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Assessing the cost of onshore wind development scenarios: Modelling of spatial and temporal distribution of wind power for the case of Poland

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ABSTRACT

Wind energy plays a key role in the transition to a low-carbon European energy system. The implementation of European and national targets for wind energy expansion is, however, challenged by technical, environmental, economic and social acceptance aspects. Further research on wind power expansion is compelled due to dynamic aspects such as land-use fluctuations, evolution of wind turbine technology, associated cost, and other factors. For that reason, a systematic approach for exploring future scenarios of onshore wind power development under techno-economic aspects and quantitative aspects of social acceptance (distributive justice and regulatory framework) was developed. The model was developed in Python, PostgreSQL and SQliteDB and encompasses a high-resolution GIS-based assessment of potential locations for wind turbines. Homogenous input data allows for analysing the wind power potential across Europe. Poland was chosen as a case study to examine the impact of the distance regulation introduced in 2016 and its subsequent amendments, which are relevant for onshore wind power development foreseen in the EU reference scenario 2016 for 2030. The findings show that Poland can reach the target of 10.3 GW set by the EU scenario at Levelized Cost of Electricity below €60/MWh. The transparent modelling framework and findings can support the decision making process on wind energy expansion, which is in the hands of policy makers, private investors and local citizens.

1. Introduction

Wind power plays a key role among renewable energy sources in decarbonizing the European energy system. The role of onshore wind power was initially manifested in the Renewable Energy Directive 2009/28/EC, which targets a 27% RES share in gross final energy consumption by 2030. This objective has been intensified to 32% with the accord between European Commission, Council and Parliament in June 2018 [1]. In 2016, the European Commission published the “EU reference scenario 2016” [2]. This scenario framework describes, in detail, the assumptions for a possible evolution of the European energy system. It is based on policies that were implemented in the spring of 2015, and assumes for the short-term that binding 2020 climate protection targets will be met by the European Union (EU) (i.e. 20% RES in gross final energy consumption). Beyond 2020, the EU reference scenario does not meet specific EU targets, but represents a baseline scenario to which new policies can be compared. In the long-term, the EU reference scenario 2016 is not very ambitious regarding RES development, and onshore wind development is primarily driven by assumptions on moderate technological improvements, improving cost-competitiveness driven by economies of scale and increasing carbon prices, power grid development, as well as the maintenance of priority dispatch for variable RES. The EU reference scenario 2016 features detailed trajectories for expected onshore wind capacities in each EU member state. However, the underlying European energy system analysis conducted with the PRIMES model does not specifically deal with

Abbreviations: 10H, 10 times the tip height of a wind turbine; Act on RES, Act on Renewable Energy Sources; c, Weibull scale parameter; CAPEX, capital expenditures; CLC2000, Corine Land Cover 2000; DEM, Digital Elevation Model; distance regulation, Act on Wind Farm Investments of 2016; E_{el}, annual electrical energy yield; E_t, electricity generated in year t; EU, European Union; €, Euro; η, the wind turbine availability; $f(V)$, the probability density function of the wind speed V; GIS, Geographical Information System; IEC, International Electrotechnical Commission; k, Weibull shape parameter; km^2, square kilometre; kW, kilowatt; kWh, kilowatt hour; LCOE, Levelized Cost of Electricity; MWh, Megawatt per hour; m/s, metre per second; NUTS, Nomenclature of Territorial Units for Statistics; OPEX, operations and maintenance expenditures; OSM, Open Street Map; %, percent; P(V), the power curve of w wind turbine; RES, Renewable Energy Sources; SRTM, Shuttle Radar Topography Mission; SQliteDB, SQLite database; V, annual average wind speed; VBA, Visual Basic for Applications; WACC, Weighted Average Cost of Capital; WDPA, World Database on Protected Areas

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local constraints that wind and renewable energy sources generally might be confronted with.

Wind energy plays an important role in addressing climate change, but its intensified expansion can also lead to land-use conflicts and adverse impacts on ecologically sensitive areas and landscape beauty [3]. This in turn may lead to social resistance against wind turbines [4]. Numerous empirical studies analysed conditions that characterize the resistance and acceptance towards wind turbines and other RES [5–8]. Sovacool et al. [9] explore nine factors that shape the socio-political, community and the market acceptance of renewable energy sources. An empirical study conducted in Poland [10] analysed similar factors that influence the wind power development prospect. This research [10] reveals that both regulatory instability and the Act on Wind Farm Investments [11] introduced in 2016 were the primary causes for the recent slowdown of wind power development in Poland. Contrarily, the same study also exposes that wind power expansion is associated with an increasing employment rate and municipal economic growth, and thereby is positively perceived by local communities. A survey [12] carried out in Poland and Germany argues that distributive justice (distribution of wind turbines across regions) is less present in Poland than in Germany. This can be explained by the fact that the exposure factor to existing wind turbines is much higher and the regional turbine distribution is a topical subject in the public discourse in Germany [12].

It is widely acknowledged that social acceptance is a relevant driver in determining the success of onshore wind projects, but this factor is usually beyond the scope of quantitative studies carried out on global, national and regional scales. Still, some local studies attempt to reflect local social preferences in the decision-making process by applying multiple-criteria evaluation techniques [13]. The optimal set of wind turbine locations usually reflects a compromise between the cost of their realization, local energy constraints (e.g. access to power grid, availability of wind resource) and some measures of quality of the potential sites, for instance the need of conservation of environmentally sensitive areas and landscape beauty [13–15].

Geographic Information Systems (GIS) have been widely used to assist the assessment of potential sites for wind turbines under a large spectrum of numerical and geo-referenced conditions [4,16–19]. Recent studies attempt to consider some aspects of social acceptance and integrate them into GIS-based assessment. A study carried out in Austria assesses the question at what costs the national targets for wind energy can be met considering socio-political and market acceptance [20]. For this purpose, land-use scenarios were defined in the participatory modelling approach with different groups of interest, which were then integrated into a GIS model. Jäger et al. [21] developed an approach to estimate the potential and costs of onshore wind energy production considering aesthetic landscape aspects. Their model incorporates a map representing landscape quality normalized to a scale from 0 to 10, which was developed by Roser et al. [22] for Baden-Württemberg, Germany. The application of this novel approach to other countries or regions is, however, strongly limited. The model is based on both a high operational resolution and a commercial land-use data set, as well as on georeferenced data on quantified aesthetic aspects of a landscape, which is not available in other countries.

McKenna et al. [23] combined GIS assessments with VBA/Microsoft Excel and Access-based models for approximating the investment costs required to meet the 2020 targets of National Renewable Energy Action Plans in 28 European countries. The assessment of areas available for wind power development across EU countries is based on a constant set of constraints and minimum distance buffers as well as suitability factors, which reflect non-techno-economic constraints.

A shortcoming of the aforementioned studies is that they estimate wind energy generation costs for a single year. The temporal and spatial changes in available surface due to the accumulation of historically installed and new wind turbines, and the possible technological evolution beyond the short-term perspective are not considered. In addition, the suitability factors, which may reflect some acceptance issues, are fixed values used across countries [23–25].

The need for research on wind power development is, thus, driven by land-use fluctuations, evolution of wind turbine technology and its associated cost, temporally decreasing availability of land resources for RES development, as well as variation of acceptance of renewable energy sources. By the same token, many findings on suitable areas and their technical and economic potential are already outdated. Moreover, many GIS-based methodologies are difficult to replicate in other case studies due to a lack of comparable mapping schemes and input data.

In this paper, a systematic approach is presented for assessing the spatial and temporal distribution of medium-term targets for onshore wind power development. The Polish perimeter serves as a test of the methodology and the conclusions to be drawn. In addition, this study presents a case for parametrizing factors shaping social acceptance, namely the regional distribution of wind power (distributive justice), the distance regulation (Act on Wind Farm Investments [11]), and the costs of wind energy. Different scenarios are developed to explore the influence of regional distribution, and distance regulation on cost.

The methodology was developed in a joint research project between the European Institute for Energy Research (EIFER) and Electricité de France (EDF) in order to evaluate the potential of onshore wind power development across European countries challenged by technical, regulatory, economic, environmental and aforementioned quantifiable social acceptance aspects. The Polish case study explores the impact of the changes to the Polish legal framework which was introduced in 2016. Since no such study has been carried out for Poland, the results presented here might help to shape a vision on wind power development until 2030.

The model, developed in Python, PostgreSQL and SQliteDB, encompasses a high-resolution GIS-based assessment of potential surfaces for wind turbines considering national regulation, and prospective economic analysis.

The research goals are as follows:

i) To identify available areas for onshore wind energy expansion in Poland according to existing regulations.
ii) To evaluate the spatial and temporal distribution of new onshore wind turbines within available areas, taking into account technical and economic parameter sets.
iii) To assess the distribution of installed onshore wind power capacity in each region under which national capacity targets can be reached at minimum cost.
iv) To study how the corresponding regional power densities, regulatory changes, wind resources, and the reference technology set applied in this study affect the expenses incurred by the Polish wind energy expansion until 2030.

2. Wind energy development in Poland

The amendment to the Act on Renewable Energy Sources (Act on RES) came into force on 1 January 2016 and replaced the previous quota system (green certificate system) by an auction-based support system for new RES installations with over 10 kW installed capacity. In 2016, the auction system favoured other RES over wind power and in 2017, only one auction for 150 MW was announced. The situation of the Polish wind market worsened further due to the Act on Wind Farm Investments that came into force on 20 May 2016 and introduced a minimum distance of wind turbines from residential buildings and protected areas (i.e. national parks, nature reserves, landscape parks, Natura 2000 networks of protected areas and promotional forest complexes) at 10 times the tip height of a wind installation (10H)[1] [11]. In practice, this means that new wind turbines must be located at a

[1] The height of the wind turbine is calculated from ground level to the highest point of the turbine including the rotor (tip height).

minimum distance of 1.6–2 km to residential buildings or settlements and sensitive ecological areas. An additional limitation is the compulsory compliance with local zoning plans [11], which cover around 30% of the Polish land area [26]. In addition, the act prevents any modernization (e.g. repowering) of existing wind turbines failing to meet the new minimum distance requirement. Only maintenance activities required for turbine operation are still allowed.

