applications [162]; each country used its own method, causing discontinuous values at national borders (e.g. Ref. [163]). Since then, statistical algorithms have been derived to best represent the extreme wind samples from single or multiple types of extreme weather events

[2] Search query on 12/15/2020: *TITLE ("onshore wind" OR "wind power" OR "wind energy" AND (evaluat* OR assess* OR analy* OR pot* OR plan* OR simul* OR optimi* OR model*)) AND TITLE-ABS-KEY (wind AND (power OR generation OR energy) AND (evaluat* OR assess* OR analy* OR pot* OR plan* OR simul* OR optimi* OR model*) AND (potential OR locat*) AND (generation OR cost OR lcoe OR econom*)) AND SRCTYPE (j) AND (LIMIT-TO (DOCTYPE, "re")).*

(e.g. Refs. [164,165]), mostly based on long-term measurements. Such measurements are often few and expensive, hence modelled data have become part of an attractive solution. For instance, Pryor and Barthelmie [166] used the global ERA5 data and calculated the 50-year wind at a height of 100 m, with a spatial resolution of about 30 km. A general issue with modelled data is however that the temporal and/or spatial resolution is often too coarse, thus the data miss the relevant wind variability, which is essential for the extreme wind estimation. To correct for this, Larsén et al. [167] developed the spectral correction method (SCM) to add the missing variability into the modelled data over the relevant frequency range, through information from limited available measurements or from a spectral model through the spectral domain. This method has been used to create an extreme wind atlas for South Africa [168], as well as for the whole globe [169].

Furthermore, tropical cyclone-affected areas have always been challenging for assessing design parameters. One example are the Chinese coasts: with measurements from 205 towers during 2003 and 2010, the ratios of the 50-year wind to the annual mean wind were calculated and can exceed the reference value by 5–10 times of the value given in the IEC61400-1 standard [12]. Using a hurricane conceptual model and best track data, Ott [170] calculated the 50-year wind for the west North Pacific. Larsén et al. [169] calibrated the SCM using the best track data and calculated the extreme wind for a tropical cyclone affected area in the northern hemisphere.

The estimation of extreme wind is still challenged by our understanding of flow across multiple scales, particularly in the range of a few kilometres to meters, the so-called spectral gap region (e.g. Refs. [171,172]). This limitation is reflected particularly in complex terrains and challenging severe conditions such as tropical cyclones and thunderstorms. It remains a problem to obtain reliable samples to assess the extreme wind climate and thereafter the distribution of these conditions when calculations cannot be achieved with high confidence. The implication for onshore wind resource assessments is that the technical potential is reduced, but as the extreme wind aspect is generally not considered, this represents a limitation in existing studies.

3.4. *Micro-siting of wind turbines*

In addition to the technical wind turbine characteristics outlined in the previous sections, the micro-siting of wind turbines within a wind park strongly influences the technical generation potential. This involves an assessment of (a) the accessibility of the site for construction, (b) land-use restrictions, (c) the detailed wind conditions on the site, and (d) the distance to other wind turbines within the park. The first two aspects are covered by the general procedure for excluding sites as described in section 2 and 5. However, the spatial resolution is generally relatively coarse to e.g. differentiate in detail between the costs of allowing access for construction between two similar sites and therefore results may deviate from actual results of micro-siting procedures in industry. The same applies to land-use restrictions: these are of course incorporated into wind power potential studies, as outlined in section 2 and 5, but may lack detail in some instances and therefore a site may not be available for development in reality.

With respect to assessing the detailed wind conditions on the site of a turbine, industry practice for wind turbine siting and planning is to consider the extreme wind and other siting parameters such as turbulence intensity and load [156]. But this is neglected in regional planning processes and most of the studies reviewed here [54,173,75], due to lack of data. Private companies rely on commercial and confidential in-house calculation methods and data. The ongoing GASP (Global Atlas for Siting Parameters) project provides additional layers of publicly available data for the GWA at a spatial resolution of 250 m, including extreme wind, turbulence and wind turbine class across the globe [137,169].

Furthermore, micro-siting also addresses how much distance is maintained to other turbines in the same park, as interference and wake effects reduce the output of wind turbines placed downwind of them. This effect constrains the capacity density of wind turbines within a wind park – and furthermore the number of wind parks that can be deployed within a region. The explicit calculation of the optimal layout of wind parks is a combinatorial problem which is computationally hard to solve [174]. For this reason, the real world problem is often simplified to make it computationally tractable – for example, by discretizing the solution space of possible turbine locations [26] and applying evolutionary algorithms with heuristics [27] or particle swarm optimization [28] to optimize wind farm location and layout. However, such methods are computationally far too demanding to deploy them on the level of regional, national, or continental scale assessments as reviewed here.

Therefore, relatively simple heuristics are employed in potential studies (see Fig. 4 panels 2a and 2b). One such heuristic is to assume a capacity density, as in e.g. Ref. [175]. Here, the number of wind turbines is simply constrained by an assumption on how much capacity, or how many turbines of a certain type, or how much rotor area can be placed on a given amount of land. A second option is to explicitly place turbines, using a rotor diameter distance heuristic [4,176]: by assuming that a certain distance between turbines has to be maintained, and that this distance depends on the size of the rotor, the number of turbines that can be potentially placed on a given stretch of land are determined by first placing a turbine and subsequently blocking land in the given minimum distance for further placements. Typical distances are in the range of 4D-7D [4], or 5D-10D [176], where D is the turbine rotor diameter (cf. Fig. 3). In real wind parks, larger offsets are maintained in the main wind direction, due to stronger wake effects. Some potential studies do take into account differences in distances between turbines depending on the main wind direction (e.g. Ref. [51]). Nevertheless, some approaches assume the same distance factor in all directions (e.g. Ref. [4]). The former is without doubt the more accurate procedure. It can be implemented by either calculating wind roses which indicate the frequency of wind directions can be calculated from reanalysis products. Alternatively, wind roses are provided e.g. by the Global Wind Atlas [137].

