TECHNICAL REPORT

STUDY ON THE WIND POWER POTENTIAL IN BULGARIA, HUNGARY, AND ROMANIA

Client:

A study conducted on behalf of the European Climate Foundation.

AIT Austrian Institute of Technology GmbH

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Study on the wind power potential in Bulgaria, Hungary, and Romania – Technical Background Report

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This study on the wind power potential in Bulgaria, Hungary, and Romania has been conducted, on behalf of the European Climate Foundation (ECF), by AIT Austrian Institute of Technology GmbH, Center for Energy, Competence Unit Integrated Energy Systems (IES) in close collaboration with REKK – Regional Centre for Energy Policy Analysis as well as with local partners from the study region, including EFdeN – Sustainable and Green Homes from Romania and the Center for the Study of Democracy (CSD) from Bulgaria. The study team gratefully acknowledges the support provided by ECF, specifically by Sorin Cebotari, acting as responsible officer at ECF.

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CONTENT

1 INTRODUCTION

1.1 Policy context

Our planet's climate emergency and Russia's war continuing to wage on Ukraine are making it clear that we need to effectively decarbonize the ways we produce and consume energy. The energy sector, including the electricity sector, transport, industry, and heating & cooling, is responsible for around 75% of the EU's Greenhouse Gas (GHG) emissions. This is why EU leaders have agreed on making the continent climate-neutral by mid-century, by substantially reducing the dependency on fossil fuels, with most of it being imported from outside Europe. Today the need to decarbonize is aggravated by severe shortages in energy supply, as well as skyrocketing inflation and energy price levels, threatening the performance of our economies. In parallel, the cost-of-living crisis is substantially reducing purchasing power among EU citizens and exposing especially vulnerable groups to poverty risks.

In this context of a multiple global crisis, the EU is in the process to agree on more ambitious climate and energy target levels, which are being revised and negotiated under the Green Deal and more recently, the REPowerEU initiative. To reduce GHG emission by 55% until 2030, Europe must significantly accelerate the transition to systems that are powered and fuelled by renewable electricity and gases, with EU institutions decide on new targets to increase the share of renewable energy and energy efficiency until 2030. This requires strong commitment among EU and national decision-makers, who are tasked to implement drastic, no-regret, measures and make the profound and systemic transformation of our economies become reality.

Within Europe as well as globally wind and solar energy are acknowledged as the key renewable energy sources for supplying our future demand for energy, done with proven and cost-effective conversion technologies that serve for the provision of electricity. Whilst solar power at small- as well as at utility-scale has increased steadily and widespread across Europe, the picture of wind power development is more diverse and inhomogeneous geographically. In overall terms, at EU level significant progress and a steady growth has been maintained but strong differences are applicable among countries and regions. Specifically in the south-eastern part of Europe – namely in Bulgaria, Hungary and Romania – actual developments have been lacking far behind earlier expectations. This was mainly driven by hurdles and changes in legislation, or a lack of political emphasis. Moreover, up to our knowledge, there is from a scientific viewpoint still a lack of detailed analysis concerning the potential that is applicable for wind power development in that part of Europe.

1.2 Goal of this study

This study aims to shed light on the applicable potentials for wind power development in Bulgaria, Hungary and Romania, indicating and informing decision makers and stakeholders how wind power may contribute to meet the future demand for electricity in a carbon-neutral manner.

For that purpose, a thorough technical analysis of the future potential for wind power at the countryside (onshore) as well as, where available, in marine areas (offshore) is conducted for the whole study region. More precisely, a detailed GIS-based analysis of the potential for wind power development is undertaken, building on a comprehensive meteorological dataset (i.e., time-series of wind speeds for past weather years) at a high geographical resolution and incorporating spatial constraints related to competing land use (i.e., nature protection, urban, agriculture, forestry, military use or other purposes that limit the suitability for wind power and related grid development). Additionally, sensitivity analyses are done for key input parameter (incl. distance rules, turbine design and preferences in land use) based on a pre-identification of the relevance of above listed factors to shape the analysis to the country specific needs. A mapping exercise is then conducted to indicate how identified promising areas for wind power development match with the transmission grid infrastructure. Complementary to the above, a model-based assessment of the impacts of an enhanced wind uptake in future years on the underlying electricity market is conducted as final analytical step.

The outcome of this assessment are detailed maps showing available areas for wind power development as well as corresponding site qualities, and a comprehensive dataset that lists the identified wind power potential at regional level within a country (i.e., by NUTS-3 region). Brief country reports inform on the results derived and the underlying approach taken, suitable for the targeted audience. A more comprehensive background report will inform interested actors on further technical details concerning methodology and results.

This technical report is dedicated to informing on **the approach and the results derived for Bulgaria, Hungary, and Romania**, describing the **identified wind power potentials** and the **electricity market impacts of an enhanced wind uptake** in future years.

1.3 Structure of this report

This report is structured as follows: After the introduction provided in Chapter 1, subsequently in Chapter 2 the method of approach is described. Chapter 3 to Chapter 5 is then dedicated to present the outcomes of the GIS-based analysis of wind power potentials in Bulgaria, Hungary, and Romania, focussing on onshore wind with respect to underlying detail. Complementary to the above, Chapter 6 sheds light on the results on offshore wind potentials within our study region. Next, Chapter 7 shows the market impacts of an enhanced wind uptake in future years. The report closes with a list of conclusions and recommendations on the way forward.

2 METHOD OF APPROACH

The work required for meeting the study objectives can be clustered into three tasks that generally follow a consecutive order, with some interactions in between, including:

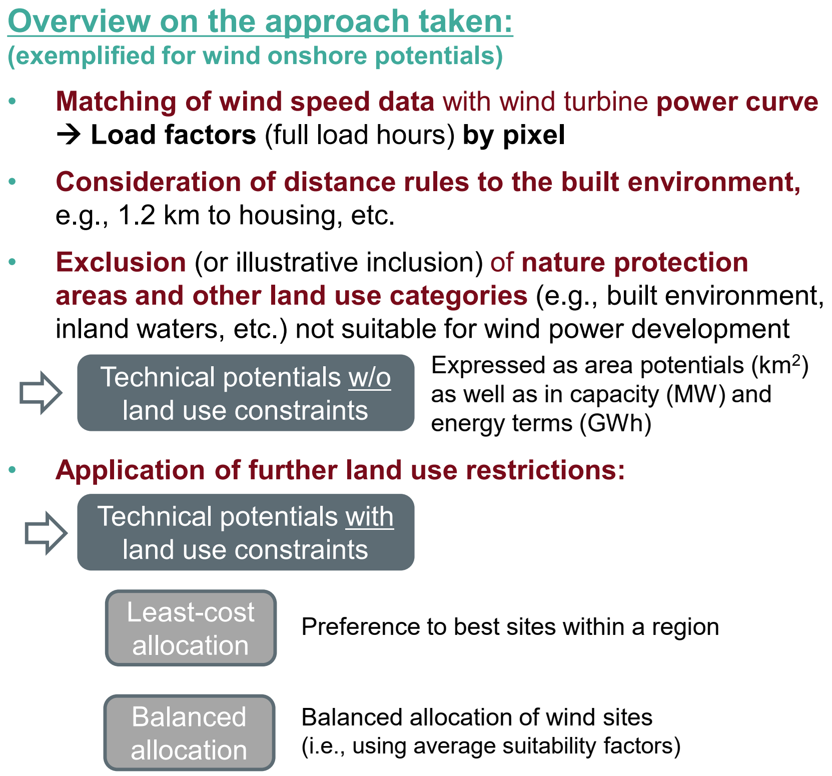
- Task 1: GIS-based analysis of the wind power potentials
- Task 2: Complementary assessment of electricity market impacts of an enhanced wind deployment
- Task 3: Stakeholder consultation and dissemination activities

Below we describe the approach and key assumptions for task 1 and 2 in further detail.

2.1 Task 1: GIS-based analysis of the wind power potential

2.1.1 Brief overview on the approach taken

As central element of this study, a thorough technical analysis of the future potential for wind power at the countryside (onshore) as well as, where available, in marine areas (offshore) is undertaken for the whole study region.



Overview on the approach taken:
(exemplified for wind onshore potentials)

- **Matching of wind speed data** with wind turbine **power curve**
  → **Load factors** (full load hours) **by pixel**
- **Consideration of distance rules to the built environment,**
  e.g., 1.2 km to housing, etc.
- **Exclusion** (or illustrative inclusion) of **nature protection areas and other land use categories** (e.g., built environment, inland waters, etc.) not suitable for wind power development

⇨ Technical potentials w/o land use constraints — Expressed as area potentials (km²) as well as in capacity (MW) and energy terms (GWh)

- **Application of further land use restrictions:**

⇨ Technical potentials with land use constraints

Least-cost allocation — Preference to best sites within a region

Balanced allocation — Balanced allocation of wind sites (i.e., using average suitability factors)

Figure 1: Overview on the approach taken for the assessment of wind potentials in the study region (exemplified for onshore wind)

As illustrated by Figure 1, we conduct a GIS-based analysis of the potential for wind power development that includes the following steps:

- A comprehensive meteorological dataset on time-series of wind speeds is processed under a detailed geographical resolution for past weather years, serving as a basis for identifying unconstrained resource potentials across the whole study region, including adjacent marine areas. The underlying weather reanalysis open-source dataset is COSMO-REA6. It provides pre-calculated hourly wind speeds at 100 m and 150 m height and at a geographical resolution of 6 km times 6 km. For our analysis, wind speed data for the years 1995 to 2018 is taken into consideration.

- As the next step within the GIS-based assessment, spatial constraints are incorporated that stem from competing land use, such as nature protection (e.g., by excluding Natura 2000 protected areas), urban, agriculture, military use or other purposes that limit the suitability for wind power production and related grid deployment. Offshore wind is according to past experiences less relevant for the Black Sea region but recently gaining key policy attention at the European as well as the national level. Specifically, for offshore wind, competing uses of the sea (e.g., main shipping routes, nature protection areas and specifically tourism) are taken into consideration (i.e., by excluding related areas from the applicable resource base as a simplification).
- Sensitivity analyses are performed for key parameter affecting the applicable wind power potential, including the impact of excluding vs including nature protection areas and, specifically for offshore wind power, details on the applied wind turbine design (i.e., rotor area in relation to generator size). These aspects appear of relevance as identified in stakeholder consultations undertaken in prior. We also illustrate the impact of further land use restrictions on those areas classified as being feasible for wind power development. That aims to increase social acceptance of wind power and may allow for a more rapid uptake in future years – once other barriers are removed. In this context, two different variants are assessed:
    - Balanced allocation: Balanced allocation of wind sites by using average suitability factors as listed in Table 1 below.
    - Least-cost allocation: Preference to best sites within a region, implying higher suitability factors as shown in Table 1 and, in turn, lower ones for less windy areas within a country.