Current wind power capacity reaches 5.87 GW and makes 68% of the total installed RES power capacity in Poland which amounts to 8.58 GW [27]. Thus, Poland was on track to reach the legally-binding 15% target of RES in final energy consumption by 2020, but due to the aforementioned changes in the regulatory framework, 2020 RES targets might be missed [28]. An observable effect was that only 50 MW of new wind power was installed in 2016 and 10 MW in 2017. In 2018 the Polish government slightly adjusted its course towards RES. The latest amendments to the Act on RES 2018 published on 29 June 2018 introduce a number of changes, which are expected to have positive impacts on the conditions for existing wind projects [29]. However, the 10H distance criterion is still applicable. Under the call for tender scheme organized for the end of 2018, approximately 1120 MW of new onshore wind farm projects may receive subsidies, which are limited to €76/MWh (PLN320/MWh) for small turbines < 1 MW and to €83/MWh (PLN350/MWh) for standard turbines > 1 MW [30].

Wind power plays the leading role among non-biomass RES in Poland. Based on the European reference scenario 2016 targets for Poland for 2030, several scenarios regarding the spatial and temporal distribution of new wind turbines are presented in this paper.

3. Methods and data

This section explains the methodology developed and the data used in the study. Homogeneous and publically available spatial data was used to assess suitable areas for wind power considering exclusion criteria derived from the regulatory framework. The model allows for exploring different scenarios of regional power deployment including wind resource data along with techno-economic data and assessing the costs of wind energy production.

3.1. Exclusion and selection criteria for wind power development

The assessment of areas for wind power development must fulfil certain conditions in order to maintain environmental benefits and prevent conflicts related to the construction of wind turbines.

Siting constraints are usually related to the land functions, which are either mutually exclusive or compatible with the wind energy production [18]. Wind turbines can be sited on agricultural land, but are usually prohibited in locations with environmental protection functions such as national parks, protected moors, or sensitive landscapes. Under special circumstances, construction of wind turbines can be allowed on sensitive sites, but compensation measures would be required to mitigate any possible impact on the biosphere or land-use [4]. Such exceptions are only granted on a local scale after an environmental impact assessment. In this study performed on the national scale, the preliminary investigation of available areas is carried out for two groups of constraints. The first and compulsory group includes roads, power lines, waters, wetlands, urban areas and buildings, airports, aerial ways, military areas, radars, forest, and areas of more than 2000 m above of sea level, but it does not include protected areas. The second group consists of the first group plus protected areas of any kind (see Table A.1). In addition, certain areas were excluded around aforementioned categories with a minimum distance buffer according to Polish legislation [11,31] and earlier studies and reports [26,32,33].

Three scenarios of different buffer zones around residential settlements and protected areas were studied. The buffer scenarios of 1.6 km and 2 km comply with the minimum distance under the current distance regulation, representing the variation in the height of current wind power plants. As settlements are very dispersed in Poland, especially in rural areas, we explore a third scenario of 1 km to compare the residual potential area for wind power expansion for a less stringent regulation. Pawlaczyk-Łuszczyńska et al. [34] argue that a distance of 1 km is sufficient to reduce turbine noise emissions to a level that is perceived as not being annoying.

3.2. Description of data input

One of the goals is to provide a preliminary estimation of available areas for wind power development at both national and regional levels. Exact site assessment is beyond the scope of this study. For this reason, two criteria determined the choice of adequate data sets: uniform and accessible data source for the European countries.

3.2.1. Land-use data

The context for a given study defines data quality requirements, i.e. the way how data is suitable for meeting certain objectives [35]. Despite the limitations that come with Volunteered Geographic Information [36–39], OpenStreetMap (OSM) data [40] has been used in many urban and energy related studies [16,41–44] and onshore wind site assessments [45].

With regard to the objectives of this study, OSM data represents a very broad spectrum of geo-referenced features. Feature categories can be differentiated according to the additional semantic information-tags. The preliminary OSM data assessment demonstrated that some OSM-tags are missing. The classification of building types was, therefore, supported by Corine Land Cover 2000 (CLC2000) [46]. The raster data with a resolution of 100 m divides European land-use into 44 classes. The CLC2000 data depicts some limitations, for instance, land-use areas < 1 ha are not represented in the data. More details are described in Refs. [47,48]. Nevertheless, the CLC2000 data was used in a wind power potential study at European scale in Ref. [23] and fulfils the requirements of this study. The OSM building objects typology classification corresponds to the selected CLC2000 classes: 111 (continuous urban fabric class), 112 (discontinuous urban fabric class), and 121 (industrial or commercial units and public facilities) [49].

Protected areas are well represented and categorized in the World Database on Protected Areas (WDPA), publicly[2] available on Protected Planet, which is an online platform managed by the United Nations Environment World Conservation Monitoring Centre [50]. The up-to-date database is a complete source on protected areas that are submitted monthly by governmental and non-governmental organizations.

A 3-arc second resolution Digital Elevation Model (DEM) which results from the Shuttle Radar Topography Mission (SRTM) of NASA [51] is used to exclude the area above 2000 m altitude.

3.2.2. Wind resource data

This study considers average wind speeds and Weibull parameters at 100 m above ground level derived from a time series collected between 1996 and 2015, available from a wind atlas for the European scope provided by Anemos GmbH [52]. This atlas is based on re-analysed data originating from the MERRA climate model and is downscaled with an MM5 meso-scale model. The data comes at a resolution of 20 km × 20 km, which is also the resolution for the optimization process. This grid size was chosen to facilitate a compromise between performance efficiency of the iteration process carried out for each cell and each year, and the cell size, which must be big enough to consider new and existing wind farms without exceeding a technical density limit. For a wind siting assessment, which is beyond the scope of the present study, the wind speed data should be of a higher resolution in order to allow for a more reliable estimation of the yield and cost in a complex terrain.

[2] Terms and conditions of data usage on https://www.protectedplanet.net/c/terms-and-conditions.

Table 1
User input.

Parameters	Value(s) applied	Unit	Level
Technical Limit (power density of wind farms)	6 and 15	MW/km^2	National
Regional power density for non-forested area	0–15	MW/km^2	Regional (NUTS1)
Regional power density for forests	0	MW/km^2	Regional (NUTS1)
Available area	1 and 2		National
Turbine lifetime (range)	25 and 20	Years	National
Turbine availability	0.85		National
Re-Powering Factor	0		National
Re-Powering Rate	0		National
Discount rate (WACC)	5.5 and 8	%	National

Table 2
User input for turbine model selection with CAPEX, OPEX, IEC class of maximum wind speed.

Manufacturer		Vestas	Vestas	Nordex	Enercon	Gamesa	Siemens
Turbine type		V90/3000	V112/3000	N117/3000	E126/7500	G128/4500	SWT/3600
Nominal power (kW)		3000	3000	3000	7500	4500	3600
Hub height (m)		90–105	84–119	91/120/141	135	81–140	80–96
Rotor diameter (m)		90	112	116	127	128	107
OPEX (€/kW/a)		45	45	45	45	45	45
CAPEX (€/kW)	2018	1172	1431	1527	2000	1480	1490
	2020	1154	1410	1504	1970	1458	1468
	2023	1129	1378	1471	1926	1425	1435
	2025	1112	1358	1449	1897	1404	1414
	2030	1071	1307	1395	1827	1352	1361
IEC class max wind speed (m/s)		10	10	8.5	10	8.5	10

3.2.3. *Historically installed wind farms*

A point that is often neglected, regarding historically installed wind power capacity, is the significant restriction to available areas for wind power development. The wind power database on existing wind farms used in the study is provided by the Wind Power [53]. The data covers 5.66 GW of 5.87 GW installed by mid-2018, including geographic coordinates of single wind farms, total power, number of wind turbines in a wind farm, and commissioning date.

3.3. *User input parameters*

The model allows a user to freely set input parameters that can be divided into general technical and economic input parameters as well as parameters related to wind turbine models (see section 3.3.1). Moreover, a user can set regional power density factors for exploring different scenarios of spatial wind power deployment. The power capacity target can be split into annual targets as described in section 3.3.2.

3.3.1. *Technical and economic input parameters*

The customizable input shown in Table 1 contains a technical limit (MW/km^2), regional power density factor inside and outside forests (MW/km^2), available area category, expected turbine lifetime (years), turbine availability (%), repowering factor and rate (%), and discount rate (%). These parameters are set at the regional and national level.

In addition to the technical limit, regional power density factors are introduced to reflect the non-technical, non-environmental, and non-economic aspects of wind power development, and are distinguished for non-forested areas and for forests. They can be set individually for Poland's six regional units at NUTS1[3] level and allow to examine the regional power densities needed for fulfilling the capacity targets for the EU reference scenario 2016 in 2030. The approach used for elaborating the regional power density factor for non-forested area is described in detail in section 4.2. On the contrary, regional power density in forests is set equal to 0 because of a lack of acceptance [33].

Depending on the turbine model, wind turbines within wind farms are typically spaced with a distance of 5–10 rotor diameters. The resulting power density in a historical wind farm ranges mainly between 2 and 10 MW/km^2, but can also reach 18 MW/km^2 [23,54]. Two parameters of technical limits of 6 and 15 MW/km^2 (see Table 1) are calculated for the turbine models outlined in Table 2. Both parameters of regional power density within and outside forests are derived from the historical wind power deployment pattern as described in section 4.2.

Available area is the remaining area after extraction of restricted areas outlined in Table A.1.

The turbine availability expresses the expected average turbine operating availability over its lifetime. This parameter is related to operating losses [55], wake effects occurring in wind farms [56] and turbine non-availability due to its failure or maintenance [57]. The wind turbine availability is on average 85% and is used to calculate the annual wind energy production (see Eq. (2) in section 3.4.3).

The repowering rate expresses the ratio of old turbines to be replaced in a given year. The repowering factor defines the power capacity upgrade of the repowered turbine.

The turbine lifetime is usually 20–25 years. This parameter is used to calculate the Levelized Cost of Electricity (LCOE) for turbines installed by the algorithm (see Eq. (3) section 3.4.3) as well as to perform the decommissioning of turbines after the technical lifetime of a turbine is reached.

Further LCOE components set by a user are capital expenditures (CAPEX), annual operational expenditures (OPEX), and the weighted average cost of capital (WACC).