However, when assessing the large-scale potential of wind energy, the impact of the upwind extraction of wind energy has to be taken into account not only on the turbine level, but also for downwind wind parks due to wake effects. For example, Lundquist et al. [177] have found that these effects can have economically significant impacts up to 50 km downwind. Very large wind farms (i.e. in the range of 10^5 km^2) have an upper limit for the power density of 1 W/m^2, while smaller wind farms can reach up to 10 W/m^2. This means building very large arrays can reduce power output per turbine by ten times due to strongly increasing wake effects. This should be considered if the density of turbines grows very large in future scenarios [178].

There is a further issue related to micro-siting which is the question how to deal with many small areas (i.e. areas around 0.3–0.6 km^2 or smaller) resulting from the stepwise exclusion of unsuitable areas outlined in section 2 (Fig. 4, 2a). The application of turbine densities (in MW/km^2) could be problematic [32] for these areas, as this could lead to a potential that is lower than that of a single turbine – the difference between the two approaches is shown in Fig. 4, panel 2. In the literature there are basically two procedures applied for dealing with small areas. Firstly, the areas that are too small to build a single wind turbine could be aggregated and added to the total potential (as in Refs. [29,179]). This would overlook the shape of the areas as well as position with respect to one-another and therefore lead to an overestimation of the potential. On the other hand, the areas could be completely excluded. However, theoretically there could be enough area to build a single turbine, as only the area of the turbine tower base (around 0.1–0.2 km^2) would be relevant for this. This approach would therefore lead to an underestimation of the potential [32]. Both of these effects can lead to an uncertainty of about ± 10% of the technical potential [32]. The problems would not occur with turbine placement at exact locations, which makes the approach from Ryberg et al. [51] superior to a calculation based on capacity densities (see Fig. 4, panel 2b).

Overall, the approaches and assumptions employed to determine the technical potential outlined in this section lead to wide range in results. Fig. 5 shows the estimated potential for onshore wind in selected European countries, to our knowledge from the only studies with this broad scope and national disaggregation. The results between the four studies clearly show a large range, in some cases leading to national potentials that diverge by over 100%. Further discussion of differences in European-level results can be found in Ref. [180].

4. Economic potentials of onshore wind

Having discussed the geographical and technical constraints relating to onshore wind resource assessments, this section addresses the economic dimension. It begins with a more elaborate definition of the economic potential and economic assessment criteria in section 4.1. Section 4.2 then presents economic characteristics of current and future HAWT technology, before section 4.3 discusses selected studies in terms of their (technical and in some cases) economic potentials. Finally, section 4.4 analyses the system integration costs of onshore wind and its implication for resource assessment methods.

4.1. Defining economic potential and economic assessment criteria

In theory the economic potential is the fraction of the technical potential that currently can be economically realized. In practice, the term is not well defined, which limits studies' comparability and generalisability. A distinction between two different perspectives is relevant in this context:

- The private economic or business perspective assesses the economics of a wind turbine or park in the context of the prevailing market and energy-political framework conditions. This perspective assumes some prevailing market design (e.g. energy-only spot markets) with perfectly competitive markets, and therefore does not consider any market-distorting effects of barriers or failures in the form of externalities, such as the noise impact on nearby settlements.
- The public or welfare economic perspective assesses the economics of increasing the share of wind power to some target, and hence looks at societal rather than the project-level economics. Externalities may also be considered in the analysis.

Both perspectives may employ similar economic metrics, e.g. Net Present Value (NPV), internal rate of return, or payback period. If the results are favourable (often in comparison to an alternative), the project or policy target is seen as economically attractive or 'profitable'. Although both perspectives assess the economic attractiveness of wind power, they differ in terms of the economic criteria employed. The different foci are for example reflected by the assumed discount rate for NPV calculations. Whereas the business perspective employs a private discount rate, often in the range of 8–15%, the welfare perspective uses societal discount rates, which are typically in the range 3–5% [181]. Because the discount rate very strongly affects the economics of capital-intensive technologies like wind power, the two perspectives generate very different results of the economic potential. Almost all studies reviewed here adopt the business perspective. We return to this perspective issue in section 5.

Of course, the business perspective – essentially the profitability of projects – depends not only on costs, but also on the revenue side, where the situation is changing from fixed-price to market premium schemes and auctions, and increasingly towards putting wind power on the general electricity market [182,183].

Assessing the economic potential is highly complicated, not only because economic parameters may vary widely across projects, but also because both costs and market conditions – and hence possible revenues – change over time. The impact of cost reductions on potential assessments can be profound. For example, recent studies have found that offshore wind at certain sites and in mature markets does not require subsidies [184], and because onshore wind generally has lower costs [73,185,186] the same will very likely apply to onshore wind too.