Table 1: Average suitability factors applied for the identification of wind power potentials with (consideration of further) land use restrictions

Land use category	Average suitability factor
Built environment, Inland waters, wetlands	0%
Agricultural areas	40%
Forestry areas	10%

- Specifically for Hungary other aspects are also included in the sensitivity analyses: For onshore wind the impact of distance rules (to the built environment) and details on the applied wind turbine design (i.e., hub height and/or rotor area in relation to generator size) is analysed there. For Hungary these aspects, i.e., restrictive distance rules and restrictions on the size of wind turbines, are of key relevance since both are barriers for an (enhanced) uptake of wind power at present.
- A mapping exercise is finally conducted to indicate how identified promising areas for wind power development match with the transmission grid infrastructure.

The outcome of this assessment are detailed maps showing available areas for wind power development as well as corresponding site qualities (in terms of capacity factors / full load hours) in dependence of sensitivity parameter, and a comprehensive dataset that lists the identified wind power potential at regional level within a country (i.e., by NUTS-3 region), incl. information on wind site qualities. Complementary to the country reports prepared, a more comprehensive background report will inform interested actors on further technical details concerning methodology and results, cf. Resch et al. (2023).

2.1.2 Background information and technical details

For the interested reader we subsequently provide further details on the approach taken for estimating and reporting on wind potentials.

Software tools: For the GIS analysis a set of software tools are used, including CDO (Climate Data Observer, cf. Schulzweida et al. (2019)), Python and GDAL (Geospatial Data Abstraction Library, cf. Rouault E., 2022). Source code and input data are available at https://github.com/ait-energy/wind.power.potential-BG-HU-RO so that derived results are reproduceable or can be adapted in the case of alternative input data etc. Complementary to the above, QGIS, an open-source software tool, is used for map generation.

Details on approach and assumptions:

- As first step, to derive estimates on the electricity generation potential, **wind speed data** taken from COSMO-REA6, representing a global reanalysis of meteorological data combined with a large set of observations (cf. Bollmeyer et al., 2014) is **matched with a wind turbine power curve.** The result is an hourly time-series for all COSMO-REA6 pixels with theoretical load factors. The average load factor over all hours, ranging from 1995 to 2018, is calculated and serves as base for further calculations. The load factor is thereby expressed as full load hours, describing the virtual hours within a calendar year that a power plant operates at its rated power.[1] The following turbine characteristics are thereby applied:
    - As default our onshore wind turbine is the Nordex N163, characterised by a hub height of 150 m and a rotor diameter of 163 m. That turbine is equipped with a 4.95 MW electric generator.
    - For offshore the standard turbine is the VESTAS V164/8000, at hub height of 150m and a rotor diameter of 164 m, equipped with an 8 MW electric generator.
- Next, processed wind data is **matched with land use information** taken from the CORINE land use database (as of 2021). Land use data comes at a detailed geographical resolution (100 m x 100 m), requiring a retransformation of the wind data.
- Retransformed data is subsequently masked, and an **efficiency factor of 0.85** is applied to account for losses due to wind shading effects within a wind farm as well as maintenance, etc.
- **Exclusion of certain areas:** The process of masking comprises also the exclusion of areas not suitable for wind power development due to different constraints and aspects:

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[1] Full load hours are derived by multiplying the load factor with 8760, representing on average the number of hours within a calendar year. In reality, a wind power plant is generally during more hours in operation than indicated by the full load hours since during many hours the plant operates at partial load.

  - Techno-economic constraints: We exclude areas above an altitude of 2000 m and above a slope of 20° to account for possible technical challenges and/or high cost related to grid connection.

    Nature protection: As default, we also exclude nature protection areas from our identification of wind development potentials. Information on protected areas is thereby taken from the UN World Database of Protected Areas (WDPA), cf. IUCN and UNEP-WCMC (2020).[2] In our GIS modelling, all nature protection areas are buffered with 1200 m (to reflect a sufficient distance of possible wind power developments) and then excluded.

    Upon request by some stakeholder, for sensitivity purposes we also illustrate the impact of including nature protection areas in our classification of go-to areas for onshore wind power development. That dataset is clearly as “Including Nature Protection Areas”. Please note further that for onshore wind we generally excluded also inland waters and wetlands to account for nature protection as well as trade-offs with other purposes like shipping. For those areas a buffering with 600 m is applied, representing a further distance restriction for possible wind power development.
  - Social acceptance and avoidance of use conflicts: Built-up areas (incl. artificial surfaces like urban fabrics, industrial or commercial units, port areas, airports, construction sites, green urban areas, sport and leisure facilities) and infrastructure areas (incl. road and rail networks and associated land, mineral extraction sites, dump sites) are generally excluded. For the built-up areas a buffering of 1200 m is applied, respecting that wind power development should not harm the local community via noise or shading, etc.
  - Economic constraints: We exclude areas of low wind speeds to account for the economic viability of wind power development. That implies to exclude areas below 1,700 effective full load hours (i.e., considering the efficiency factor of 0.85 as discussed above) in the case of onshore wind, and below 2,000 effective full load hours for offshore wind.

  Please note that for the calculation of offshore wind potentials, the same principles apply concerning nature protection. There are no land cover restrictions considered but shipping routes in the Black Sea are excluded instead. Starting with raster data from global shipping traffic densities[3], the mostly used shipping routes are manually drawn as lines with 10 km width and then excluded.

- **Classification by area:** For the further processing in database format, the values of the usable (i.e., not excluded) pixels are aggregated by administrative boundaries. For onshore wind this implied a breakdown by NUTS region and a distinction between wind

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[2] According to the provided information on the respective website (https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA), the WDPA is the most comprehensive global database of marine and terrestrial protected areas. It is a joint project between UN Environment Programme and the International Union for Conservation of Nature (IUCN) and is managed by UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), in collaboration with governments, non-governmental organisations, academia and industry.

[3] Cf. https://datacatalog.worldbank.org/search/dataset/0037580

power site qualities (i.e., 12 categories of different wind site qualities, represented by ranges of full load hours, predefined for the whole study region) and by land use type (i.e., into 14 land use categories according to the level two classification of the CORINE land use database). For offshore wind the breakdown into 12 categories respects differences in water depth and distance to the shore.

2.2 Task 2: Complementary assessment of electricity market impacts of an enhanced wind deployment

Based on the wind potential assessment of the previous task, REKK, using the EPMM model, estimates the economic impacts of these developments under varying levels of wind capacities. This is a crucial aspect of this development, as wind generation was lagging in all analysed countries – i.e., mainly in Hungary and Bulgaria, but also in Romania wind development has stopped after 2014.

The modelling focusses on the following economic aspects:

- Impact on wind market value: in contrast to the PV developments, wind capacity expansion generally maintains the market values of wind generation, due to its less cyclical nature, which in a long term could give high advantages to wind-based generation.
- The modelling will also reveal the impacts on the reserve marked developments in these countries. Higher wind development can increase the demand for reserve capacity services, but they could also contribute to downward regulation, so the modelling can reveal how can wind contribute to this market segment.
- Impact on baseload prices, on import/export positions of the countries as well as on carbon emissions will also be reported and analysed.

Below we present the underlying modelling approach and related key assumptions in further detail whereas the outcomes of this assessment are shown in Chapter 7 of this report.

2.2.1 Modelling approach

The European Power Market Model (EPMM) is a unit commitment and economic dispatch model. Electricity consumption is satisfied simultaneously in all modelled countries at a minimum system cost, spinning reserve requirements, capacity constraints of the available power plants and cross-border transmission capacities. The cost elements considered in the model include start-up and minimum down-time of the power plants, production (mainly fuel and CO_2 costs) and curtailment. The model simultaneously optimises all 168 hours of a modelled week and determines the hours of operation and reserve levels. The model is executed for 12 representative weeks of the given year (each month is represented by one week). The EPMM endogenously models 41 electricity markets in 38 countries of the ENTSO-E network.

2.2.2 Scenario set-up

Three scenarios are modelled, which differ by the assumed uptake of wind in all analysed countries:

- low wind penetration
- moderate wind penetration
- high wind penetration

In all other aspects there are no differences between the scenarios. Below Figure 2 illustrates the assumed country-specific wind capacities for the three scenarios for the assessed years (2030, 2040 and 2050).

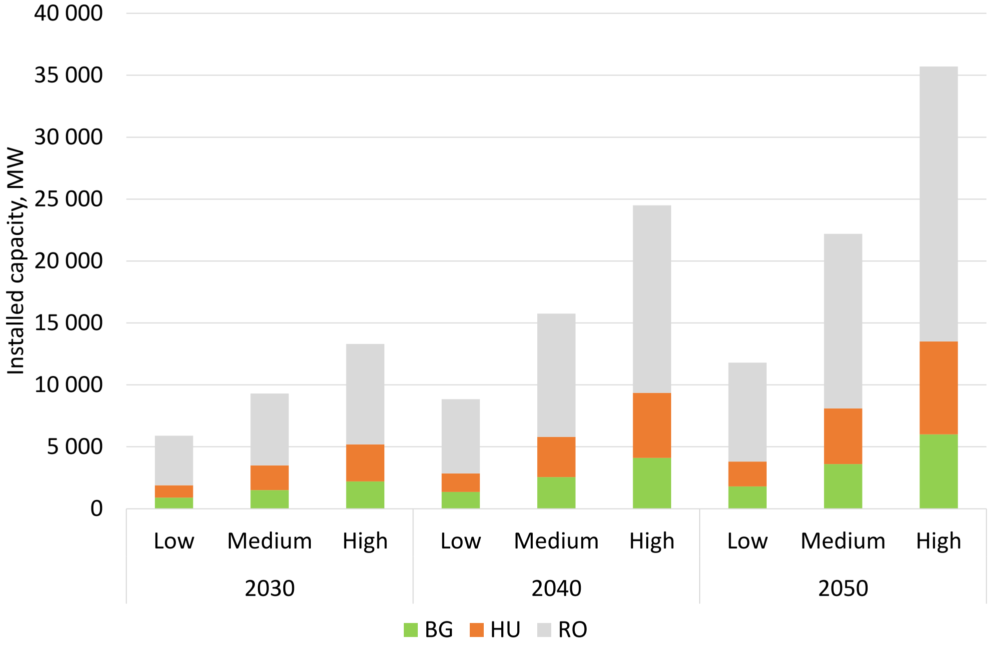

Figure 2: Wind installed capacities in the three analysed scenarios in the modelled years, MW

Assumptions taken in this respect for Bulgaria are as follows:

- The “low wind penetration” scenario implies an increase of wind deployment from at present (2021) 0.7 GW to 0.9 GW by 2030, increasing steadily further up to 1.8 GW by 2050.
- In contrast to the above, in the “high wind penetration” scenario a significantly stronger uptake of wind power is presumed, reaching 4 GW already by 2030. Wind is then expected to increase further up to 8.0 GW by 2050.
- The scenario of “moderate wind penetration” implies a moderate growth of wind power in future years, with assumed installed capacities lying in between the low and the high. For Bulgaria this results in an increase of wind deployment from at present (2021) 0.7 GW to 1.5 GW by 2030, increasing further up to 3.6 GW by 2050.