The WACC depends on the investment risk associated to a potential project and differs in theory for each project [58]. CAPEX cover the equipment costs, project planning and development, as well as the grid connection [32,58,59]. OPEX cover all operational (e.g. environmental and safety monitoring, annual leases, fees, insurance, operation, management and administration) and maintenance expenses. Although

[3] The Nomenclature of Territorial Units for Statistics (NUTS) is a geographical nomenclature subdividing the economic territory of the European Union (EU) into regions at three different levels. The NUTS is based on Regulation (EC) No 1059/2003 of the European Parliament and of the European Council of 26 May 2003.

Table 3
Breakdown of capacity trajectory for EU reference scenario 2030 [2].

Year	2015	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
EU ref.sc. (MW)	**5100**			**5728**					**9669**					**10339**
Interpolation (MW)	5700	5700	5700	5728	6400	7200	8000	8800	9669	9800	9950	10080	10200	10339
Trajectory (MW)	–	0	0	28	672	800	800	800	869	131	150	130	120	139

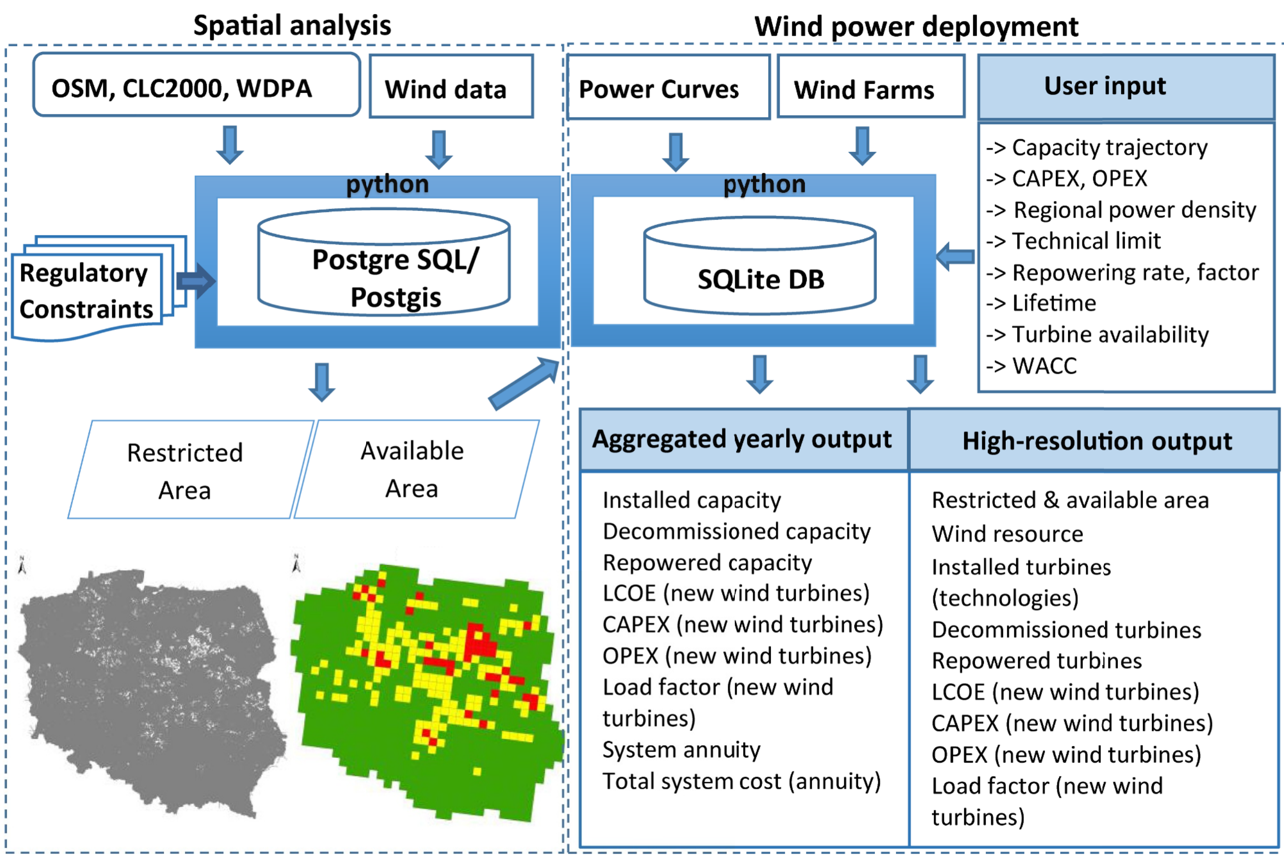

Fig. 1. Schematic representation of the workflow for data input and output.

CAPEX and OPEX differ from site to site, LCOE is based on average figures set by the user at the national level. Table 2 shows CAPEX and OPEX for the reference turbines, which are based on literature research [58,60,61] and expert interviews. For the historical wind power capacity installed between 1990 and 2017, uniform CAPEX, OPEX and capacity factors are applied for reasons of simplicity (see Table B.1).

Another technical parameter, which affects the selection of an appropriate turbine in the model is the maximum average wind speed of standardized wind classes (see Table 2).

Wind classes, created by the International Electrotechnical Commission (IEC), reflect wind turbine design conditions and are determined by three parameters, average wind speed, extreme gust and turbulence [62,63]. The model considers only maximum average annual wind speeds, since more detailed information on 50 years of extreme gusts or local turbulences is not easily accessible.

For the purpose of this study, from more than 600 models provided by the Wind Power [64], a set of six representative reference turbines (see Table 2) was applied to the model.

3.3.2. Scenarios for wind power development

The EU reference scenario 2016 [2] provides the wind onshore net generation capacity, added to existing wind turbines in European countries every fifth year. This study uses this capacity trajectory for Poland until 2030, which was linearly interpolated between base years as shown in Table 3.

3.4. Model description

The approach is illustrated in Fig. 1 and consists of two consecutive steps including 1) spatial analysis of potentially available areas for onshore wind turbines, and 2) spatial and temporal wind power deployment under technical, economic and wind power density constraints.

The approach is split in two models. The reason for this is that the spatial potential of available areas explored in the first model would only change if regulatory constraints or the availability of spatial data change. This spatial data on available area is used multiple times in the second model, which deploys an annual onshore wind capacity taking into account user input to the model.

3.4.1. Spatial analysis of available area for wind turbine deployment

In the first step "spatial analysis", the OpenStreetMap dataset is

Table 4
Criteria for spatial wind power distribution.

Approach	Results	Pros	Cons
According to minimum LCOE.	Wind turbines are placed in cells with lowest LCOE. If maximum technical density is reached in a cell, no more turbines can be installed.	Ensures minimal system costs.	In reality, there are other cost and non-economic factors affecting spatial distribution. For this reason a second constraint is superimposed at regional level – regional power density factor.
According to the historical distribution of wind turbines.	Wind turbines are placed proportionally to their historical distribution in each cell.	Ensures wind turbines to be installed in less favourable locations.	Non-cost-optimal spatial distribution.
According to equal distribution over all cells.	Each installed MW is equally distributed over the entire country, proportionally to the available area per cell.	Simplest implementation. In line with the public acceptance issue of distributive justice.	Not realistic and non-cost-optimal distribution.

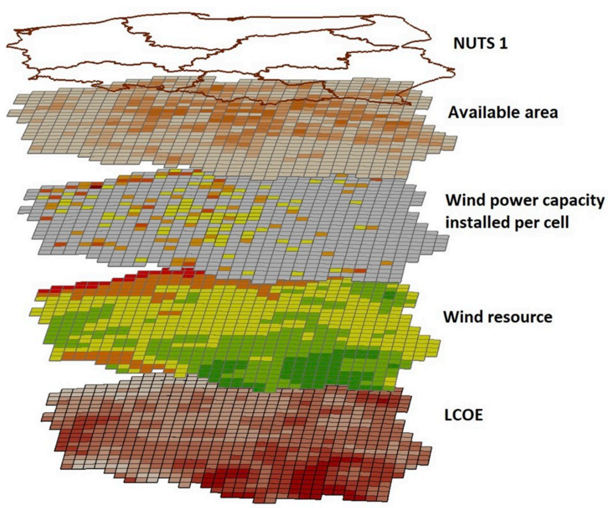

Fig. 2. Input layers used to determine and distribute optimal wind turbines.

downloaded from Geofabrik's server [40] for European countries. The open source Java program osm2pgsql is used to load the dataset into PostgreSQL, a free and open source object-relational database with PostGIS extensions.

Once the spatial data is stored in the PosgreSQL database, PostGIS functions implemented in SQL queries are executed in Python scripts to explore the restricted area for onshore wind power development defined according to the national and regional regulations. This way, restricted and available areas are identified at very high resolution. Next, a grid layer of 20 km × 20 km containing the wind resource data is superimposed to the available areas.

The spatial data treatment process in the first step is automatized in a model developed in Python 3.5.

The final output of the spatial analysis, which combines two groups of available areas with wind resource data migrates from PostgreSQL to a SQLiteDB, which is a relational and portable database embedded into the second step.

As shown in Fig. 1, additional data is imported to the SQLiteDB. This includes power curves for about 600 wind turbines, georeferenced wind farm data, as well as technical and economic parameters set by a user while modelling a new scenario or sensitivity analysis.

3.4.2. Wind power distribution approach

Different possible approaches for the spatial allocation of wind turbines were identified and elaborated. Potential alternatives with their pros and cons are outlined in Table 4. Having considered all these issues, the first least cost-approach based on minimizing LCOE was selected to study the power deployment across regions.

3.4.3. Wind power deployment method

Consequently, the approach implemented in the second model (wind power deployment) is based on a least-cost iteration facilitated by SQLite query language. Annual wind power capacity trajectories are deployed year-by-year until 2030 taking into account a) the available area from the spatial analysis, b) existing onshore wind farms in a given year and c) user input factors. The algorithm iterates for each trajectory year over the subsequent steps:

a) Identify optimal turbine technologies for each cell and year until 2030.

First, the wind speed distribution for each turbine is calculated based on the Weibull function [65] shown in Eq. (1) and then the annual wind energy yield is calculated according to Eq. (2).