Consequently, many studies economically assess the technical potential, by employing some of the metrics outlined above in relation to discounted cash flow calculations. For example, a common approach is to relate the levelized costs of energy (LCOE) to the possible revenues, for example the average market price or achievable tariff [32]. These studies then find a potential generation that can be achieved at or below some particular cost. The LCOEs are calculated according to Equation (1), where n is the lifetime of the technology, I_0 the investment [$], M_t the annual costs in year t [$/year], E_t energy produced in year t [MWh/year] and i the interest rate.

$$LCOE = \frac{I_0 \cdot \sum_{t=1}^{n} \frac{M_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \tag{1}$$

The LCOE comprises the total discounted costs over the lifetime divided by the discounted energy production over the lifetime, and is a comprehensive metric to compare generation costs. But it ignores system integration and other external costs, and because project-specific data is often lacking, it usually relies on generic assumptions for the cost of capital [187] (see next sections). Because of its intuitive simplicity, LCOE has become the dominant metric for costs of renewable power [73,188]. It often employs the weighted average cost of capital (WACC) concept [189], which accounts for the source of and interest rates applied to the capital to finance the project. The WACC is defined according to Equation (2), with N the number of sources of capital, r_i the required rate of return of security i and MV_i the market value of all outstanding securities i.

$$WACC = \frac{\sum_{i=1}^{N} r_i . MV_i}{\sum_{i=1}^{N} MV_i} \tag{2}$$

In the case that the project is financed solely with equity and debt, the WACC simplifies to Equation (3), with debt D and equity E, and the cost of each as K_d and K_e respectively.

$$WACC = \frac{1}{D+E}(DK_d + EK_e) \tag{3}$$

4.2. Economic characteristics of turbines

Onshore wind energy is a near-zero marginal cost generator, which means that (almost) all of the cost is attributed to the construction of the asset, and 70–80% [190] of the costs are made up by the turbine itself. IRENA states the total installed costs (i.e. turbine, foundation, grid connection, etc.) in 2019 at 1,473 $\$_{2019}$/kW [73], whereas the U.S. Department of Energy sees indexed turbine costs, including tower and delivery to site, of around 700–900 $\$_{2018}$/kW for early 2019 [74]. This is roughly comparable with the “2018 Cost of Wind Energy Review” by NREL, which assumes 1011 $\$_{2018}$/kW for the entire wind turbine (i.e. rotor, nacelle and tower assembly, but without foundation and electrical connection), and even more comparable to the “2019 Cost of Wind Energy Review” which states 911 $\$_{2019}$/kW [78]. The ‘balance of plant’ difference of 462 $\$_{2019}$/kW between the turbine (i.e. 1011 $\$_{2018}$/kW) and the entire system is further split out in the “2018 Cost of Wind Energy Review”, whereby the turbine rotor module accounts for 29%, the nacelle for 49%, and the tower for 22% of the cost respectively. The difference between the wind turbine and the total installed cost of 1470 $\$_{2019}$/kW arises from grid connection cost (32%), foundation (13%), construction and engineering (20%), engineering (8%) and financial cost (28%) [77]. Most sources however only provide the cost for the turbines and total costs and overlook some specific turbine characteristics, such as the drive train (i.e. gearbox or gearless), tower construction, tower height or rotor diameter. Table 6 gives an overview ot HAWT economic characteristics according to selected studies.

Markets for wind turbines strongly depend on regional and national energy-political and economic framework conditions, resulting in wind turbine prices being location-specific. Hence, modelling LCOEs can be carried out using a bottom-up approach, where all components such as blades, towers and balance of plant are costed, even going as far as indicating materials prices [76,194]. This is often carried out by academics and project developers, for example based on NREL's Wind Turbine Cost Model (LandBOSSE) [195]. This approach cannot reliably reveal the exact costs, however, due to the dynamic nature of turbine markets, their location-dependence and the reliance on privileged, business-sensitive, and thus non-publicly available, information. This is addressed by analysts, such as the Bloomberg NEF wind turbine price index, which averages prices over many turbine types [196]. Hence, other approaches have evolved, which either cicrumvent the costing by using audited information to estimate costs [197] or using auction results [184,198], with both methods yet to be applied to onshore wind. Audits can be used to verify LCOE figures from the literature to match up “with the books” of publicly traded companies, based on the real costs of a project from an accounting point of view. Auctions on the other hand can provide an up-to-date proxy for LCOE in the near future, by estimating the underlying revenues of a particular project – and under the assumption of low cost margins, this is an estimate of the near-future LCOE.

The WACC (Equations (2) and (3)) has a large influence on the LCOE of renewables [199–201], which is potentially larger than the differences in CAPEX across countries. For onshore wind power in Europe, average WACCs vary strongly, from 3% in Germany to 11.7% in Greece, whereas the data for offshore wind is sparse, but range from around 6% in Germany and Belgium to over 12% in Great Britain [200]. Reducing the WACC from 7.5% to 5% reduces the LCOE by around 20%, so this assumption is similarly important as technology cost, performance, and other technical metrics [73]. Hence, support schemes that lower project risk, such as feed-in tariffs have attracted low interest rate financing, enabling the relatively low WACC to contribute to the cost reductions in these technologies, alongside reductions in CAPEX and OPEX and an increase in the capacity factor over time. On the other hand, if general interest rates increase again after the economic crisis, wind power WACCS and hence LCOEs may increase again.

Recent estimates find that the LCOE of onshore wind power has decreased by 39% from 2010 to 2019 [73]. Whether and how fast technology costs will continue decreasing is debated and uncertain [54,76,202]. In the past, cost predictions have in some cases been accurate, such as the finding of the expert survey of Wiser et al. [203] in 2015: the surveyed experts expected a 10% cost reduction between 2015 and 2020, which is roughly what can be observed today, and adds some credibility to their estimated overall cost reduction to 2030 of 25%.