Assumptions taken in this respect for Hungary are as follows:

- The “low wind penetration” scenario implies an increase of wind deployment from at present (2021) 0.3 GW to 1.0 GW by 2030, increasing steadily further up to 2.0 GW by 2050.
- In contrast to the above, in the “high wind penetration” scenario a significantly stronger uptake of wind power is presumed, reaching 3.0 GW already by 2030. Wind is then expected to increase further up to 7.5 GW by 2050.
- The scenario of “moderate wind penetration” implies a moderate growth of wind power in future years, with assumed installed capacities lying in between the low and the high.

Assumptions taken in this respect for Romania are as follows:

- The “low wind penetration” scenario implies an increase of wind deployment from at present (2021) 3.0 GW to 4.0 GW by 2030, increasing steadily further up to 8.0 GW by 2050.

- In contrast to the above, in the “high wind penetration” scenario a significantly stronger uptake of wind power is presumed, reaching 8.1 GW already by 2030. Wind is then expected to increase further up to 22.2 GW by 2050.
- The scenario of “moderate wind penetration” implies a moderate growth of wind power in future years, with assumed installed capacities lying in between the low and the high. For Romania this results in an increase of wind deployment from at present (2021) 3.0 GW to 5.8 GW by 2030, increasing further up to 14.1 GW by 2050.

2.2.3 Main inputs and further assumptions

Fuel and CO_2 prices

The natural gas price forecast is based on the European Gas Market Model, as can be seen in Figure 3. REKK’s European Gas Market Model has been developed to simulate the operation of an international wholesale natural gas market in Europe, covering the EU28 and the EnC Contracting Parties. The demand and supply side of the gas market, pipeline, LNG and storage infrastructure are included at the country level. Major external markets, such as Russia, Norway, Libya, Algeria and LNG exporters are represented by exogenously assumed market prices. All long-term supply contracts and physical connections to Europe are included in the model.

According to the modelling results, the average wholesale gas price drops significantly to around 30 €/MWh in 2026 and remains around this level thereafter. After 2030, there are only minor differences in the gas prices between the assessed countries. The cheapest is in Romania, while the most expensive is in Hungary.

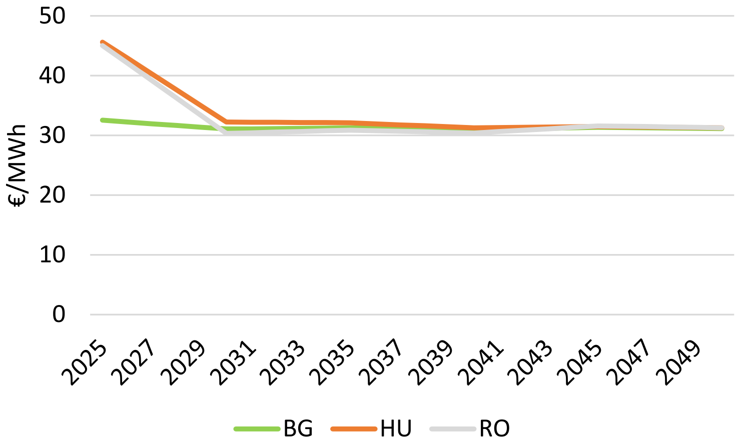

Figure 3: Wholesale Natural gas price assumptions. Source: EGMM modelling results

In the long term, we assume that the coal price will fall below 50 $/t (1.6 €/GJ), based on the latest IEA World Energy Outlook (2022). For the price of CO_2 under the European Emission Trading Scheme, we assume that the price will be the same in real terms staying at a level of 90 €/t.

Electricity demand trends

The yearly demand growth rate is based on the European Commission's FIT55 Mix (until 2030) and REF scenario (after 2030), modified by the starting values with the actual ones. Different trends are visible in the three countries, as depicted in Figure 4:

- Stagnating consumption in Bulgaria
- High growth rates in Hungary and Romania until 2030; after which consumption stagnates in Romania and continues to grow in Hungary.

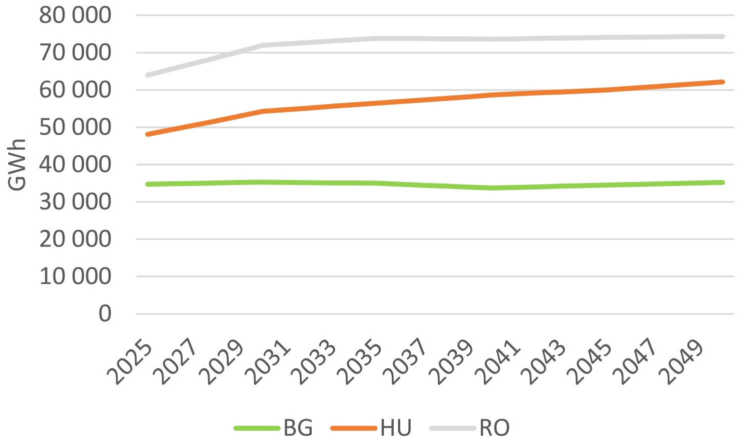

Figure 4: Yearly electricity consumption in GWh. Source: EC REF and MIX scenario; EMBER and Eurostat database

Future trends on the capacity mix

The future trends on installed capacities in the power sector is mostly taken from National Energy Strategies and other strategic documents, while the RES figures are based on the most up-to-date CESEC study (European Commission et al. (2022)). The mix of installed capacities is shown per country in Figure 5 to Figure 7.

The main trends in the countries assessed are as follows:

- Coal phase-out almost fully realized by 2030, and by 2040 no coal and lignite capacity exist in these countries.
- A small increase in natural gas between 2030 and 2040 – due to the new Romanian gas capacities -, but a sharp decline thereafter.
- Stagnation, and small decline in nuclear generation, mainly because we assume no new nuclear capacities in Hungary.
- Very high penetration of PV, reaching 16 GW in 2030, 43 GW in 2040, and more than 63 GW in 2050.
- Only minor new hydro and other RES capacities are assumed.

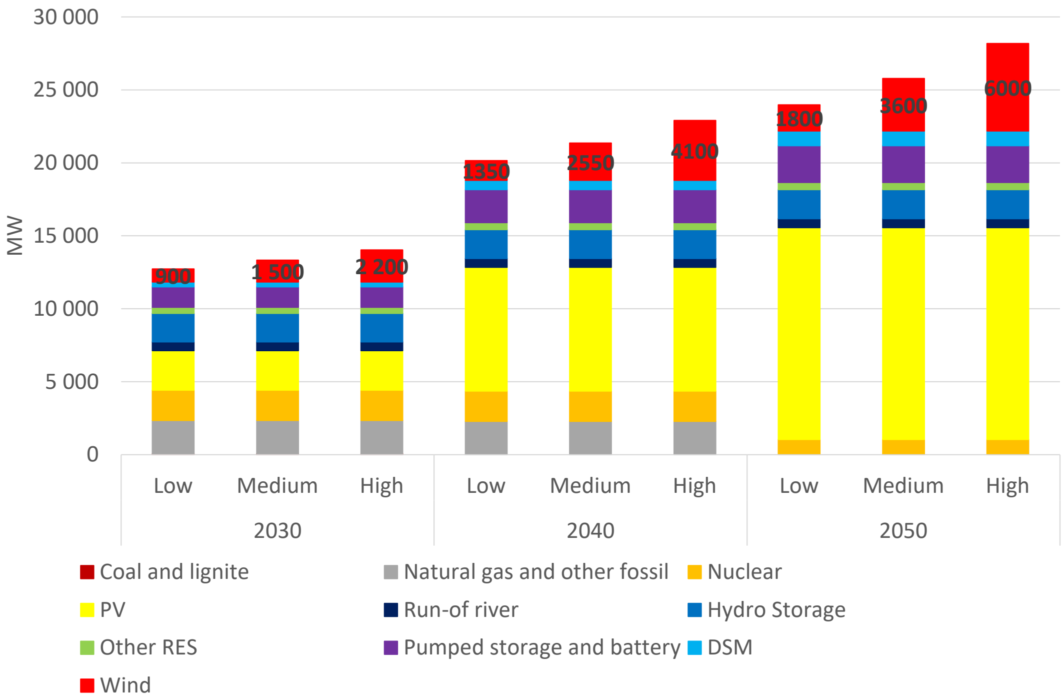

Figure 5: Installed capacity mix in Bulgaria. Source: Own elaboration based on National Energy Strategies, European Commission et al. (2022)

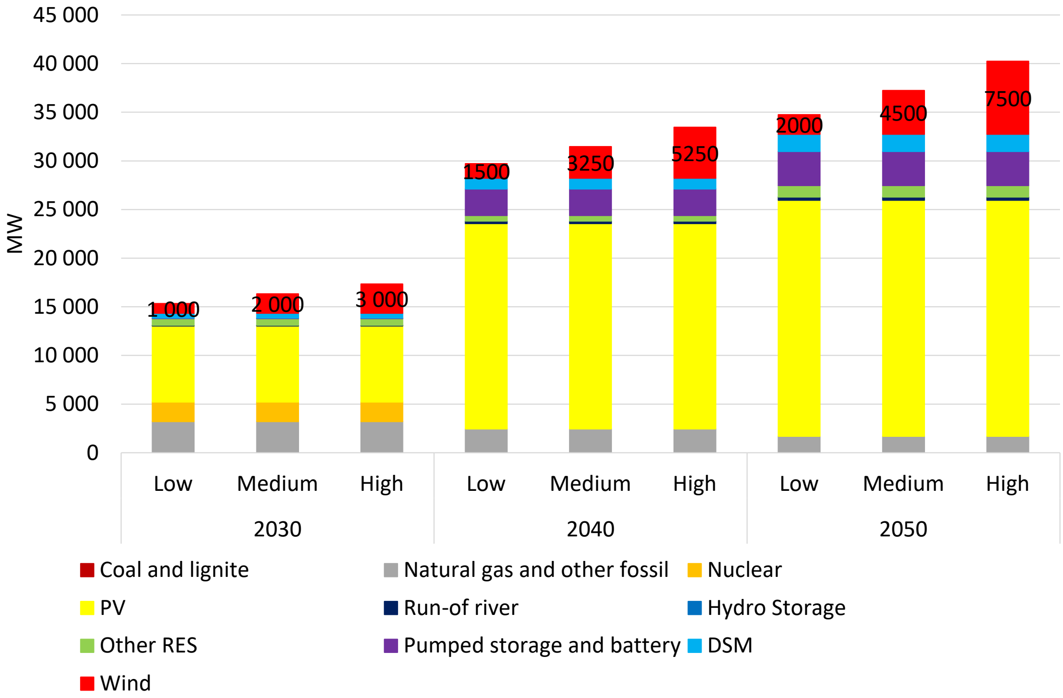

Figure 6: Installed capacity mix in Hungary. Source: Own elaboration based on National Energy Strategies, European Commission et al. (2022)