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} e^{-(V/c)^k} \quad 0 \le V < \infty \tag{1}$$

where k, c are Weibull shape and scale parameters, and V is the annual average wind speed [m/s].

$$E_{el} = 8760 * \eta * \int_0^\infty (f(V) * P_j \quad (V))\mathrm{d}v \tag{2}$$

where E_{el} is the annual electrical energy yield [MWh], 8760 is the total number of load hours per year [h], η is the wind turbine availability

Table 5
Available area for onshore wind development in Poland.

Buffer distance scenarios Categories	Units	Sc. 1 with 1 km		Sc. 2 with 1.6 km		Sc. 3 with 2 km	
		Forest excluded	Forest included	Forest included	Forest excluded	Forest excluded	Forest included
Available area with constraint group 1	10^3 km^2	34.3	89.8	26.8	48	13.3	34.6
Share of Poland's land area	%	11.0	28.8	8.5	15	4.3	11.1
Available area with constraint group 2	10^3 km^2	**21.5**	40.4	**13.7**	19	**7.9**	16.3
Share of Poland's land area	%	**6.9**	12.9	**4.4**	6.1	**2.5**	5.2

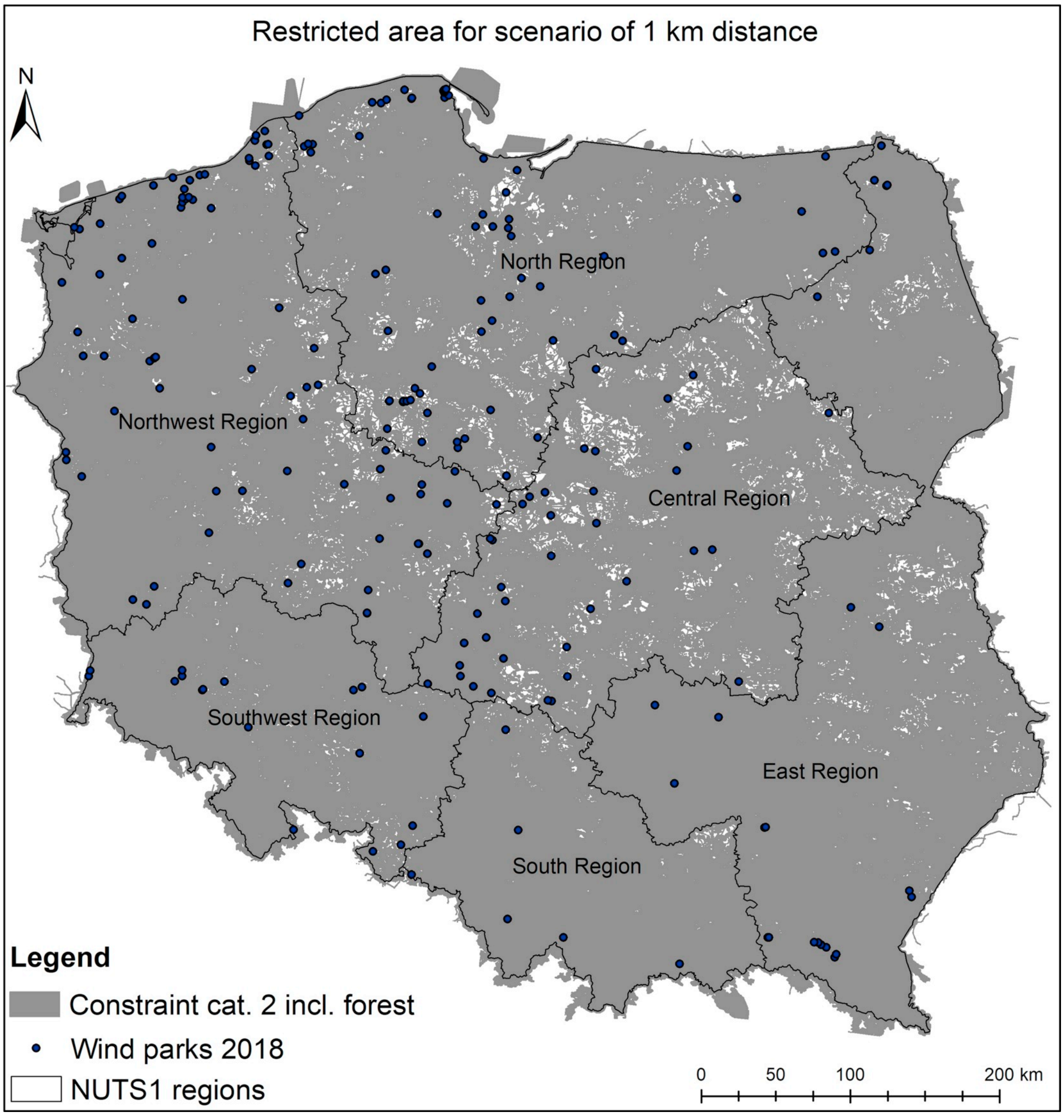

Fig. 3. Restricted area in constraint group 2 with 1 km buffer distance.

[%], $f(V)$ is the probability density function of the wind speed V, and $P_j(v)$ is the power curve [kW] of selected turbine j for a site with wind speed V.

Next, the LCOE is calculated for each turbine as shown in Eq. (3).

$$LCOE = \sum_{t=1}^{n} \frac{Capex_t + Opex_t}{(1+r)^t} / \sum_{t=1}^{n} \frac{E_t}{(1+r)^t} \tag{3}$$

where, n is the lifetime of the wind turbine, $Capex_t$ is the investment cost for a wind turbine in year t, $Opex_t$ is the operational cost in year t, E_t is the electricity generated (in kWh) in year t, and r is the discount rate, equals to WACC (in %).

The result of this iteration is the identification of an optimal turbine with minimum LCOE for each cell and given year, which is stored in a table in SQLiteDB.

b) Find all turbines installed in the past that reached their end of technical lifetime (decommissioning process). The user sets the lifetime factor for this purpose.
c) Calculate repowered capacity as a multiplication of three components: repowering factor, repowering rate, and decommissioned power.
d) Read capacity to be installed in each year of the model horizon. The capacity is a sum of annual trajectory targets and the repowered power capacity.
e) Install the trajectory into available areas at minimum LCOE.

Three types of constraints are considered here, including (1) available power capacity at the regional level (called Admin_Unit), which is determined by the regional power density parameters, (2) available power capacity at the cell level determined by the technical limit parameter, and (3) the maximum average wind speed in a given cell that cannot exceed 10 m/s according to ICE standards for wind turbines. The lowest-cost cells are identified through an iterative process evoked each year by means of the formula described in Eq. (4) considering three types of constraints and ascending ranking of cells according to their LCOE:

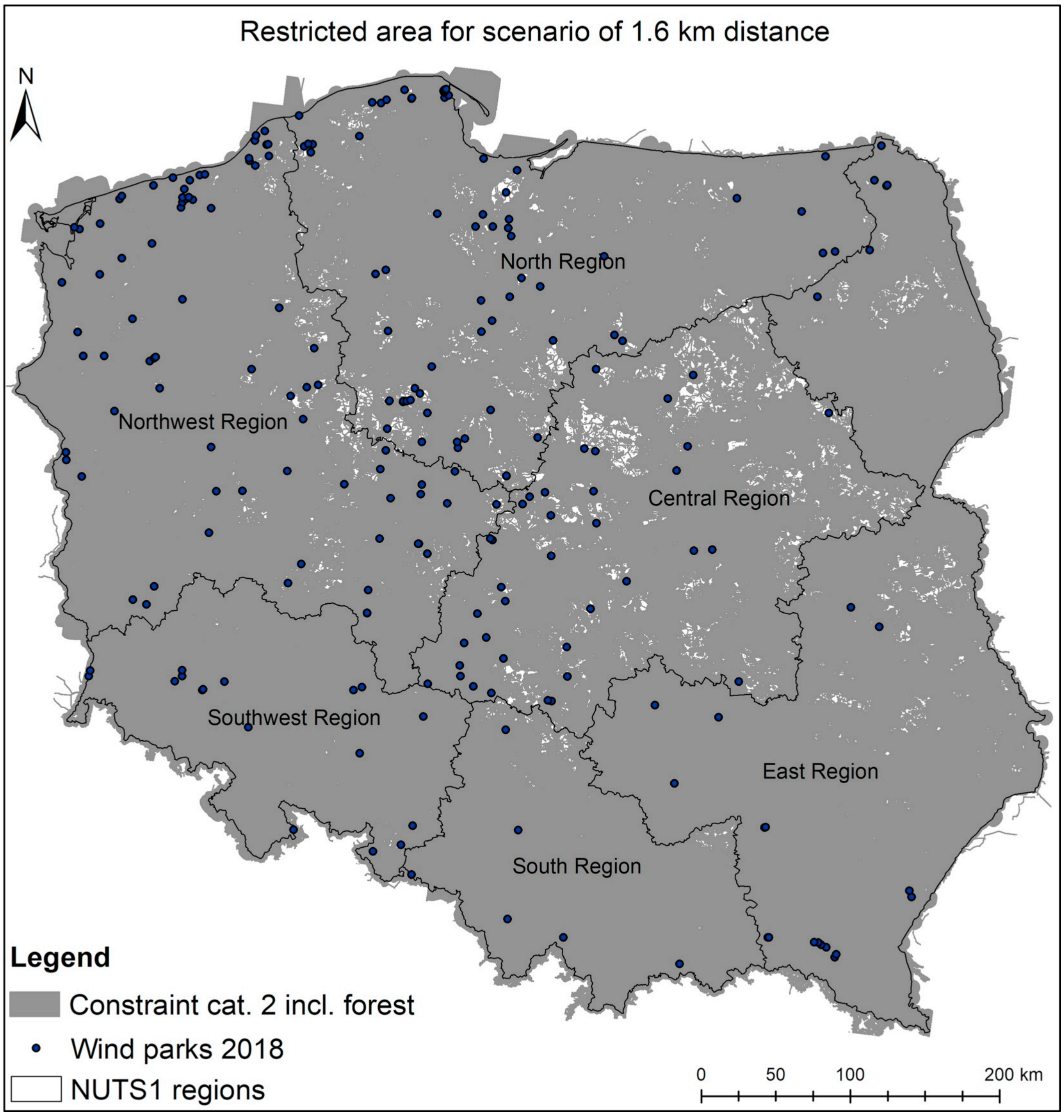

Fig. 4. Restricted area in constraint group 2 with 1.6 km buffer distance.