4.3. Economic assessments for onshore wind

Economic assessments of onshore wind have been a focal point of many European studies, as shown in Table 7. For example, the European Environment Agency [54] estimated the economically competitive potential of 8.9 PWh/a at a price of 55 €$_{2005}$/MWh or lower in 2020 and 25.1 PWh/a in 2030 and almost 60% of the total unrestricted potential. However, cost assumptions quickly become outdated (see previous section), which in turn likely increases the economic potential using current, lower costs.

Many studies define the economic potential as the capacity (or energy production) under certain cost thresholds (e,g, EEA [54], Ryberg [51]). Differences are identifiable in the approach taken and more crucially, cost estimates and projections for onshore wind influence the results significantly. The use of scenarios up to 2050 by some (e.g. IRENA [76]) is an alternative approach to evaluate the economic potential compared to the technical potential.

In addition, forward-facing studies on a global scale, with time horizons of up to 2050 attempt to estimate future growth within economic and socio-economic contraints of each market, pointing towards large growth potentials in Africa, Asia and North America [76], which in some cases comment on socio-economic value [76,204].

Overall, then, the economic potential for onshore wind based on the studies in Table 7 ranges from about 7 to 120 PWh globally and around 5 to 27 PWh in Europe. Only a small number of studies in Table 7 include technical and economic potentials [54,51,42,47,64], making generalizations from this small sample difficult. These studies differ widely in their methodologies, assumptions and dates of publication, meaning these results should be understood in the context of a specific source.

4.4. System integration costs

Most of the reviewed studies for potential assessment of onshore wind investigate only LCOE as the economic benchmark (e.g. Refs. [51,32]). These studies overlook important aspects of integrating non-dispatchable onshore wind into energy systems. According to Ueckerdt et al. [205] and Hirth et al. [206] the so-called *system LCOEs* include three additional cost components:

- *Profiling costs*, i.e. costs for additional dispatchable generation technologies to meet the residual load;
- *Balancing costs*, i.e. costs related to the deviation between forecast and actual non-dispatchable onshore wind generation;
- *Network costs*, i.e. costs for grid reinforcement and extension required to connect wind turbines to the network.

There are rudimentary estimates of the integration costs of onshore wind power for different contexts, valid for low penetrations. Typically, these studies analyze the short-run integration costs [205] by only considering the balancing and operational costs associated with marginal increases in installed wind capacities and generation. For this reason, they overlook more extensive long-run measures and their associated costs, such as network expansion and densification, which may either "happen anyway" or in the context of measures directed at wind energy integration; they also ignore wider developments in the power system. Therefore these rudimentary estimates of integration costs are only indicative and can only be applied to lower levels of wind energy penetration into the energy system. For example, a review by the European Wind Energy Association [54] revealed additional balancing and operational costs of 2.6–4.6 €ct/kWh for wind energy penetrations from 10 to 20% of gross demand. In addition, Heptonstall et al. [207] have estimated that these costs are approximately 10–20 $€_{2017}$/MWh, for VRE penetration below 50% and with large uncertainties.

However, since these estimates depend on the specific system and are subject to significant uncertainty, the system LCOEs have to be explicitly considered in high-penetration assessments [206]. As wind (or PV) penetration increases, the stability of the power system is increasingly affected [208]. In Reichenberg et al. [209], for example, the system LCOEs increase sharply above 80% penetration (of wind and solar), especially due to the required strong expansion of transmission capacity. Whilst some studies take into account all the above-mentioned aspects of system LCOEs (e.g. Ref. [210]), the approaches to assess the technical potential of onshore wind do not. Nevertheless, initial approaches to include some of these effects have also already been developed for onshore wind potential assessments: in Ref. [211], wind turbines are clustered to wind farms and the grid connection costs (i.e. network costs above) are calculated for every technically feasible wind farm in GB showing that marginal and total costs more than double. The importance of system costs are further demonstrated by a recent study from China, showing that onshore wind power there has not reached grid parity[3] if system LCOEs are considered instead of LCOEs for generation only [212].

Nevertheless, there is still controversy about the costs of integrating wind power into electricity systems, including strong disagreement about how to measure them. Therefore, in future research, the results of sophisticated energy system models should be compared with economic approaches and empirical data from systems and markets where large wind penetrations already exist [207].

5. Feasible onshore wind potentials

The geographical potential (see section 2) is derived by excluding certain land areas for wind power development, for example, based on technical or legal constraints. The underlying assumption is that there is general agreement on these criteria, as implied for example by legislation. Although the geographic potential provides a good understanding about where *not* to build turbines, it does not imply that wind parks can unquestionably be deployed within the defined eligible lands. The required access to and use of land for wind parks may lead to conflicts with other land uses such as recreation, agriculture, subsistence, ecosystem services, or other renewable generation [213–215]. In addition, several externalities are associated with wind turbines, for example, related to noise, bird and bat fatalities [216], landscape and ecosystem impacts [217–219]. As a consequence, opposition against new projects in different world regions increased [220–222]. Therefore, land-use conflicts and externalities are increasingly considered in modelling wind power potentials [3,4,6,175,223–226]. In the present paper, these studies are referred to as modelling the 'feasible' wind power potential (cf. Table 1). In this context, it should however also be acknowledged that the environmental footprint of onshore wind power – quantified by means of Life Cycle Assessment (LCA) – is very small in comparison to other electricity generation technologies [227–230] and that this fact can have a positive impact on the acceptance of wind power [231,232].