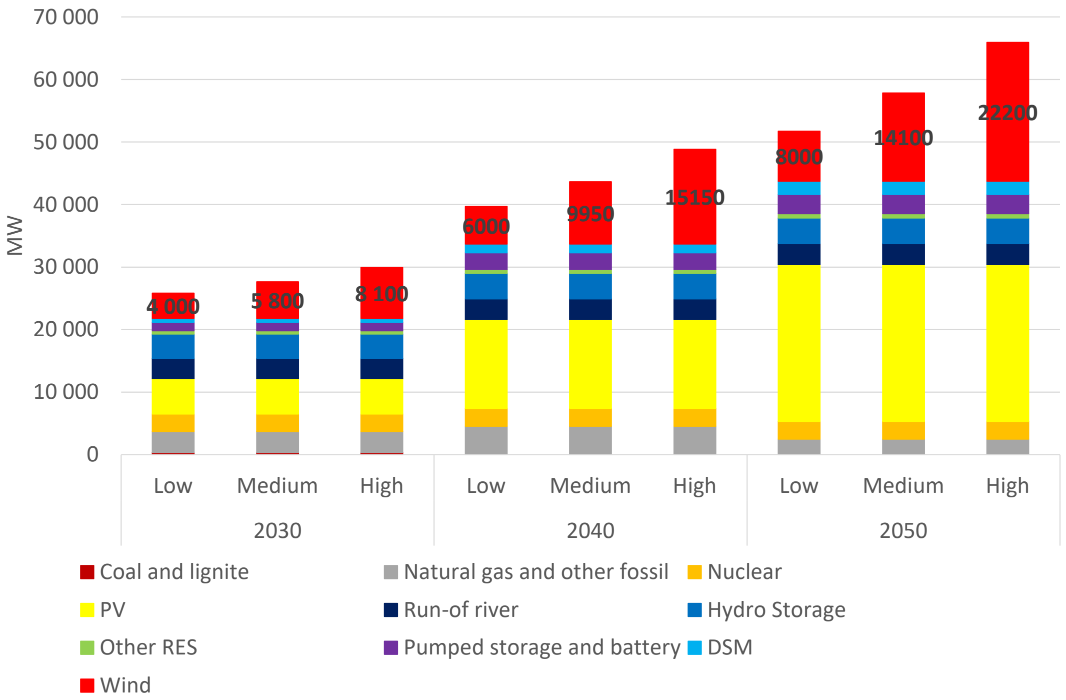

Figure 7: Installed capacity mix in Romania. Source: Own elaboration based on National Energy Strategies, European Commission et al. (2022)

3 RESULTS OF THE GIS-BASED ANALYSIS OF WIND POTENTIALS IN BULGARIA

This chapter is dedicated to informing on the results of the GIS-based analysis of wind power potentials in Bulgaria, comprising wind development at the countryside (onshore) and in marine areas (offshore). Building on the approach described in the previous chapter, specifically section 2.1, we discuss subsequently the results related to onshore wind. Next to that results on offshore wind are presented briefly.[4] Finally, the study findings are put into a broader energy system context, illustrating the role wind may be able take in future electricity supply within Bulgaria.

3.1 Onshore wind potentials

Looking at the topographical context as described in Wikipedia[5], the relief of Bulgaria is varied. In the territory of the country there are extensive lowlands, plains, hills, low and high mountains, many valleys, and deep gorges. Bulgaria's natural landscape is divided among mountains (28 percent), hills (41 percent), and plains (31 percent). In terms of size the country is ranked number sixteen within Europe, covering an area of 111 thousand square km. The main characteristic of Bulgaria's topography is four alternating bands of high and low terrain that extend east to west across the country. From north to south, those bands, called geomorphological regions, are the Danubian Plain, the Balkan Mountains, the Transitional region and the Rilo-Rhodope region. The easternmost sections near the Black Sea are hilly, but they gradually gain height to the west until the westernmost part of the country is entirely high ground.

3.1.1 Technical potentials at the national level

According to the GIS-based analysis conducted in this study, slightly more than a eight of the country (i.e., 13.4% of the total area) appears suitable for onshore wind power development, considering constraints ranging from a techno-economic, a societal and a nature conservation perspective (i.e., by excluding nature protection areas) as described in section 2.1.2. If all identified sites being classified as feasible would actually be used for wind power development, an enormous technical potential for wind power occurs: Thus, as listed in Table 2, the country area suitable for wind power development comprises 14.9 thousand square km, corresponding to a capacity potential of 137.0 GW. That would allow to generate electricity in size of 278.5 TWh per year, reflecting average meteorological conditions. To put that into a perspective, Bulgaria's final electricity consumption amounted to 38.5 TWh in 2021. From a technical potential, Bulgaria could generate more than seven times more electricity from onshore wind power than currently consumed. Apart from other barriers, a limiting factor to that is however the power grid infrastructure which is far from being ready to absorb these enormous amounts of electricity.

If one classifies nature protection areas as being suitable for wind power development, the technical potential increases further on, cf. Table 2: The area potential would then grow up to 38.9 thousand

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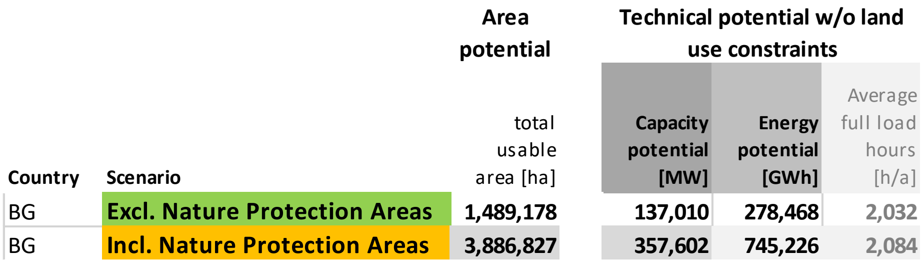
[4] Please note that Chapter 6 offers a detailed discussion on the results related to offshore wind from a regional perspective.

[5] Cf. https://en.wikipedia.org/wiki/Geography_of_Bulgaria

square km, corresponding to a capacity potential of 357.6 GW and a yearly electricity generation of 745.2 TWh.

Table 2: Technical potentials for onshore wind power development in Bulgaria, neglecting land use constraints (at feasible areas), expressed in area, capacity and energy terms. Source: own analysis.



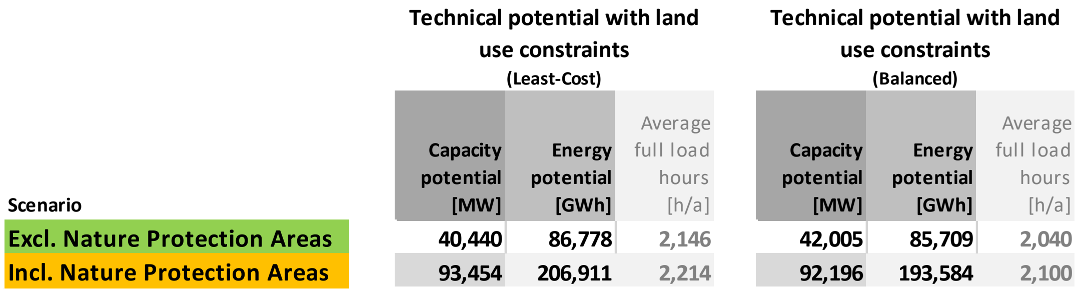
		Area potential	Technical potential w/o land use constraints		
Country	**Scenario**	total usable area [ha]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]
BG	**Excl. Nature Protection Areas**	**1,489,178**	**137,010**	**278,468**	**2,032**
BG	**Incl. Nature Protection Areas**	**3,886,827**	**357,602**	**745,226**	**2,084**

If we limit the wind power development by applying further land use restrictions on those areas classified as being feasible for wind power development, we still end up with significant potentials for onshore wind development in Bulgaria as shown in Table 3. Doing so may maintain social acceptance of wind power in general, and it may also allow for a more rapid uptake in future years – once other barriers are removed. As discussed in section 2.1.1, two different variants are assessed:

- Balanced allocation: Balanced allocation of wind sites by using average suitability factors for agricultural (40%) and forestry areas (10%).
- Least-cost allocation: Preference to best sites within a region, implying higher suitability factors as shown in Table 1 and, in turn, lower ones for less windy areas within a region.

According to Table 3, the identified technical potential for onshore wind in Bulgaria, with consideration of (further) land use restrictions, amounts to ca. 40.4 GW – about one third of the unconstrained technical potential. The corresponding yearly electricity generation varies among both allocation options: following a balanced approach implies a yearly electricity generation in size of 85.7 TWh whereas the adoption of a least-cost allocation within each region increases the generation potential up to 86.7 TWh.

Table 3: Technical potentials for onshore wind power development in Bulgaria, with (further) land use constraints (at feasible areas), expressed in capacity and energy terms for assessed allocation options (least-cost vs balanced). Source: own analysis.



	Technical potential with land use constraints (Least-Cost)			Technical potential with land use constraints (Balanced)		
Scenario	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]
Excl. Nature Protection Areas	**40,440**	**86,778**	**2,146**	**42,005**	**85,709**	**2,040**
Incl. Nature Protection Areas	**93,454**	**206,911**	**2,214**	**92,196**	**193,584**	**2,100**

A graphical illustration of the identified onshore wind development potentials in Bulgaria is provided by Figure 8. From this graph the large differences between the technical potentials where all areas classified as suitable for wind power development (i.e., without land use constraints) would be used versus the smaller technical potentials derived by consideration of further land use restrictions. Thus, if only 40% of agricultural areas and 10% of forestry areas (not classified as nature protection areas) would be used, the technical potentials are reduced to about one fourth of the unconstrained one.

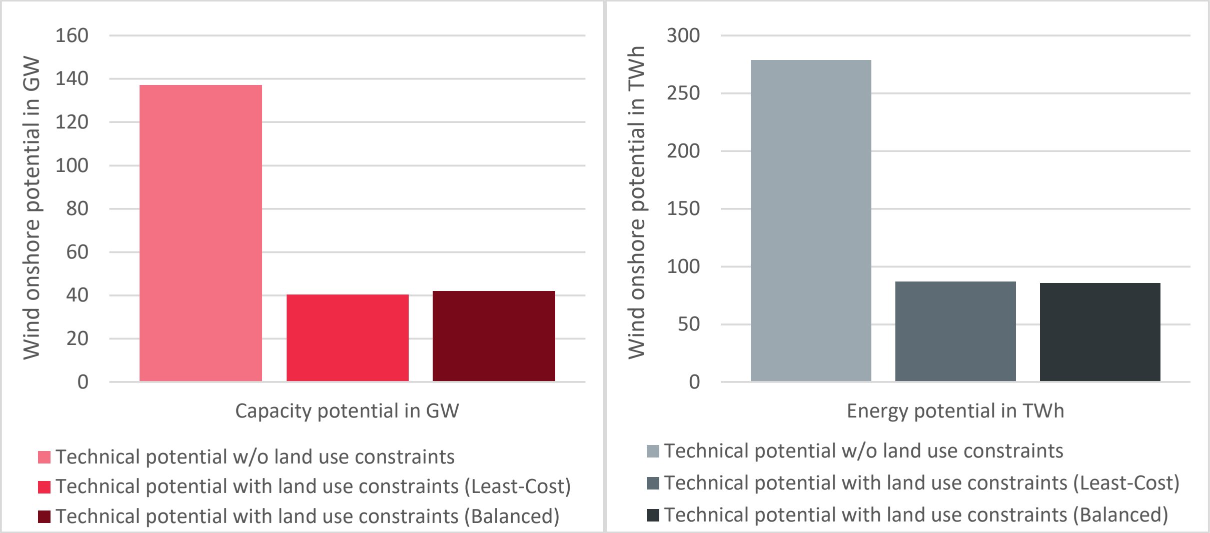


Figure 8: Technical potentials for onshore wind in Bulgaria, w/o and with (further) land use constraints (at feasible areas), expressed in capacity (left) and energy terms (right) for assessed allocation options (least-cost vs balanced). Source: own analysis.