$$
\begin{aligned}
&(1)\mathit{Power\_Installed\_in\_Ad}\min\mathit{\_Unit}\ [MW] \leq \\
&(\mathit{Area\_with\_Forest}\ [km^2] - \mathit{Area\_without\_Forest}\ [km^2])^{*}\mathit{Forest\_}\operatorname{Reg}\mathit{ional\_Power\_Density}\ [km^2/MW] \\
&+ \\
&\mathit{Area\_without\_Forest}\ [km^2]^{*}\mathit{Land\_}\operatorname{Re}\mathit{gional\_Power\_Density}\,[km^2/MW] \\
&(2)\mathit{Power\_Installed\_in\_Cell}\ [MW] \leq \\
&(\mathit{CASE\ WHEN\ Forest\_Regional\_Power\_Density}\ [km^2/MW] > 0\ \mathit{THEN\ Area\_with\_Forest}\ [km^2]\ \mathit{ELSE\ Area\_without\_Forest}\ [km^2])^{*} \\
&\mathit{Technical\_Limit}\,[km^2/MW] \\
&(3)\mathit{Average\_Wind\_Speed}\ [m/s] < 10[m/s] \\
&\mathit{Order\ By\ LCOE}\,[€/MWh]\,\mathit{ASC}
\end{aligned} \tag{4}
$$

Fig. 2 shows the data input layers, which are stored in SQLiteDB tables and queried by the algorithm shown in Eq. (4). The first constraint in the query addresses the wind power potential calculated at a regional level. The available area in an administrative unit is multiplied by two distinct regional power density factors defined for forest areas and outside forest areas called Forest_Regional_Power_Density and Land_Regional_Power_Density. For that purpose, the georeferenced output from PostgreSQL distinguishes between available area including forest area and available area without forest area.

The next constraint concerns the cell level. The available area for wind development is multiplied by the technical limit factor (an installed power capacity per square kilometre), which equals to the average power density per wind farm. The available power potential must be higher than already installed wind capacities excluding decommissioned wind power capacity. The regional power density factors are much lower than the technical limit factor. Accordingly, the sum of the power potential in cells cannot exceed the power potential available in the administrative unit to which the cells belongs. When the available annual potential at the regional level is taken, the same procedure is repeated for next "optimal cells" in another administrative unit until the globally set annual power capacity trajectory is reached. However, if the annual capacity trajectory exceeds the available power potential, then only the "allowed" wind power capacity (derived from the regional density factor) is installed. The iteration over all cells in a given

Fig. 5. Restricted area in constraint group 2 with 2 km buffer distance.

Table 6
National average and regional power density factors (MW/km^2) and technical limit factors (MW/km^2).

Regulatory scenarios		Regional power density factors						Poland
		Central	South	North-West	North	South-West	East	Technical limit factors applied at cell level
Scenario 1 (1 km)	**National Low**	0.5	0.5	0.5	0.5	0.5	0.5	6
	National High	0.5	0.5	0.5	0.5	0.5	0.5	15
	Regional Low	0.1	0.4	1.1	0.5	1.3	0.3	6
	Regional High	0.1	0.4	1.1	0.5	1.3	0.3	15
Scenario 2 (1.6 km)	National Low	0.78	0.78	0.78	0.78	0.78	0.78	6
	National High	0.78	0.78	0.78	0.78	0.78	0.78	15
	Regional Low	0.2	1.9	2.2	0.9	6	0.5	6
	Regional High	0.2	1.9	2.2	0.9	6	0.5	15
Scenario 3 (2 km)	**National Low**	1.3	1.3	1.3	1.3	1.3	1.3	6
	National High	1.3	1.3	1.3	1.3	1.3	1.3	15
	Regional Low	0.3	5.9	3.6	2.1	6	1.2	6
	Regional High	0.3	5.8	3.6	2.1	15	1.2	15

year identifies the available and optimal least-cost cells that fulfil the three above-mentioned conditions with the lowest LCOE.

The entire process (a-e) is repeated year after year between 2018 and 2030. The information on optimal turbines, installed wind power, energy production, and LCOE per cell is written back to the SQLiteDB. The model results in location-specific figures on installed, decommissioned and repowered capacity, average yearly load factors, LCOE, CAPEX, and OPEX. In addition, some indicators related to the installed

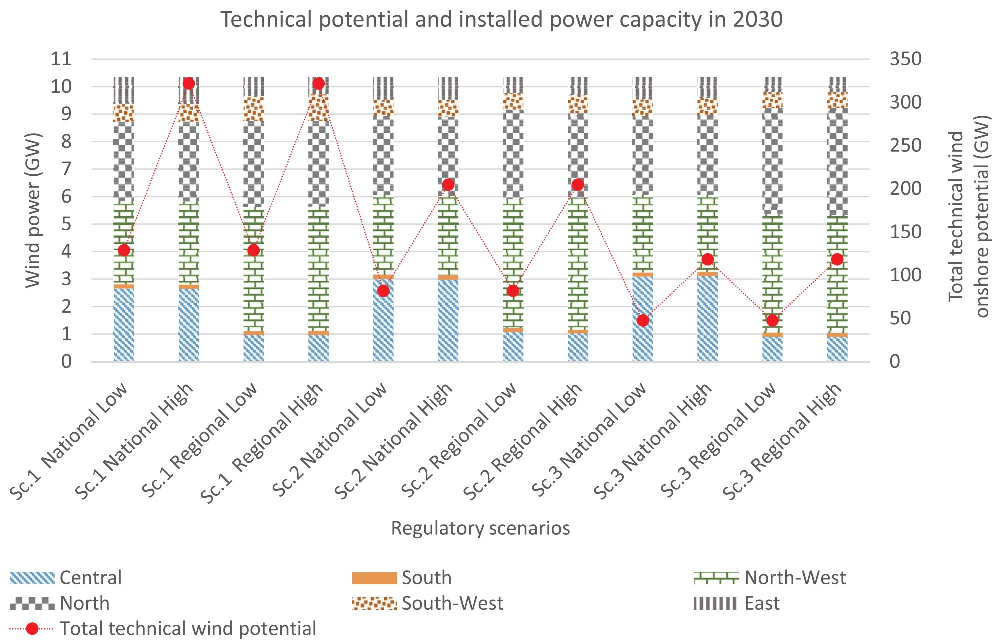

Fig. 6. Total technical potential and distribution of installed power capacity in 2030 according to power density factors.

capacity in a given year are calculated, including total annual system cost, system LCOE, and annuities. For instance, system LCOE are calculated as the volume-weighted average LCOE of the whole wind power capacity in Poland's energy system operated in a given year, including all historical turbines as well as new turbines.

The entire process in the second step (a-e) is implemented in Python 3.5. The final set of Python modules was converted to a standalone executable tool using PyInstaller in order to make it easy to launch the analysis on a computer with a standard installation of Microsoft Windows©.

4. Results and discussion

The following section presents and discusses findings elaborated for the EU reference scenario 2016 on onshore wind capacity extension in Poland until 2030. The technical and economic power potential is explored for three regulatory scenarios with distance buffer zones of 1 km, 1.6 km and 2 km around residential settlements and protected areas.

4.1. Available and restricted area for onshore wind development in Poland

The available area according to constraint group 2 (see Table A.1) resulting from the analysis amounts to 21.5 × 10^3 km,^{2} 13.7 × 10^3 km^2 and 7.9 × 10^3 km^2 respectively for distance buffers of 1 km, 1.6 km and 2 km. This represents 6.9%, 4.4% and 2.5% of the total land area of Poland. The available area is shown for three scenarios in Table 5 and Figs. 3–5.

Hajto et al. [33] analysed the impact of a distance buffer of 1 km and 2 km around residential settlements on the area available for onshore wind development and they reported an available area equal to 6% and 1% of Poland's total land area. The minor variation to the results can be explained by differences in constraints, buffer zones around other restricted areas and the input data applied in this and their study.

Wind turbines in forests are a controversially debated subject in Poland and are not widely accepted [33]. For this reason, wind turbine construction in forests is not allowed in the scenarios presented in this study (conform to available area of group 2).

4.2. Regional power density factors and derived onshore wind potentials

In the next step, the region-specific power densities required to install the onshore wind power capacity foreseen in 2030 by the EU reference scenario 2016 for Poland (i.e. 10.3 GW) were determined. The impact of these region-specific power density factors on the geographical distribution, choice of technology, and thus on the LCOE was analysed. To do so, first, the existing wind turbine penetration was estimated by dividing the currently installed power capacity by the available area, in order to gain an insight into current regional power densities. Second, the information about historical turbines was used to infer three sub-scenarios for the future power density. These can be distinguished between region-specific factors according to historical regional distribution, and a national average power density factor.

To almost double the currently installed wind power capacity and reach 10.3 GW by 2030 (see Table 3), the existing national average and regional power density factors were approximately doubled, and applied as regional density factors. The national average power density factor is 0.5 MW/km^2, 0.78 MW/km^2 and 1.38 MW/km^2 depending on the regulatory scenario. Regional density factors range between 0.1 MW/km^2 in Central Poland and 15 MW/km^2 in southwestern Poland (see Table 6). The sub-scenarios “high” and “low” are related to the technical power density limits 6 MW/km^2 or 15 MW/km^2 applied at cell level in order to cover the set of reference turbines.

In regulatory scenarios 2 and 3 for the southwestern region, power density factors were applied that equal the technical limit factors due to the high existing power density. The surplus of power capacity that cannot be installed in this region (due to the upper threshold set by the technical limit parameter) is distributed proportionally over the other five regions to correct this issue.