Here, we first present methodological approaches which assess feasible potentials (section 5.1) and afterwards discuss which new data sources and indicators have been or might be used to represent these concerns in the modelling of wind power potentials (5.2).

5.1. Considering non-technical impacts in potential assessments

All wind power potential modelling approaches have to decide which indicators are included, which thresholds are applied, and which buffer distances are used. Some parameters can be directly derived from legal or technical information. However, when modelling feasible potentials, this is mostly not the case. Therefore, recent modelling studies have relied on different approaches: the standard practice is that modellers choose the parameters (e.g. Refs. [3,211]) and/or stakeholders have been actively setting parameters in participatory approaches (e.g. Ref. [4]). Alternatively, patterns of wind power expansion have been transferred from regions with high levels of deployed wind power to regions with low levels (e.g. Ref. [175]), or acceptance and rejection of regulators have been used for statistical modelling of the likeliness of wind power projects being realized at specific locations [5,211]. Below we discuss how, once parameters are defined, feasible potentials are derived.

Mostly, *land-eligibility studies* (see Table 8A) are used to assess feasible potentials. In contrast to traditional studies of geographical potentials, they consider a larger set of indicators related to conflicts in land-use and externalities. They apply a binary concept: land is assumed to be eligible or ineligible for the erection of wind turbines, depending on the chosen indicators. For instance, Jäger et al. [3]. use assessments of landscape quality by citizens to differentiate between eligible and ineligible areas, resulting in an economic potential of 11.8–29.1 TWh in Baden-Württemberg, which is less than 50% of the technical potential, while Turkovska et al. [223] exclude all land-use with low anthropogenic activity from wind power development. This is a pragmatic approach, but it does not reflect the complexities of real siting decisions and particularly the trade-offs between different siting scenarios. In the following, we describe two alternative methodologies which transcend land eligibility studies.

The assessment of the *socially optimal expansion of wind power* seeks to identify one optimal spatial allocation of wind turbines. Therefore, the full social costs arising, for example, from wind turbines' impact on the valuation of landscapes [242] or the environment [224], and benefits, for instance from lower integration costs of wind turbines compared to alternative sources of renewable electricity [243], need to be taken into consideration. Based on a quantitative valuation of social costs and benefits, allocations in terms of capacities and locations can be identified, which lead to the highest welfare gains or lowest welfare losses. To the best of our knowledge, a full welfare analysis has not yet been conducted, even though the social cost side has been explored (see Table 8B). As the analysis of social welfare is concerned with the effects of wind

[3] Defined as the equivalence of the LCOEs for a (decentralized) renewable generator with the purchase costs of electricity from the grid (including all grid fees and taxes). Once grid parity is achieved, the economic incentive to utilize own-generated electricity rather than import from the grid becomes stronger, in some cases justifying the investment in battery storage systems to increase this fraction [307–309].

Table 8
Examples of modelling approaches which determine 'feasible' potentials for onshore wind.

Modelling approach	Details	Region	Reference
A - Land-eligibility			
Participatory modelling	Exclusion zones and buffering zones are defined by input from stakeholder groups	Austria	[4]
Empirically observed saturation of wind power deployment	Characteristics of Austrian and Danish expansion are taken as basis for expansion in Czech Republic	Czech Republic	[175]
Landscape quality indicators	Regions with specific aesthetic landscape value, as measured by surveys and extrapolated to the whole state, are excluded	Baden-Württemberg, Germany	[3]
	Public landscape scenicness evaluation of crowd-sourced geotagged photographs for all of Great Britain	Great Britain	[211]
Avoidance of biodiversity impacts	Exclusion of all natural vegetation areas based on land-use and land cover maps	Brazil, Canada, global	[223,225,226]
Influence of wind turbines on property value	Acceptance costs derived from compensation/property purchase costs, property value loss and surveys	Denmark	[257]
B Welfare analysis			
Minimum social cost of wind power expansion	Total social cost of wind power development is minimized	West-Saxony, Germany	[224]
C Multi-criteria analysis			
Multi-criteria framework	Trade-off between three different objectives (bird collisions, settlement distance, energy performance) made explicit and aggregated to indicator.	Germany	[6]
Multi-criteria decision analysis	Trade-off between economic potential and social acceptance, as measured by statistically modelling the influence of variables on rejection rates of wind power projects	UK	[5]
Multi-criteria decision analysis	Analytical hierarchy process to derive weights for economic, social, environmental and technical criteria	Oman	[251]

power expansion on society as a whole, it is not suited to study individuals' or interest groups' patterns of technology acceptance. Moreover, welfare analysis is criticized for requiring comparisons of individuals' "happiness", which is possible only under the assumption of cardinal (i.e. meaningfully measurable) utility [244]. Furthermore, it is questionable whether a complete set of relevant welfare effects can be incorporated into actual, applied analysis. Conditional on these assumptions, welfare analysis allows to draw conclusions, for example, on potential compensation schemes for the ones affected by possible negative impacts of a specific wind turbine allocation.