3.1.2 Technical potentials at the regional level

In accordance with the above, we now undertake a deep dive into the regions within Bulgaria, presenting the outcomes of our GIS-based analysis of the onshore wind potentials at a regional level. In practical terms, we thereby follow the standardised NUTS-3 classification for the European Union and consequently undertake a breakdown of the results for the whole of Bulgaria by region. In the case of Bulgaria this implies to distinguish between 28 regions as applicable in the subsequent graphs and tables.

In this context, Figure 9 provides a graphical illustration of areas suitable for wind power development within Bulgaria. More precisely, this figure shows wind maps for Bulgaria, indicating for wind power development areas via a colour code that informs on corresponding wind site qualities, expressed via on average achievable full load hours, using the underlying state-of-the-art onshore wind power turbine (cf. section 2.1.2). This figure contains two graphs, the upper one shows the wind map excluding nature protection areas whereas to one at the bottom informs also on wind site qualities for those parts within nature protection areas. As applicable from these depictions, some of the best wind sites can be found in the north-eastern part of Bulgaria, specifically stretching from the Danube plains south to the city of Shumen to the east of the country until the Gulf of Varna. Large parts of the provinces Dobrich, Shumen and Varna are classified as nature protection areas which consequently reduces the wind power development potential there, supposing that those areas are not classified as suitable for wind power development. Despite of these constraints, the technical potential for wind power development is significant: these three regions alone have space for 10.8 GW of wind power, corresponding to a yearly electricity generation of 29.0 TWh – more than three quarters of the electricity Bulgaria needed in 2021. There are however more regions within Bulgaria that do offer promising wind conditions. If we expand the list to the five best regions within the country, in addition to the provinces Dobrich, Shumen and Varna, also the provinces of Razgrad and Silistra have to be named. The technical potential for wind power sums then up to 14.7 GW or 38.1 TWh, respectively. Achievable full load hours of wind sites within these regions are on average (well) above 2,100 hours per year – this characterises also from a European perspective comparatively good wind development areas.

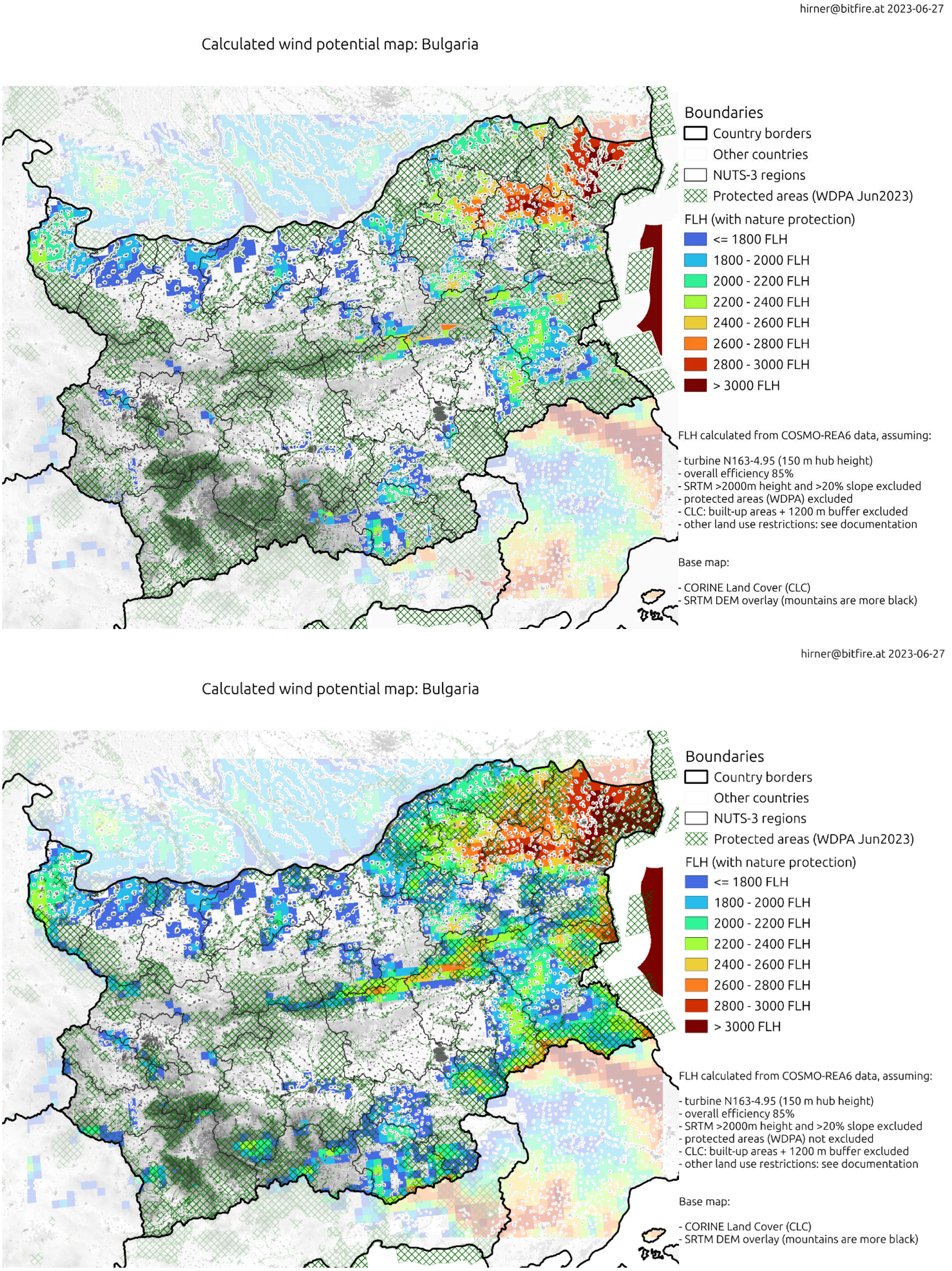


Figure 9: Wind maps for Bulgaria, indicating site qualities (expressed in full load hours) and by excluding (top) vs including (bottom) nature protection areas. Source: own analysis.

The technical details on wind potentials and average site qualities per region as discussed above are listed in Table 4 below. This table offers a breakdown of the technical potentials for wind power development in Bulgaria by NUTS-3 region, without consideration of further land use constraints for available areas and by excluding (left) or including (right) nature protection areas.

Table 4: Breakdown of the technical potentials for wind power development in Bulgaria by NUTS-3 region, without consideration of further land use constraints for available areas and by excluding (left) or including (right) nature protection areas. Source: own analysis.

	Excl. Nature Protection Areas				**Incl. Nature Protection Areas**			
	Area potential	**Technical potential w/o land use constraints**			**Area potential**	**Technical potential w/o land use constraints**		
Region	total usable area [ha]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]	total usable area [ha]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]
Sofia	21,077	1,939	3,424	1,766	61,920	5,697	10,228	1,795
Burgas	199,997	18,400	36,566	1,987	566,845	52,152	109,754	2,105
Dobrich	**92,591**	**8,519**	**24,638**	**2,892**	**305,984**	**28,152**	**80,874**	**2,873**
Shumen	**88,993**	**8,188**	**19,656**	**2,401**	**176,710**	**16,258**	**36,957**	**2,273**
Lovech	15,214	1,400	2,464	1,761	44,005	4,049	7,171	1,771
Veliko Tarnovo	82,366	7,578	13,445	1,774	111,166	10,228	18,358	1,795
Pleven	94,853	8,727	15,344	1,758	161,852	14,891	26,128	1,755
Varna	**77,665**	**7,145**	**17,392**	**2,434**	**209,142**	**19,242**	**44,775**	**2,327**
Vidin	92,646	8,524	16,878	1,980	173,878	15,997	31,651	1,979
Montana	81,771	7,523	13,136	1,746	121,340	11,164	19,712	1,766
Targovishte	51,345	4,724	9,605	2,033	135,643	12,480	24,492	1,963
Vratsa	70,923	6,525	11,280	1,729	106,829	9,829	17,054	1,735
Blagoevgrad	1,307	120	208	1,731	33,225	3,057	5,738	1,877
Pernik	10,833	997	1,786	1,792	20,117	1,851	3,351	1,810
Plovdiv	12,177	1,120	1,872	1,671	45,500	4,186	7,154	1,709
Kyustendil	6,776	623	1,052	1,687	38,400	3,533	6,218	1,760
Kardzhali	84,707	7,793	14,756	1,893	202,905	18,668	35,833	1,919
Gabrovo	23,963	2,205	3,938	1,786	61,951	5,700	10,839	1,902
Stara Zagora	27,729	2,551	5,225	2,048	78,351	7,209	15,195	2,108
Sofia (stolitsa)	3,490	321	595	1,854	9,643	887	1,593	1,795
Razgrad	**70,971**	**6,530**	**15,367**	**2,353**	**157,240**	**14,467**	**33,706**	**2,330**
Pazardzhik	862	79	129	1,629	49,702	4,573	8,774	1,919
Smolyan	30,615	2,817	5,163	1,833	105,193	9,678	17,721	1,831
Silistra	**44,165**	**4,063**	**8,604**	**2,118**	**190,275**	**17,506**	**39,070**	**2,232**
Haskovo	52,503	4,830	8,467	1,753	227,838	20,962	38,802	1,851
Sliven	35,687	3,283	6,936	2,113	156,963	14,441	31,860	2,206
Yambol	69,911	6,432	12,662	1,969	163,889	15,078	31,521	2,090
Ruse	44,041	4,052	7,878	1,944	170,321	15,670	30,696	1,959
Bulgaria	**1,489,178**	**137,010**	**278,468**	2,032	**3,886,827**	**357,602**	**745,226**	2,084

As stated above, if we limit the wind power development by applying further land use restrictions on those areas classified as being feasible for wind power development, we still end up with significant potentials for onshore wind development in Bulgaria. This is shown in Table 3 at the country level and in Table 5 at a regional level, following a least-cost allocation by giving preference to best sites within Bulgaria. A graphical illustration of the numbers listed in Table 5 is given by Figure 10, indicating the capacity potentials (top) and the corresponding average full load hours per region, again by including or excluding nature protection areas.

Table 5: Breakdown of the technical potentials for wind power development in Bulgaria by NUTS-3 region, with consideration of further land use constraints for available areas (via a least-cost allocation) and by excluding (left) or including (right) nature protection areas. Source: own analysis.