The technical limit parameter has an impact on the deployment of wind turbines within cells and makes up the upper threshold of wind power density. This means that a parameter of 15 MW/km^2 allows for installation of more capacity in “best available areas within the cell”. Contrarily, the national power density is relevant at regional level, as it determines the maximum capacity installed in the available area within one region. The assumed total technical wind potential and the wind

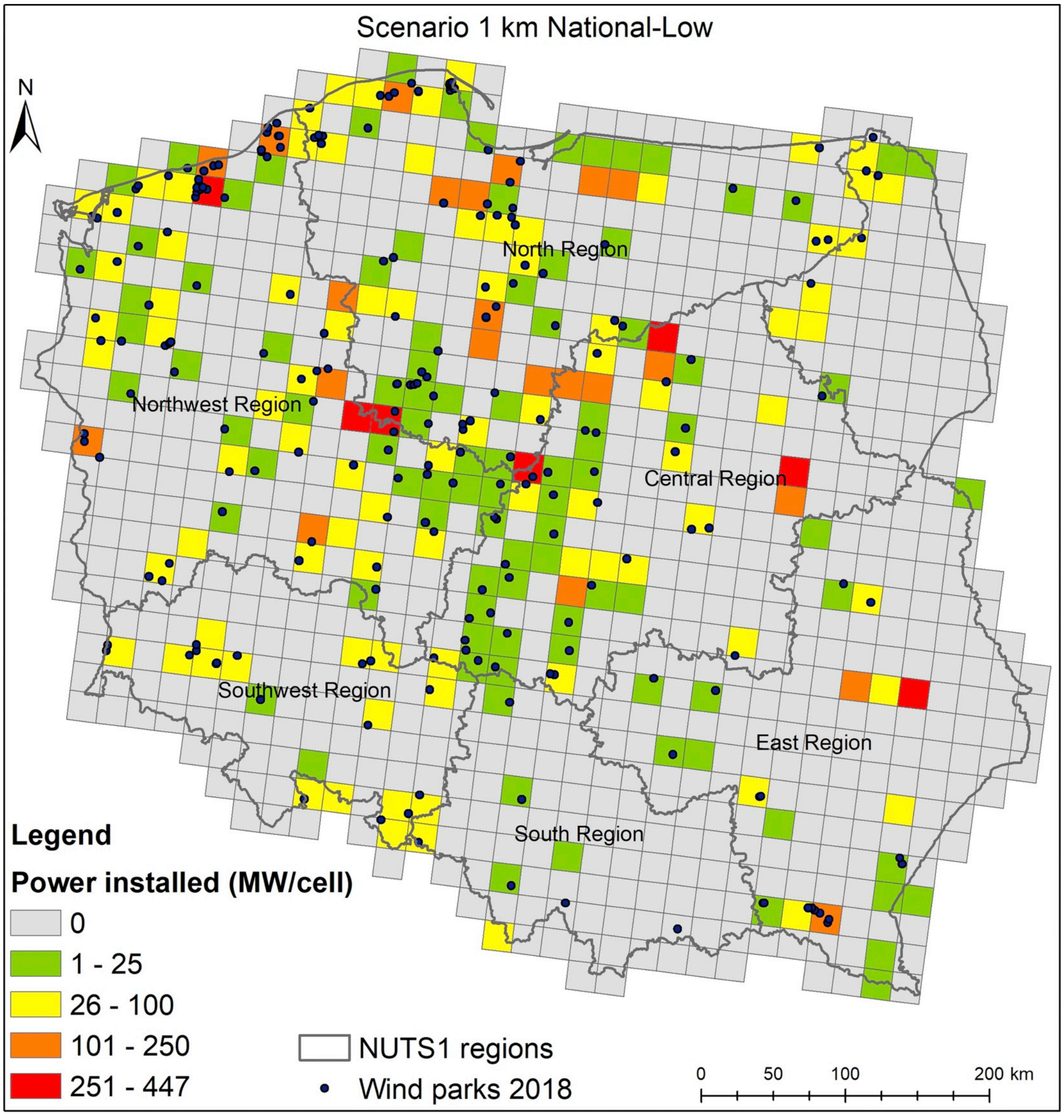

Fig. 7. Wind power capacity installed in 2030 in regulatory scenario 1 km National-Low.

potential limited by the regional density factors are presented in Fig. 6. The technical wind potential is derived from the total available area per regulatory scenario, multiplied with the technical limit factors (high and low sub-scenarios). It represents the theoretical power potential that might be reached without considering additional restrictive parameters such as cost or quantifiable aspects of social acceptance.

The maximum technical wind onshore potential in Poland ranges between 47.8 GW and 321.8 GW, depending on the regulatory scenario and the technical limit factor sub-scenario. We further restrict the technical wind potential by the above described national and regional power densities to exactly match 10.3 GW, which allows for reaching the goals of the EU reference scenario 2016 in 2030. Applying higher regional power densities than those outlined in Table 6 would also increase the wind onshore potential implied by these factors. This way, the study makes a first attempt to gain insight into one quantified parameter for the so-called distributive justice, here expressed by regional power density, and in this sense the authors chose to identify the parameters needed for fulfilling the EU reference scenario 2016 in 2030.

Fig. 6 and the following four maps (Figs. 7–10) illustrate the impact of the power densities (regional vs. national) and the minimum distance buffer around residential settlements and protected areas (exemplarily shown for regulatory scenarios Sc. 1 and Sc. 3) on the distribution of wind power capacity over the 20 km × 20 km raster cells and Polish regions. The total power capacity in 2030 consists of 5.66 GW installed before 2018 and still operational, and 4.68 GW installed between 2018 and 2030, according to the cost-optimal distribution of the model. It can be seen that a national power density factor leads to a more equal distribution of new turbines across Poland. Contrarily, regional power density factors (proportionate evolution according to historical distribution) lead to more turbines built in Central (factor 2.8) and Eastern Poland (factor 1.5). A variation of the minimum buffer distance from 1 km to 2 km in Sc. 3 leads to a proportionate increase of installed capacity in Central Poland with a national power density, and in Northern Poland with regional power density factors. In these scenarios fewer turbines are installed in the southwestern region, as its potential is considerably reduced by strict distance regulation. The regional power density factor only affects the total potential per region, but not the relative distribution for the trajectories.

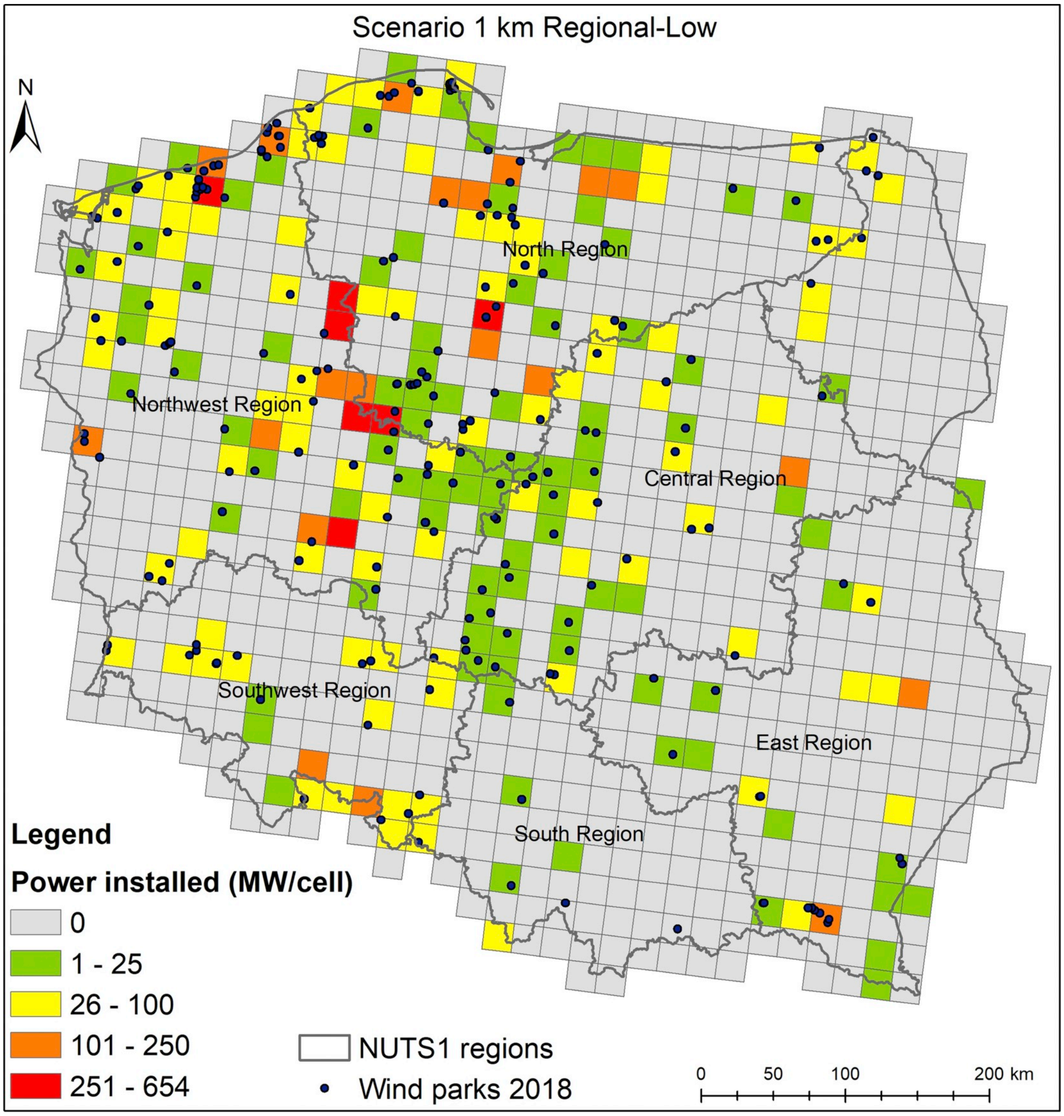

Fig. 8. Wind power capacity installed in 2030 in regulatory scenario 1 km Regional-Low.

4.3. The cost of onshore wind expansion in Poland

Fig. 11 illustrates cost-potential curves for different scenario combinations and their respective power density applied to the entire available area without taking into account historically installed capacity. These curves, therefore, represent a situation in which Poland would start from scratch and commission all wind turbines "overnight" in 2030 in order to reach the 10.3 GW target. The analysis shows that the largest part of the target could be reached at costs below €70/MWh, regardless of the scenario combination and the resulting distribution of the turbines.

In Fig. 12, the analysis was extended by taking into account historically installed wind turbines. Depending on the regulatory scenario, between 89%–97% of these turbines are located in areas excluded by the distance regulation retroactively put in place in 2016 (Sc. 2, Sc.3). Thus, the authors assume that historically installed turbines are placed in available areas surrounding those restricted areas for the purpose of the capacity trajectory between 2018 and 2030. This increases existing power density and decreases residual potential in these areas. Being built at higher CAPEX (see Table B.1), the largest part of the 5.66 GW power capacity built between 1990 and 2017 is considerably more expensive, as can be seen in the sharp increase of the cost-potential curve for the EU reference scenario 2030 trajectory. The new power capacity built between 2018 and 2030 (4.68 GW) can be realized at lower cost between €45/MWh and €60/MWh.