In contrast, *multi-criteria analysis* (see Table 8C) makes the trade-off between different objectives explicit. Eichhorn et al. [6], for instance, show the trade-off between minimizing wind turbine impacts on birds, maximizing their distance to settlements, and their total energy generation for different allocations of wind parks. As another example, Harper et al. [5] analyze the trade-off between social acceptance and the costs of wind power projects. They measure social acceptance by means of a statistical analysis that assesses which variables are correlated with regulatory acceptance or rejection of projects. Multi-criteria analysis has also been used to evaluate (onshore) wind power regarding its sustainability in comparison to other electricity generation technologies and trade-offs between for example costs, social acceptance, impacts on ecosystems, human health, and scarcity of resources have been highlighted [231,232,245–247]. Multi-criteria analysis can also be used in a multi-objective optimization framework. This approach allows to explicitly derive so-called efficient frontiers, which

Table 9
Example indicators for modelling social, environmental, and economic impacts of wind power generation.

Type of Impact	Data sources	Indicator	Reference
Landscape quality	Housing prices	Change in property prices	[242,257]
	Choice experiments	Willingness-to-pay, Willingness-to-accept	[224,257]
	Life satisfaction surveys	Life satisfaction (11-point Likert scale)	[258]
	Licensing decisions by regulators	Probability of licensing	[211,261]
	Photo rating experiments	Rating of landscape quality	[211,259]
	Measurement of physiological and behavioural reactions to renewable energy installations	Electrodermal activity	[260]
Local/regional impacts on ecosystems	Remote sensing & GIS analysis	Direct land footprint and replaced land-use by the wind park	[223,262,263]
	GPS Tracking	Spatial movement corridors	[264]
	Maps on biodiversity	Natural habitat maps	[265–267]
Land access	Public GIS data	Property right information	[268]
	GIS data and remote sensing	(Traditional) land-use	[269,270] (not wind power related)
	Participatory maps	(Counter)maps claiming access to and use of 'undesignated' public lands by e.g. traditional and indigenous communities	[221] (not wind power related)
	Global environmental justice atlas	Conflicts over wind power projects	[271]
Overall, life-cycle based impacts on climate change, human health, ecosystems, and resources	Life Cycle Assessment (LCA) studies	Impacts on climate change Impacts on human health Impacts on ecosystem quality Consumption of biotic and abiotic resources	[272–275]

indicate Pareto-efficient loci in the solution space and corresponding trade-offs [248]. For example, Drechsler et al. [249] analyze trade-offs between the equity of spatial distributions of wind turbines and the corresponding total system cost. Multi-criteria decision analysis aims at aggregating the different objectives to one joint indicator which can be used to directly inform policy making. The Analytical Hierarchy Process (AHP) [250] is frequently used for that purpose in wind power potential modelling studies. Here, experts or decision makers define relative weights for the different objectives in a structured process [62,251,252].

The data models, visualizations and maps employed in wind potential assessments make implicit arguments. As cognitive and normative devices, they constitute specific acts in the social production of space and are therefore deeply interwoven with power and knowledge [253,254]. As McCarthy and Thatcher [255] highlight in the context of the World Bank's renewable energy resource mapping initiative, a critical examination of spatial databases, key visual technologies and representations is important, by evaluating the geographical potential of rendered eligible land to attract global investment in wind power or other renewable energy production over other (perhaps traditional) land use systems [256]. Here, the hierarchization of indicators in data models also tends to underestimate the issue of land tenure insecurities, collective and informal property regimes, and the relevance of access to and control of 'marginal' lands for livelihoods, which is a major problem given the current spatial expansion of wind power in the Global South.

5.2. Employed data sources and indicators for feasible potentials

An understanding of the broader concerns surrounding wind power installations requires additional indicators for measuring related impacts. We discuss four interesting research avenues here, which have seen substantial contributions in recent years. They represent empirical research on the impacts of wind power installations and have not necessarily been applied to feasible potential studies yet (see Table 9). The first category of impacts relates to landscape quality, measured by direct indicators such as surveys on the willingness-to-pay or willingness-to-accept [224,257], by life satisfaction surveys [258], by surveys rating landscape quality [211,259], or by experiments measuring the physiological and behavioural reaction of participants to audio-visual impacts of renewable installations [260]. Changes in property prices [242,257] and decisions by regulatory authorities [261] have been used as proxies for the revealed individual or community preferences over wind power installations (see Table 9).

Another stream of research has assessed the local and regional impacts of renewables on ecosystems. Traditionally, potential studies exclude environmentally protected areas and, sometimes, forests when defining the geographical potential. This practice, however, does not acknowledge the environmental vulnerability of land outside of these two categories. Savannas, shrublands, natural grasslands, amongst others, also provide a series of ecosystem services, such as stabilizing the local climate [276] and providing a natural habitat for endangered terrestrial species [277,278]. Multiple studies on various physical impacts of wind power showed that its development often occurs in such areas [223,279–282]. Furthermore, wildlife movements, particularly bird movements, have been tracked with GPS devices to understand how they are affected by turbine placements [264], while natural habitat maps have also been used to assess the impact of wind parks on biodiversity [265–267].

In addition to local and regional impacts on the environment, also global environmental burdens in terms of impacts on climate change, human health, ecosystem quality, and resources can have an (indirect) effect on feasible wind power potentials – be it due to an influence on the public opinion [283,284], or due to prioritisation of wind power in energy policy and planning [285–287]. Such global burdens are quantified employing Life Cycle Assessment (LCA) [288]. These life-cycle environmental burdens of onshore wind power are well known [272,274] and in general low compared to other technologies with the exception of indicators related to toxicity and metal demand [229,230,275,289]. Sacchi et al. recently identified the main factors driving these environmental burdens from a technological, temporal, and geographical perspective in a very transparent way and concluded that diversity of turbine designs, wind availability, service time and the year of turbine manufacture have a major influence on the environmental performances of wind turbines [275].