	Excl. Nature Protection Areas			**Incl. Nature Protection Areas**		
	Technical potential with land use constraints (Least-Cost)			**Technical potential with land use constraints (Least-Cost)**		
Region	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]
Sofia	298	531	1,785	753	1,358	1,804
Burgas	4,737	9,535	2,013	11,643	24,776	2,128
Dobrich	**4,990**	**14,479**	**2,901**	**15,249**	**44,364**	**2,909**
Shumen	**2,868**	**7,177**	**2,502**	**4,889**	**11,901**	**2,434**
Lovech	342	606	1,769	668	1,182	1,769
Veliko Tarnovo	1,703	2,975	1,748	2,190	3,856	1,761
Pleven	2,593	4,583	1,767	4,096	7,228	1,765
Varna	**2,908**	**7,385**	**2,540**	**6,197**	**15,399**	**2,485**
Vidin	2,668	5,344	2,003	4,145	8,314	2,006
Montana	2,216	3,884	1,752	3,042	5,381	1,769
Targovishte	1,268	2,620	2,065	3,114	6,188	1,987
Vratsa	1,907	3,313	1,737	2,784	4,852	1,743
Blagoevgrad	17	29	1,730	383	719	1,878
Pernik	219	391	1,784	343	617	1,801
Plovdiv	302	502	1,661	825	1,387	1,682
Kyustendil	124	209	1,688	492	861	1,750
Kardzhali	1,353	2,586	1,910	3,050	5,931	1,944
Gabrovo	423	753	1,781	941	1,785	1,897
Stara Zagora	422	851	2,014	1,080	2,278	2,110
Sofia (stolitsa)	64	123	1,902	122	225	1,835
Razgrad	**2,511**	**5,973**	**2,379**	**5,072**	**11,915**	**2,349**
Pazardzhik	24	39	1,629	518	1,012	1,955
Smolyan	354	660	1,862	1,122	2,089	1,861
Silistra	**1,429**	**3,044**	**2,130**	**5,604**	**12,659**	**2,259**
Haskovo	1,023	1,801	1,760	4,029	7,535	1,870
Sliven	487	1,064	2,184	2,309	5,179	2,243
Yambol	2,032	4,046	1,991	4,280	8,976	2,097
Ruse	1,156	2,278	1,971	4,514	8,944	1,981
Bulgaria	**40,440**	**86,778**	**2,146**	**93,454**	**206,911**	**2,214**

Complementary to the above, Table 6 provides further insights on the distribution of the region-specific technical potentials among wind site classes, expressed by the respective range of full load hours. This is done under consideration of land use constraints, assuming again a least-cost allocation as well as by excluding nature protection areas.

Table 6: Breakdown by wind site class (i.e., full load hour ranges) of the region-specific technical potentials for wind power development in Bulgaria, expressed in capacity terms (MW), with consideration of land use constraints (least-cost allocation) and with exclusion of nature protection areas. Source: own analysis.

Technical potential with land use constraints (least-cost) in capacity terms (in MW) in total (left column) and by wind site class, expressed by the range of respective full load hours (all other columns)

Region	all wind classes [MW]	flh 1600-1850 [MW]	flh 1850-2100 [MW]	flh 2100-2300 [MW]	flh 2300-2500 [MW]	flh 2500-2700 [MW]	flh 2700-2900 [MW]	flh 2900-3100 [MW]	flh 3100-3300 [MW]
Sofia	298	237	60	0	0	0	0	0	0
Burgas	4,737	910	2,070	1,547	210	0	0	0	0
Dobrich	**4,990**	**0**	**0**	**0**	**2**	**509**	**1,488**	**2,922**	**70**
Shumen	**2,868**	**334**	**320**	**198**	**263**	**537**	**682**	**535**	**0**
Lovech	342	276	66	0	0	0	0	0	0
Veliko Tarnovo	1,703	1,435	193	54	20	0	0	0	0
Pleven	2,593	1,845	747	0	0	0	0	0	0
Varna	**2,908**	**189**	**215**	**310**	**302**	**634**	**854**	**404**	**0**
Vidin	2,668	613	1,192	592	271	0	0	0	0
Montana	2,216	1,795	421	0	0	0	0	0	0
Targovishte	1,268	317	238	431	269	13	0	0	0
Vratsa	1,907	1,418	490	0	0	0	0	0	0
Blagoevgrad	17	17	0	0	0	0	0	0	0
Pernik	219	169	50	0	0	0	0	0	0
Plovdiv	302	302	0	0	0	0	0	0	0
Kyustendil	124	124	0	0	0	0	0	0	0
Kardzhali	1,353	526	628	196	0	3	0	0	0
Gabrovo	423	377	11	26	8	0	0	0	0
Stara Zagora	422	100	151	120	46	5	0	0	0
Sofia (stolitsa)	64	17	48	0	0	0	0	0	0
Razgrad	**2,511**	**19**	**223**	**648**	**838**	**450**	**333**	**0**	**0**
Pazardzhik	24	24	0	0	0	0	0	0	0
Smolyan	354	192	133	29	0	0	0	0	0
Silistra	**1,429**	**46**	**646**	**542**	**120**	**74**	**0**	**0**	**0**
Haskovo	1,023	790	214	19	0	0	0	0	0
Sliven	487	151	28	59	155	65	30	0	0
Yambol	2,032	697	513	536	287	0	0	0	0
Ruse	1,156	318	554	210	73	0	0	0	0
Bulgaria	**40,440**	**13,238**	**9,213**	**5,518**	**2,864**	**2,289**	**3,386**	**3,861**	**70**

A closer look at the regional breakdown of technical capacity potentials and corresponding average full load hours shown in Figure 10 reveals that five regions within Bulgaria can be classified as (very) good concerning wind site qualities. As discussed above, that top-five list includes the regions Dobrich, Varna, Shumen, Razgrad and Silistra. Achievable full load hours of wind sites within these regions are on average (well) above 2,100 hours per year. The overall technical potential for wind power of all five regions together sums up to 34.4 GW or 85.7 TWh, respectively, cf. Table 4. If we now apply further land use constraints and thereby assume a least-cost allocation for the whole of Bulgaria, then this would limit the technical potential to the half, i.e., 14.7 GW or 38.1 TWh, respectively. However, even the smaller number in terms of generation potential nearly as high as the electricity consumption of the whole of Bulgaria at present. Bulgaria's final electricity consumption amounted to 38.5 TWh in 2021. Focussing on these areas may allow to better tackle one key barrier to an enhanced wind power uptake: the necessary grid expansion. At present many Bulgarian stakeholders classify this as the central hurdle for a rapid uptake of this promising carbon-free energy carrier.

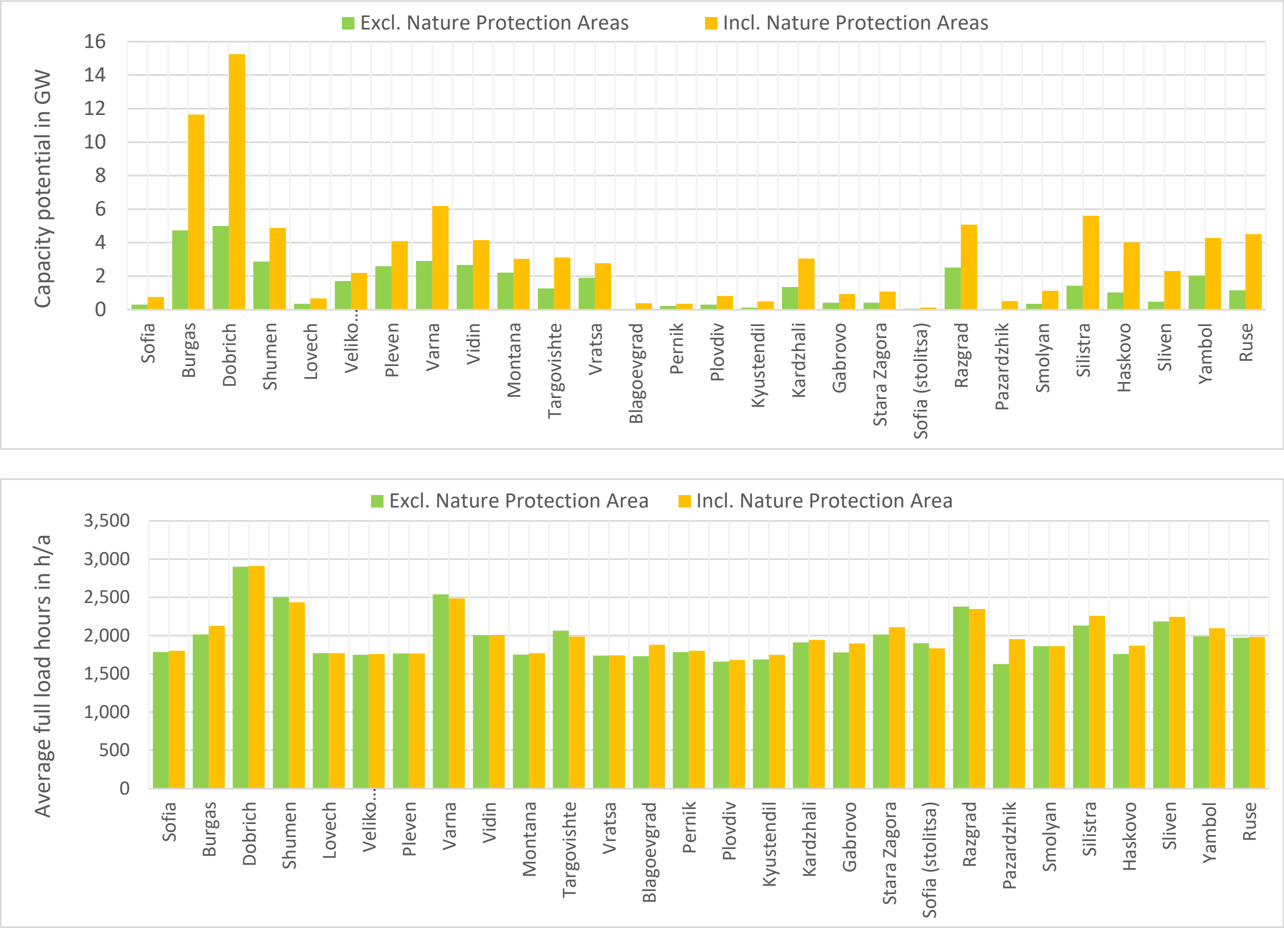


Figure 10: Breakdown of the technical potentials for wind power development in Bulgaria by NUTS-3 region, with consideration of further land use constraints for available areas (via a least-cost allocation) and by excluding or including nature protection areas. Expressed are capacity potentials (top) and average site qualities (full load hours) per region. Source: own analysis

3.1.3 Mapping with the grid infrastructure

A mapping exercise is finally conducted to indicate how identified promising areas for onshore wind power development match with the transmission grid infrastructure. We consequently add to the dataset an indicator that shows the average distance to the next grid node for feasible wind development areas, on average by region as well as on average for each available wind site class within a region, cf. Table 7. Thus, on average wind farms in Bulgaria are 29 km distant to the next grid node, with variations among individual sites but with hardly any differences by wind site class.

Table 7: Average distance to the next transmission grid node of region-specific feasible wind development areas in Bulgaria, considering the technical potentials with land use constraints (least-cost allocation) and with exclusion of nature protection areas, expressed on average by region (left column) as well as by wind site class (all other columns). Source: own analysis.