Adjusting the WACC from 5.5% to 8% results in a LCOE increase by 9% to a range from €50/MWh to €68/MWh for new turbines installed between 2018 and 2030. In addition to the WACC a reduction of the technical lifetime to 20 years would increase LCOEs by an additional 4% corresponding to the range of €52/MWh to €73/MWh. The generation costs reported in this paper are still well below the maximum auction reference price of €83/MWh for new and existing onshore wind power plants that is applicable to the call for tender events in autumn 2018 in Poland.

The spatial allocation of new turbines has an impact on the system-level electricity generation cost, which is an indicator for the average cost per kWh generated from wind energy in Poland in a given year. Fig. 13 shows an overview of the system LCOE for the total wind power

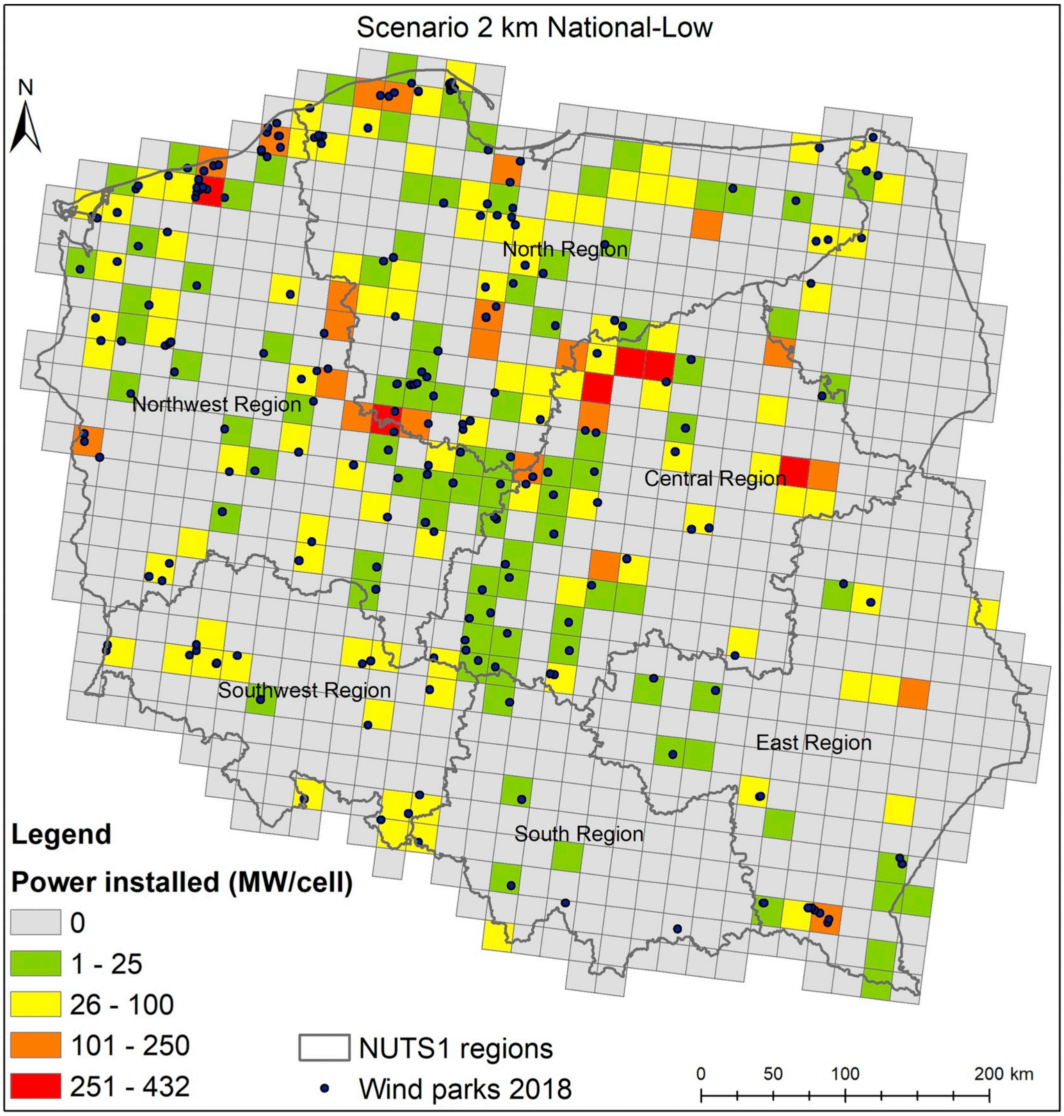

Fig. 9. Wind power capacity installed in 2030 in regulatory scenario 2 km National-Low.

capacity installed according to the EU reference scenario in 2030, differentiated by scenario.

The comparison shows that regional power density factors decrease the unit cost of electricity generation, because they allow a greater benefit of wind resources in northwestern and southwestern Poland, which are already being traditionally harvested. A national approach to power density leads to the situation that unitary generation costs increase by an order of €0.59/MWh in Sc. 2 and €2.7/MWh in Sc. 1. In addition, the results show that the impact of the new distance regulation introduced in 2016 particularly comes into play if regional power density is differentiated regionally and technical density is high. In this case, there is a markup of €1.9/MWh to be paid.

4.4. Limitations and outlook

The approach and findings are subject to several limitations and uncertainties, which could be relativized by the use of other methods or data sets.

A main uncertainty is related to the 20 km × 20 km resolution of the wind data, which leads to “mean effects”, i.e. excellent local wind conditions might be averaged-out. In order to improve the accuracy of the study, wind data with a resolution of 1 km^2 can be applied.

The data on historical wind farms contains two main drawbacks: some information on the installed wind power is missing (representing of 3–7% of total installed capacity as compared to official statistics), and wind farm locations are only described by a single georeferenced point. This uncertainty related to completeness, positional, temporal and thematic accuracy of OSM data has an effect on the final output representing the potentially available area for wind power development.

The study considers static distance regulation scenarios, applying today's regulation on wind turbines to be built in the future. The past has shown that regulation is subject to change, which led to the fact that wind turbines were formerly built in areas that are today excluded by regulation.

The quantitative aspects of social acceptance, namely the regional power density, distance regulation, and costs of wind energy are sensitive parameters that affect the eventual allocation of wind turbines

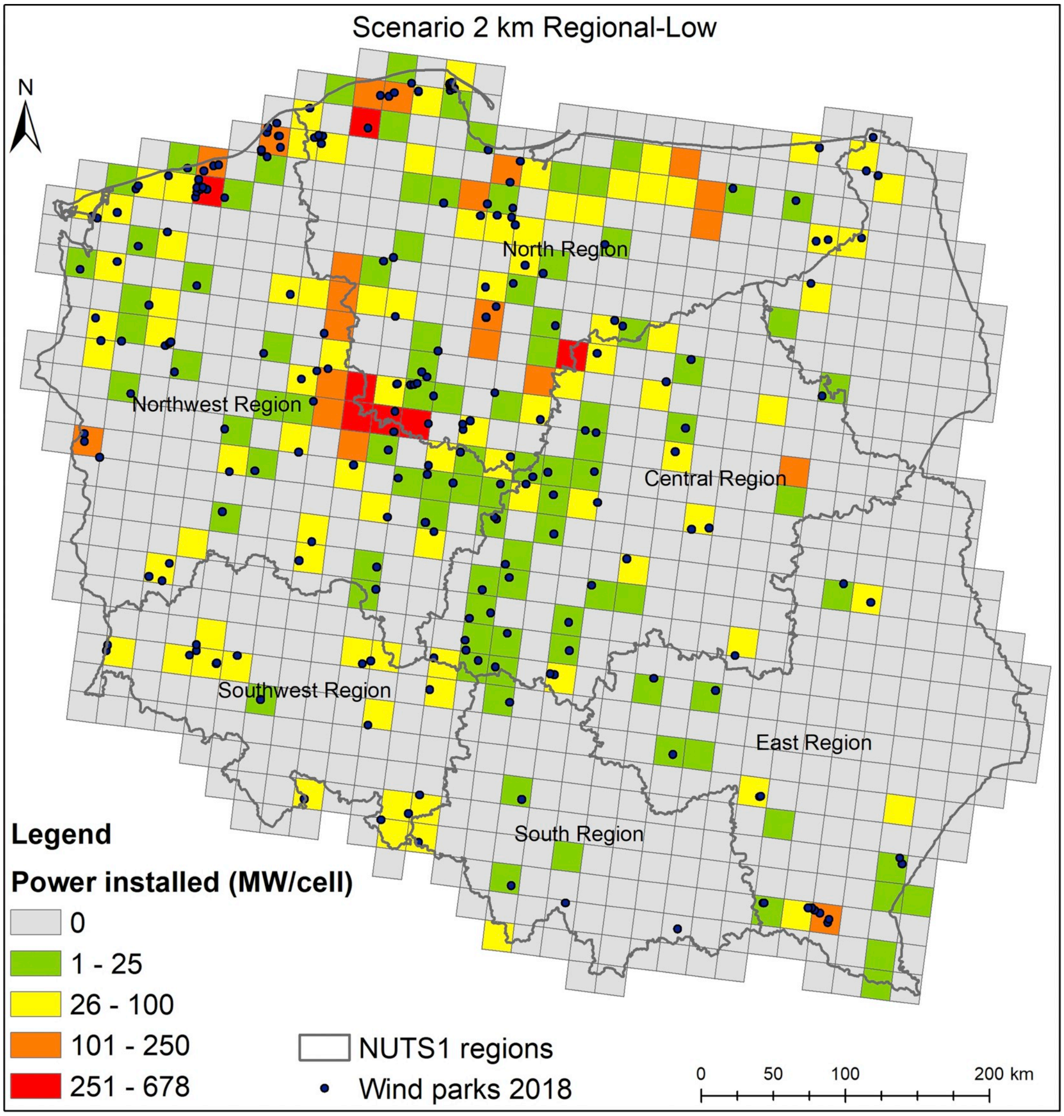

Fig. 10. Wind power capacity installed in 2030 in regulatory scenario 2 km Regional-Low.

across regions. The average regional power density factors are a first attempt for quantifying the potential and hypothetical opposition against wind turbines. The authors see a main point of interest in further research on empirical evidence on regional acceptance of wind distribution, which strongly impacts availability of sites for onshore wind development. A cross-country comparison with focus on distance regulation and regional power densities would shed light on the achievability of national and European objectives and could allow for the identification of levers to reduce costs of onshore wind deployment.