Finally, studies on opposition against wind power projects in the Global South have shown that territorial conflicts and livelihood impacts resulting from land tenure insecurity, displacement processes, distributive injustices and missing options for financial and procedural participation emerge frequently [220–222,290–292]. In comparison, studies from the Global North emphasize more strongly the interrelations between socioeconomic (e.g. housing prices), environmental (e.g. biodiversity threat) and cultural (e.g. aesthetic cultural landscape values) effects of wind power [242,259,293,294]. We therefore consider the inclusion of ownership information [268], (traditional) land-uses [269,270], participatory mappings [221], and land conflict databases related to renewable infrastructures [271] into wind power potential studies, a very important research avenue.

6. Summary and conclusions

6.1. Summary of existing methods

In this section we synthesise the main limitations of existing methods, where appropriate referring to best practice, based on the structure of sections 2-5 in the paper. In general, the analysis demonstrates a lack of consistency in the definition and application of the terminology about potentials, which are often used incorrectly and in some cases not used at all, so that it is not always clear which type of potential has been calculated [52,180,295].

In terms of the geographical potentials, the main challenge lies in formulating a stringent definition of this potential. Once a set of criteria and buffer distances have been defined, they are generally applied to the whole region under consideration without any regional differentiation. This is problematic because it overlooks important regional differences in legal and political requirements that may strongly impact the onshore wind potential. On the other hand, potential estimates at the international scale are required to include a plethora of different regulations, which is a very resource-intensive and challenging task. For this reason, most resource assessments for onshore wind tend to be more or less static, reflecting the situation at a snapshot in time and overlooking temporal dynamics in framework conditions, technologies and costs – the exception here is obviously explorative studies that explicitly analyse possible future developments in technology efficiency and costs (cf. Table 6). One further limitation relating to the geographical dimension of the analysis, is that a sensitivity analysis is only rarely performed. This means that the impacts of employing different databases, from a variety of time periods and at different spatial resolutions, on the results is not well understood. Exceptions here include Ryberg et al. [51], who did assess this and can be considered best practice in this regard.

In relation to the technical potentials, several aspects should be highlighted. There is a growing number of climatological datasets, some of them specifically targeted towards wind energy, which can be used to quantify mean wind power generation and its spatio-temporal variability. While these datasets generally provide a solid base to estimate wind energy technical potentials, no single dataset serves all purposes. Whether observations, reanalyses or a wind atlas provide the most suitable information often critically depends on the specific context. Cross-validation of results obtained using multiple climate data sources generally increases robustness of results given that biases and disagreements between different datasets exist. In terms of the technical turbine characteristics, some studies are backward-looking, using smaller and shorter turbines than are currently employed (e.g. Refs. [54,75]); rather than forward-looking and considering the next-generation turbines that could be expected for the near-term future. Other problematic assumptions observed in previous studies include: assuming a single turbine type in all locations (e.g. Refs. [52,54,75,241]), when in reality models with lower specific power are used in lower-wind locations; assuming a skewed power density (e.g. all Class III) which gives high capacity factor and thus energy yield (e.g. Refs. [52,296]); and assuming single capacity factors for all locations (e.g. Ref. [52]), when there is notable heterogeneity across Europe. Assumed capacity factors range widely across previous studies, from 20 to 30% (1720–2630 full-load hours). In addition, extreme winds and turbulence intensities are typically not considered in studies of onshore wind potentials, despite being important siting parameters. This implies, at best, an inappropriate selection of turbine/IEC class for a specific location and, at worst, an overestimation of the energy yield. Turbine characteristics are often overlooked, with very simplified assumptions employing one or only a few different turbines. Turbine spacing is typically very rough and only a few studies actually place turbines in the landscape.

Next to the feasible potential, **the economic potential** is probably the most roughly defined. As well as the business and welfare economics perspectives, researchers have employed market energy prices and subsidy levels, as well as other thresholds to define their economic potential. The application of the LCOE as the main economic yardstick to compare and assess renewable technologies is problematic due to its limited scope, overlooking integration costs and other externalities. Therefore, in future research, the results of sophisticated energy system models should be compared with economic approaches and empirical data from systems and markets where large wind penetrations already exist [207]. These approaches also enable a departure from the purely business perspective that many studies adopt, in order to derive resource distributions for onshore wind energy that are optimal from a welfare economics perspective. Quantification of future economic potentials should also anticipate the introduction of CO_2 pricing in economic sectors beyond power generation, which might have an effect on the competitiveness of wind power, for example wind turbine costs are likely to be sensitive to CO_2 prices once employed in the steel sector.

The discussion in section 5 demonstrated the emergence of a relatively new research field over the past decade, which tries to go beyond purely spatial and techno-economic potential assessments and assess actually **feasible potentials** which might be realistically achieved in practice. This research is diverse in terms of the perspectives, methods and indicators adopted, but has in common the aim to apply quantitative methods to questions surrounding possible future locations of onshore wind energy generators. In economic terms, much of this research attempts to internalize externalities relating to wind power development, such as those concerning visual landscape impact, noise, biodiversity, and land use competition aspects. This new research thread also has in common the attention to the interaction between the technical system of wind energy and the wider social and ecological systems. The relationship between these systems has been extensively researched and documented in the literature relating to the social acceptance of renewable energies [297,298]. This literature shows that, for example, social acceptance strongly depends on the distance to the turbines and their number [299,300].