Average distance of individual pixels to the next grid node (in km) on average (left column) and by wind site class, expressed by the range of respective full load hours (all other columns)

Region	all wind classes [km]	flh 1600-1850 [km]	flh 1850-2100 [km]	flh 2100-2300 [km]	flh 2300-2500 [km]	flh 2500-2700 [km]	flh 2700-2900 [km]	flh 2900-3100 [km]	flh 3100-3300 [km]
Sofia	17	16	20	0	0	0	0	0	0
Burgas	24	24	24	23	27	0	0	0	0
Dobrich	**47**	**0**	**0**	**0**	**69**	**23**	**53**	**50**	**33**
Shumen	**22**	**17**	**20**	**18**	**23**	**26**	**26**	**19**	**0**
Lovech	30	31	22	0	0	0	0	0	0
Veliko Tarnovo	22	22	21	21	19	0	0	0	0
Pleven	23	25	18	0	0	0	0	0	0
Varna	**15**	**28**	**25**	**17**	**13**	**10**	**9**	**6**	**0**
Vidin	22	32	24	9	14	0	0	0	0
Montana	25	26	25	0	0	0	0	0	0
Targovishte	29	24	31	30	36	14	0	0	0
Vratsa	29	28	31	0	0	0	0	0	0
Blagoevgrad	29	29	31	0	0	0	0	0	0
Pernik	14	13	15	0	0	0	0	0	0
Plovdiv	33	33	0	0	0	0	0	0	0
Kyustendil	23	23	0	0	0	0	0	0	0
Kardzhali	63	66	58	67	0	76	0	0	0
Gabrovo	20	22	11	6	9	0	0	0	0
Stara Zagora	21	15	23	22	21	17	0	0	0
Sofia (stolitsa)	13	9	16	0	0	0	0	0	0
Razgrad	**38**	**16**	**35**	**39**	**42**	**36**	**32**	**0**	**0**
Pazardzhik	11	11	0	0	0	0	0	0	0
Smolyan	66	65	71	54	0	0	0	0	0
Silistra	**70**	**51**	**73**	**71**	**60**	**59**	**0**	**0**	**0**
Haskovo	22	20	29	25	0	0	0	0	0
Sliven	18	12	23	19	26	12	22	0	0
Yambol	28	24	30	31	36	0	0	0	0
Ruse	28	25	27	31	42	0	0	0	0
Bulgaria	**29**	**26**	**29**	**30**	**31**	**30**	**28**	**25**	**33**

3.2 Offshore wind potentials

This section is dedicated to put, complementary to the analysis of onshore wind potentials, offshore wind power into the spotlight. It provides a brief overview on the results gained from our respective analysis whereas a detailed discussion is presented in Chapter 6.

Offshore wind is according to past experiences less relevant for the Black Sea region but recently gaining key policy attention at the European as well as the national level. Specifically, for offshore wind, competing uses of the sea (e.g., main shipping routes, nature protection areas) are taken into consideration within our analysis, done by excluding related areas from the applicable resource base as a simplification. For offshore wind Bulgaria has promising sites at hands but generally offshore comes at higher cost compared to onshore. For an offshore wind farm upfront investment cost are about 50% to 100% higher in comparison to onshore due to higher cost for the foundations and for grid connection. Thus, this needs to be compensated by better resource qualities.

As applicable from the detailed result representation in Chapter 6, the overall technical potential for offshore wind in Bulgaria is significant – i.e., 363.1 GW in capacity terms and 1,019.1 TWh in energy terms, respectively, when considering the standard offshore turbine for that purpose. Large parts of the most promising potentials are however far distant from the shore (cf. Table 8), at sites characterised by moderate water depth or at sites with high water depth whereby the latter would recommend using a floating turbine design.

3.3 Brief summary of results & comparison with national energy planning

This section is dedicated to summarising the results of our GIS-based analysis of wind power development potentials in Bulgaria. To put them into perspective, we also undertake a comparison to the role of wind power in current energy planning. As starting point, Table 8 provides an overview on the identified technical potentials for wind power development in Bulgaria, distinguishing between onshore (left) and offshore resources (right).

Table 8: Overview on identified technical potentials for wind power development in Bulgaria, distinguishing between onshore (left) and offshore wind (right). Source: own analysis.

Technology		Onshore wind				Offshore wind			
Type of potential		potential with land use constraints (Least-cost), incl. nature protection areas	potential with land use constraints (Balanced), incl. nature protection areas	potential with land use constraints (Least-cost), excl. nature protection areas	potential with land use constraints (Balanced), excl. nature protection	Near/Mid shore, low water depth	Near/Mid shore, low-medium water depth	Far shore, low-medium water depth	High water depth (floating turbines)
Installed capacity	GW	93.5	92.2	40.4	42.0	15.6	17.5	48.7	281.4
Electricity generation	TWh	206.9	193.6	86.8	85.7	34.5	43.5	130.4	810.7
Full load hours	h/a	2214	2100	2146	2040	2207	2491	2678	2881

Table 9: Comparison of 2030 deployment targets for wind power and renewables in general in Bulgaria according to current planning (left column) and under consideration of the newly established 2030 EU targets (all other columns). Sources: Republic of Bulgaria (2019) and own analysis.

NECP targets		Current planning	New 2030 EU target (w/o top-up)	New 2030 EU target (with top-up)
Planned 2030 RE share in GFEC	%	27.1	35.1	37.3
Planned 2030 RE share in gross electricity demand	%	30.3	39.3	41.8
Planned 2030 RE electricity generation	TWh	42.98	55.7	59.2
Planned 2030 wind generation	TWh	2.05	2.7	2.8
Planned 2040 wind generation	TWh	3.61	4.7	5.0
Planned 2030 wind capacity	GW	0.95	1.2	1.3

Table 9 above undertakes of comparison of 2030 deployment targets for wind power as well as renewables in general in Bulgaria. Here we show the planned renewable and wind power uptake according to current planning as indicated in the 2019 National Energy and Climate Plan (NECP) of Bulgaria (Republic of Bulgaria, 2019). Recently, all EU Member States agreed on a strengthening of the renewables ambition, given the urgency to combat climate change as well as to respond on the Russian invasion of the Ukraine as well as the impact of that on Europe's gas, and, in consequence, also on electricity supply. To acknowledge that strengthening of the renewables ambition, all EU

Member States, including Bulgaria, are currently revising their previous national energy planning. To indicate the implications on renewables in general as well as specifically on wind in energy planning, Table 9 contains deployment figures for both under the newly established EU framework on 2030 energy and climate targets. Note that these deployment figures for wind are purely indicative, derived by proportionally increasing wind in relation to the strengthened RES ambition.

Finally, Figure 11 summarise all the above. More precisely, this graph shows the status quo of wind power development (as of 2021) and compares that with the 2030 deployment targets (both according to current planning and the possible implications on that from the strengthened RES ambition) as well as with the identified wind development potentials, here exemplified for onshore wind only. Apparently, we can conclude that when considering the available wind resources in Bulgaria that there is sufficient room for enhancing the wind uptake in future years. Given the resources at hands, wind power deserves to take a more prominent role in future energy planning in Bulgaria. Any strengthening of the wind ambition should however go hand in hand with a strengthening of the power grid infrastructure, both at transmission and, where affected, also at the distribution grid level.

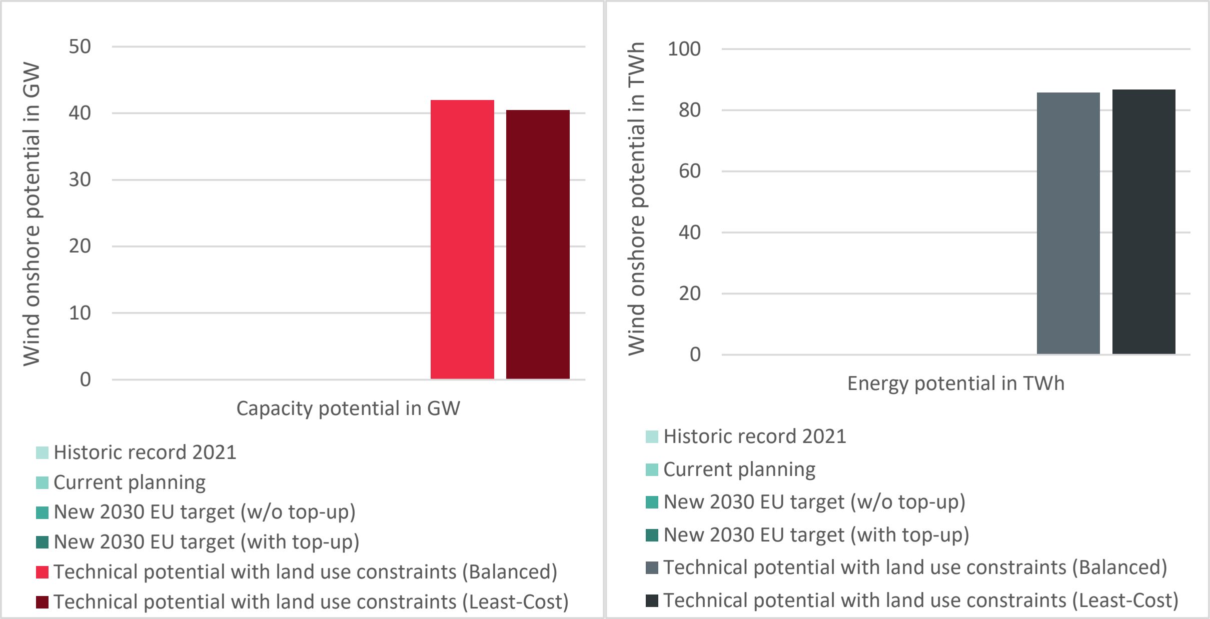


Figure 11: Wind energy at present and in future: Comparison of the status quo (2021), of 2030 deployment targets according to current planning (NECP) and under consideration of new 2030 EU targets as well as of identified technical potentials (with land use constraints). Sources: Eurostat (2023), Republic of Bulgaria (2020) and own analysis.

3.4 Brief consideration of economics

As a teaser for Chapter 7 that indicates the electricity market impacts of an enhanced wind uptake in future years within the study region, we conclude our resource analysis with a snapshot on the economics of wind power. At the example of onshore wind, Figure 12 depicts so-called cost-resource curves of wind onshore for all countries within our study region, including apart from Bulgaria also Hungary and Romania. These cost-resource curves show the potentials for wind onshore, using technical least-cost potentials with consideration of land use and nature protection constraints, broken down by wind site class (i.e., by full load hours) on the horizontal axes. Lines are derived by complementing the data on the resources with information on the corresponding Levelized Cost of Electricity (LCOE), using typical assumptions for cost and financial parameter as listed below. The graph confirms the previous statement that Bulgaria offers promising wind sites at comparatively cheap cost, considering current prices on electricity wholesale markets.