Finally, the scope of the cost assessment of wind onshore scenarios is limited to direct costs for the power plants and does not take into consideration further RES integration cost, such as profile cost, balancing cost, and grid-related cost [66]. The reason is that these costs depend on the composition of the power system, including transmission and distribution network capacity, mix of technologies, or European market integration and market design, all of which are indeed dynamic over time. An in-depth analysis of these costs from 1990 to 2030 was out of scope for this study.

5. Conclusions

The methodological approach and findings address the wind power expansion scenarios under different technical, economic, environmental and quantitative aspects of social acceptance, namely the regional distribution of wind power, the distance regulation and the costs of wind energy.

The research extends the approaches and findings of previous studies. The method allows to analyse the spatial distribution of past and future onshore wind power plants under dynamic techno-economic and regulatory aspects. In addition, the study implemented a tailored limitation to the entire technical and economic wind energy potential in Poland that attempts to reflect the distribution of wind power allocation across regions. The study considers the evolution and decommissioning of the historically installed wind farms, and the limits of technical and regional power densities by studying different scenario combinations. The spatial assessment of the technical wind onshore potential is in line with previous studies on Poland. The findings demonstrate that the impact of the distance regulation considerably reduces the technical

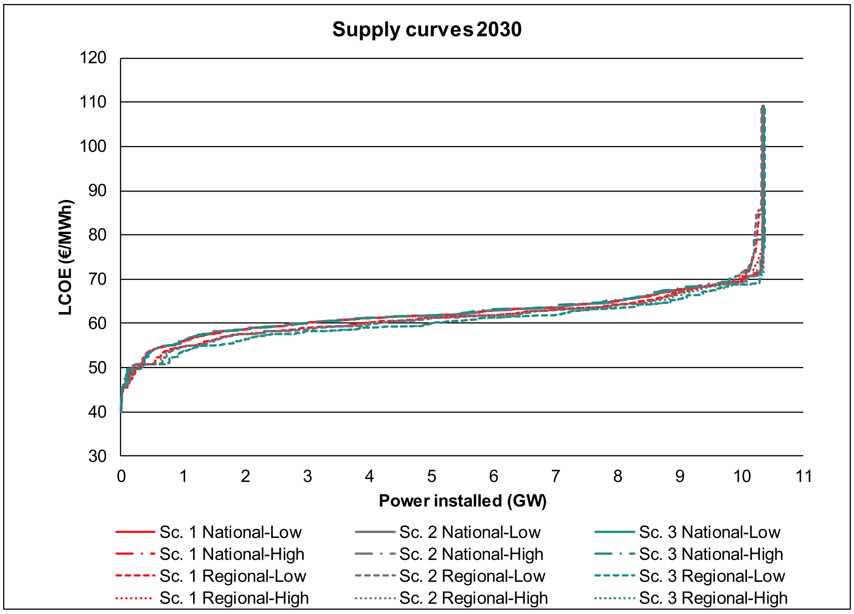

Fig. 11. Cost-potential-curves for set of scenarios analysed implying a development from scratch in 2030.

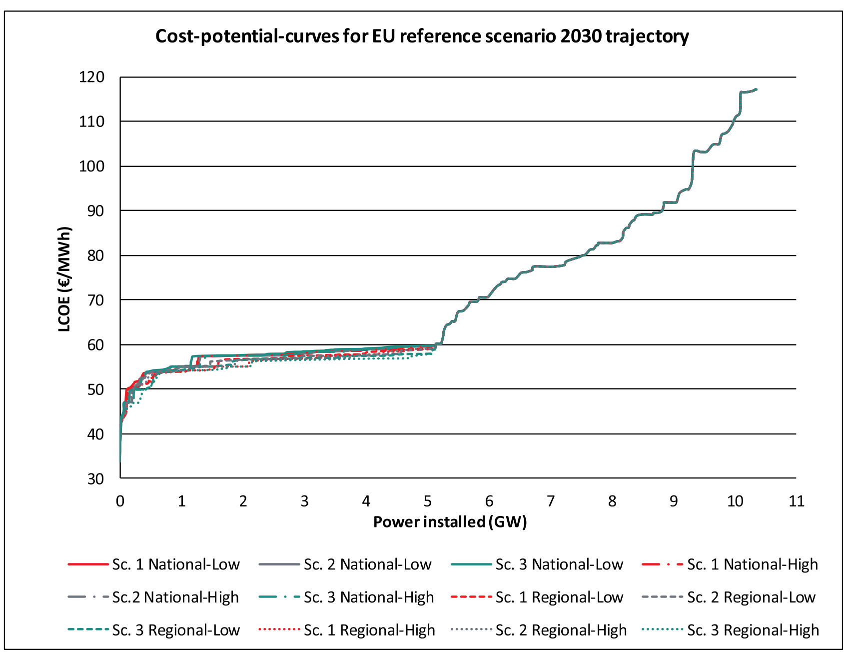

Fig. 12. Cost-potential-curves of wind power capacity installed from 1990 to 2030 for set of scenarios analysed.

wind onshore potential on Poland's land area by up to 63%, compared to a buffer distance of 1 km. The resulting technical potential is reduced to between 47 GW and 82 GW, depending on the turbine technology chosen. The technical potential exceeds the 10.3 GW target figure for 2030 by a factor of 4, at least. This shows that there is still potential for a more ambitious development of wind onshore capacity, by increasing regional power densities. The cost of such a progressive scenario was not in the scope of the study, though.

A main consequence of the regulatory change is that under the hypothesis of a cost-optimal siting of wind turbines, Central and Northern Poland, both characterized by a high existing wind power density, will also disproportionally be held liable in the future on the basis of the 2030 target capacity of EU reference scenario 2016, while this will not be the case in northwestern Poland. The amplitude of this distributional effect differs depending on whether the power density factor is applied at national or regional level. The analysis shows that new turbines can be installed at a cost of €45–50/MWh in the following years, if the best locations are selected. Overall, the 10.3 GW target for 2030 can be reached at LCOE below €60/MWh. The spatial distribution of future turbines impacts the average unitary generation cost of wind power operations for Poland. Depending on the scenario, this cost ranges between €68.77/MWh and €71.50/MWh in 2030, including operational existing turbines and new turbines built between 2018 and 2030. Depending on the competition level in the call for tender schemes and the resulting subsidy levels granted, profitable business cases seem possible on the Polish wind market, even if comparably higher WACC rates are applied to compensate for project-related risks.

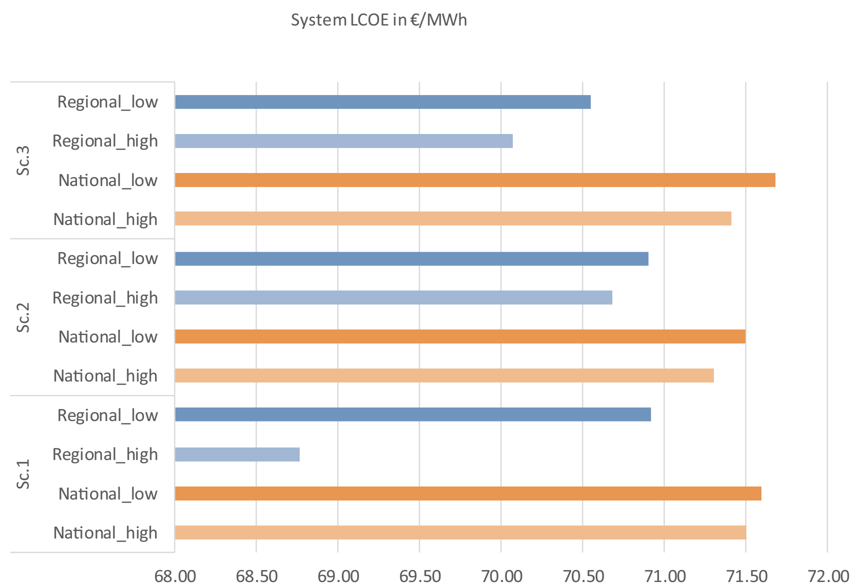

Fig. 13. Total cost of wind power operations in 2030 according to scenario, expressed as System LCOE.

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Appendix A

Table A.1
Constraints with buffer zones for the distance scenarios applied in Poland.

Constraints	Scenario 1 (buffer in m)	Scenario 2 (buffer in m)	Scenario 3 (buffer in m)
Buildings urban	1000	1600	2000
Buildings residential	1000	1600	2000
Buildings commercial	250	250	250
Power lines	200	200	200
Motorways	160	160	160
Roads	160	160	160
Waterways	250	250	250
Railways	160	160	160
Airports	3000	3000	3000
Aero ways	2500	2500	2500
Aerial ways	300	300	300
Radars	5000	5000	5000
Above 2000 m	0	0	0
Military	2000	2000	2000
Wetlands	100	100	100
Forest	100	100	100
Protected areas	1000	1600	2000

Appendix B

Table B.1
Average value of Capex and Opex for historically installed turbines in Poland.

Year	CAPEX (EUR/kW)	OPEX (€/kW/a)
1990	2500	60
1991	2583	60
1992	2333	60

(*continued on next page*)

Table B.1 (*continued*)

Year	CAPEX (EUR/kW)	OPEX (€/kW/a)
1993	2250	60
1994	2125	60
1995	2000	60
1996	1917	60
1997	1967	60
1998	1933	60
1999	1742	60
2000	1717	60
2001	1783	60
2002	1833	60
2003	1917	60
2004	2000	60
2005	2050	60
2006	2100	60
2007	2167	60
2008	2000	60
2009	2183	60
2010	1833	60
2011	1550	60
2012	1625	60
2013	1483	60
2014	1492	60
2015	1467	60
2016	1440	55
2017	1350	55

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