6.2. Recommendations for future research: closing the methodological gaps

Whilst there is certainly scope to improve the approaches discussed here, these improvements are mainly constrained within one discipline or area so benefit from an established conceptual framework and common understanding. Arguably improvements in the methods considered within section 5 are more important, because of the relative newness of the field and the need to enhance some basic approaches, whereas the more technical fields already show a high degree of sophistication but would especially benefit from improved uncertainty handling, transparency and protocols for more efficient data updates. The feasible and economic potential analysis is also the most interdisciplinary area and analysis of both economic and feasible potentials strongly depends on normative and subjective assumptions, for example about future financing costs or the acceptance of new wind farms, which makes unambiguous or objective results impossible. Because of this, it is essential that model assumptions are based on empirical observation of recent trends and are fully transparent, to allow for intelligent, constructive discussion about trade-offs and (policy) options; such discussion, rather than producing definitive numbers, is likely the most fruitful application for studies of feasible potentials. To a large extent, this contradicts the ongoing strive to increase detail and complexity in energy modelling – but increased complexity may also hide the normative and socially constructed nature of the assumptions determining the model output [301]. It is essential that models include not only technical detail but also the social and political constraints that determine where, how much, and how fast wind power can be expanded: focussing only on technology will increase model complexity and *apparent precision*, but it will not necessarily make the model more useful for real-world wind power planning [302].

Based on this discussion, we provide the following suggestions for further work:

- **Resource assessments for onshore wind need to adopt a more self-critical stance,** meaning improving validation of results with measured wind speed/wind turbine data and verifying assumptions with literature, other experts and wider key stakeholders. This means reflecting upon the consequences that the model output and its spatial assumption on wind potentials might trigger, e.g. as stories and narratives for energy policy-making [303,304].
- **Uncertainties surrounding all data inputs** should be explored with sensitivity analyses. Best practice would be to provide a broad range of scenarios which represent the multitude of available options, for example relating to the assumed turbine spacings. Data transparency and public availability of data and models are also key goals for more effective science-policy networking [305].
- **Potential assessments must explicitly include social and political factors** to be relevant for wind power planning, because these factors are currently, and in the foreseeable future, the main barriers to continued wind deployment and designation of new expansion areas. Ignoring them may lead to misleading, typically overestimated, results [302]. If, in contrast, these *soft* factors are explicitly included, models and potential assessments can make an important contribution to wind power planning and policy by showing where and how much wind power could be placed, under which conditions.

- In terms of the **technical turbine characteristics**, onshore wind resource assessments should explore the impact of the chosen turbine design(s). Best practice is to employ a state-of-the-art turbine and/or expected future developments in turbine configurations. Where this is not the case, the implications of employing a typical or simplified turbine(s), specific power and/or capacity factors should be quantified.
- In terms of **wind turbine spacing and park planning**, if wind power potentials are assessed over large areas, the extraction of wind energy from the atmosphere may have a significant effect and therefore should be addressed [306]. In addition, the influence of small areas on total potentials should also be checked, using e.g. a sensitivity analysis.
- **Much of the reviewed literature adopts a static viewpoint**, meaning a consideration of one moment in time due to data availability and for other reasons. The dynamic nature of energy transitions in general and wind technologies in particular means that these results quickly become outdated. More useful are studies that develop a modelling framework and/or dataset that can be employed and adjusted by stakeholders for their own analysis (e.g. Refs. [5,6]).
- The focus for future research into feasible potentials therefore needs to **explicitly embrace a diversity of approaches and perspectives**, and reflect this in the collaborative research teams. **Holistic frameworks** need to be developed that include multiple dimensions of wind energy impacts as well as their interactions and interdependencies. It is encouraging that two reviewed studies in Table 8 adopt such an MCDA approach, but at the same time an indication of an urgent need for further work.
- **Assessments of wind potentials need to draw up a complete balance sheet**, including all costs and benefits, to be assessed within a systems framework – again, here too are some promising examples, but these are limited in number as well as in terms of their focus on specific impact categories.

CRediT (contributor roles taxonomy) author statement

The authors' names are ordered according to the following logic: RM through IS reflects leading contributions as noted below, CB through JW are in alphabetical order. The following abbreviations are used: Conceptualization (C), Methodology (M), Formal Analysis (FA), Writing – original draft (WO), Writing – review & editing (WR), Supervision (S), Project administration (PA), Funding acquisition (FU), Visualisation (V). **RM**: C, M, FA, WO, WR, S, PA, V; **SP**: C, M, FA, WO (section 3 lead), WR, S; **HH**: C, M, FA, WO (section 2 lead), WR, S; **JS**: C, M, FA, WO (section 5 lead), WR, S, FU; **IS**: C, M, FA, WO (section 3 lead), WR, V, FU; **CB**: FA, WO (sections 5 and 6), WR; **KG**: FA, WO (section 3), WR; **AH**: C, FA, WO (section 3), WR, S; **MJ**: M, FA, WO (sections 3 and 4), WR, FU; **MK**: M, FA, WO (section 5), WR; **NL**: FA, WO (section 2), WR; **XL**: M, FA, WO (section 3), WR; **JL**: FA, WO (sections 2, 4 and 6), WR, FU; **BP**: FA, WO (section 3), WR; **MR**: C, M, FA, S; **TT**: FA, WO (section 2), WR; **OT**: FA, WO (section 5), WR; **SW**: C, M, FA, WO (section 5), WR; **JMW**: C, M, FA, WO (sections 1, 3, 4), WR, V; **JW**: FA, WO (section 3), WR.

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.

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