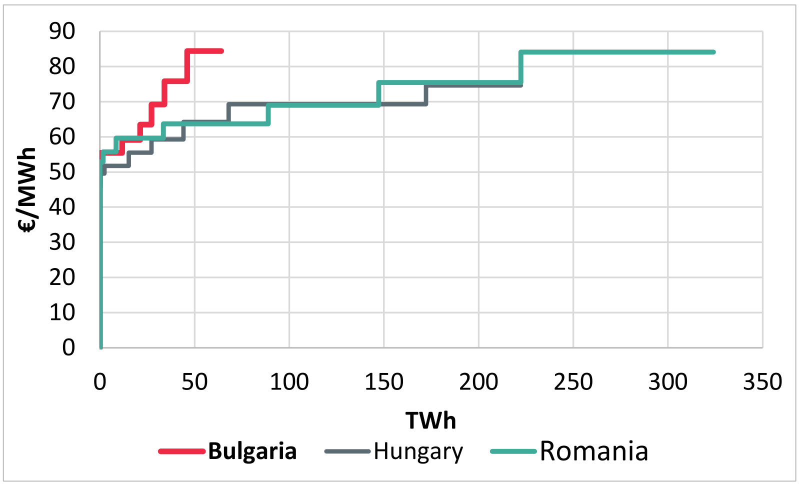


Figure 12: Cost-resource curves of wind onshore in the study region (using technical least-cost potentials with consideration of land use constraints). Source: own analysis

<u>Note on the assumptions for LCOE calculation:</u> Investment cost: 1,500 EUR/kW, O&M cost: 3% p.a. (of investment cost), Interest rate: 6.5%, Depreciation time: 20 years

4 RESULTS OF THE GIS-BASED ANALYSIS OF WIND POTENTIALS IN HUNGARY

This chapter is dedicated to informing on the results of the GIS-based analysis of wind power potentials in Hungary. Since Hungary is a landlocked country, wind power can only be developed at the countryside (onshore). Building on the approach described in the previous chapter, specifically section 2.1, we discuss subsequently (section 4.1) the results related to onshore wind within Hungary. Next to that, within section 4.2 we illustrate how current legislation affects the feasibility for wind power development within the country. Finally, the study findings are put into a broader energy system context in section 4.3, illustrating the role wind power may be able take in future electricity supply within Hungary.

4.1 Wind potentials in Hungary

Looking at the geographical and topographical context as described in Wikipedia[6], Hungary can be classified as a landlocked country in the south-eastern region of Central Europe, bordering the Balkans. Situated in the Carpathian Basin, it has a land area of 93 thousand square km, measuring about 250 km from north to south and 524 km from east to west. Most of the country has an elevation of less than 200 m. Although Hungary has several moderately high ranges of mountains, those reaching heights of 300 m or more cover less than 2% of the country. The country is rich of fertile land, despite varying soil qualities. About 70% of the country's total territory is suitable for agriculture, of which 72% is classified as arable land.

4.1.1 Technical potentials at the national level

According to the GIS-based analysis conducted in this study, slightly less than a fourth of the country (i.e., 32.6% of the total area) appears suitable for onshore wind power development, considering constraints ranging from a techno-economic, a societal and a nature conservation perspective (i.e., by excluding nature protection areas) as described in section 2.1.2. If all identified sites being classified as feasible would actually be used for wind power development, an enormous technical potential for wind power occurs: Thus, as listed in Table 9, the country area suitable for wind power development comprises 30 thousand square km, corresponding to a capacity potential of 279 GW. That would allow to generate electricity in size of 651 TWh per year, reflecting average meteorological conditions. To put that into a perspective, Hungary's gross electricity consumption amounted to 49 TWh in 2021. Considering the technical potential, Hungary could generate more than thirteen times more electricity from onshore wind power than currently consumed. Apart from other barriers like current legislation, a limiting factor to that is however the power grid infrastructure which is far from being ready to absorb these enormous amounts of electricity.

If one classifies nature protection areas as being suitable for wind power development, the technical potential increases further on, cf. Table 10: The area potential would then grow up to 56 thousand square km (i.e., 60.5% of the total area), corresponding to a capacity potential of 518 GW and a yearly electricity generation of 1,202 TWh.

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[6] Cf. https://en.wikipedia.org/wiki/Geography_of_Hungary.

Table 10: Technical potentials for onshore wind power development in Hungary, neglecting land use constraints (at feasible areas), expressed in area, capacity and energy terms. Source: own analysis.

	Area potential	Technical potential w/o land use constraints		
Scenario	total usable area [ha]	Capacity potential [MW]	Energy potential [GWh]	Average full load hours [h/a]
Excl. Nature Protection Areas	**3,032,574**	**279,008**	**650,883**	**2,333**
Incl. Nature Protection Areas	**5,627,234**	**517,726**	**1,202,273**	**2,322**

If we limit the wind power development by applying further land use restrictions on those areas classified as being feasible for wind power development, we still end up with significant potentials for onshore wind development in Hungary as shown in Table 11. Doing so may maintain social acceptance of wind power in general, and it may also allow for a more rapid uptake in future years – once other barriers are removed. As discussed in section 2.1.1, two different variants are assessed:

- Balanced allocation: Balanced allocation of wind sites by using average suitability factors for agricultural (40%) and forestry areas (10%).
- Least-cost allocation: Preference to best sites within Hungary, implying higher suitability factors as shown in Table 1 for those, and, in turn, lower ones for less windy areas within the country.

According to Table 11, the identified technical potential for onshore wind in Hungary, with consideration of (further) land use restrictions, amounts to ca. 93.5 GW – about one third of the unconstrained technical potential. The corresponding yearly electricity generation varies among both allocation options: following a balanced approach implies a yearly electricity generation in size of 217 TWh whereas the adoption of a least-cost allocation focussing on best sites across the whole country increases the generation potential to 223 TWh.

Table 11: Technical potentials for onshore wind power development in Hungary, with (further) land use constraints (at feasible areas), expressed in capacity and energy terms for assessed allocation options (least-cost vs balanced). Source: own analysis.

	Technical potential with land use constraints (Least-Cost)			Technical potential with land use constraints (Balanced)		
Scenario	Capacity potential [MW]	Energy potential [GWh]	Average full load hours [h/a]	Capacity potential [MW]	Energy potential [GWh]	Average full load hours [h/a]
Excl. Nature Protection Areas	**93,548**	**223,479**	**2,389**	**93,544**	**217,085**	**2,321**
Incl. Nature Protection Areas	**155,229**	**371,341**	**2,392**	**155,236**	**358,917**	**2,312**

A graphical illustration of the identified onshore wind development potentials in Hungary is provided by Figure 19. From this graph the large differences between the technical potentials where all areas classified as suitable for wind power development (i.e., without land use constraints) would be used versus the smaller technical potentials derived by consideration of further land use restrictions. Thus, if only 40% of agricultural areas and 10% of forestry areas (not classified as nature protection areas) would be used, the technical potentials are reduced to about one third of the unconstrained one.

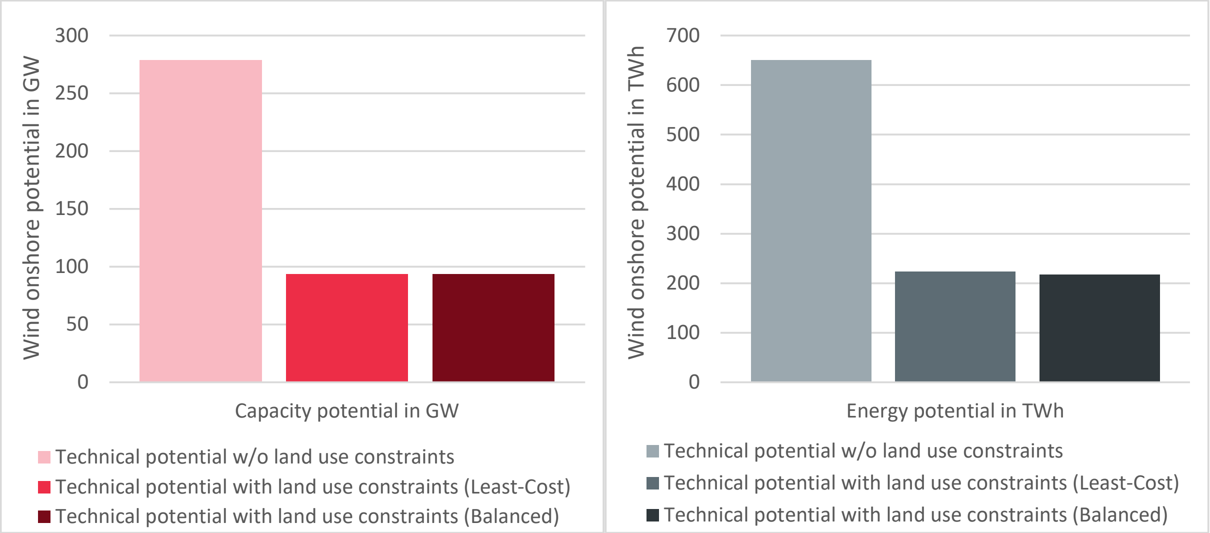


Figure 13: Technical potentials for onshore wind in Hungary, w/o and with (further) land use constraints (at feasible areas), expressed in capacity (left) and energy terms (right) for assessed allocation options (least-cost vs balanced). Source: own analysis.

4.1.2 Technical potentials at the regional level

In accordance with the above, we now undertake a deep dive into the regions within Hungary, presenting the outcomes of our GIS-based analysis of the onshore wind potentials at a regional level. In practical terms, we thereby follow the standardised NUTS-3 classification for the European Union and consequently undertake a breakdown of the results for the whole of Hungary by region. In the case of Hungary this implies to distinguish between 20 regions as applicable in the subsequent graphs and tables.

In this context, Figure 14 provides a graphical illustration of areas suitable for wind power development within Hungary. More precisely, this figure shows wind maps for Hungary, indicating for wind power development areas via a colour code that informs on corresponding wind site qualities, expressed via on average achievable full load hours, using the underlying state-of-the-art onshore wind power turbine (cf. section 2.1.2). This figure contains two graphs, the upper one shows the wind map excluding nature protection areas whereas the one at the bottom informs also on wind site qualities for those parts within nature protection areas. As applicable from these depictions, some of the best wind sites can be found in the western part of Hungary, specifically at the border to Austria and the southwestern end of Slovakia. The best sites for wind development in Hungary can specifically be found in the regions Győr-Moson-Sopron and Veszprém, followed by Vas, Zala, Fejér and Komárom-Esztergom. There are however more regions within Hungary that do offer promising wind conditions. If we expand the list to the ten best regions within the country, in addition to the above also Csongrád, Szabolcs-Szatmár-Bereg, Somogy and Hajdú-Bihar have to be named. Common among all these regions is that achievable full load hours of wind sites within are on average (well) above 2,350 hours per year. Expanding the list implies geographically to involve also other parts of the country since for example Hajdú-Bihar and Szabolcs-Szatmár-Bereg are located in the northeast of Hungary. The technical potential for wind power development of all ten best regions sums up to 128.7 GW or 324.1 TWh, respectively. In energy terms this is more than six times higher than the current electricity consumption of Hungary. A comparison of generation and capacity potentials indicate on average across all ten regions full load hours in the order of 2,520 hours per year – a value that characterises also from a European perspective very promising wind power development areas.

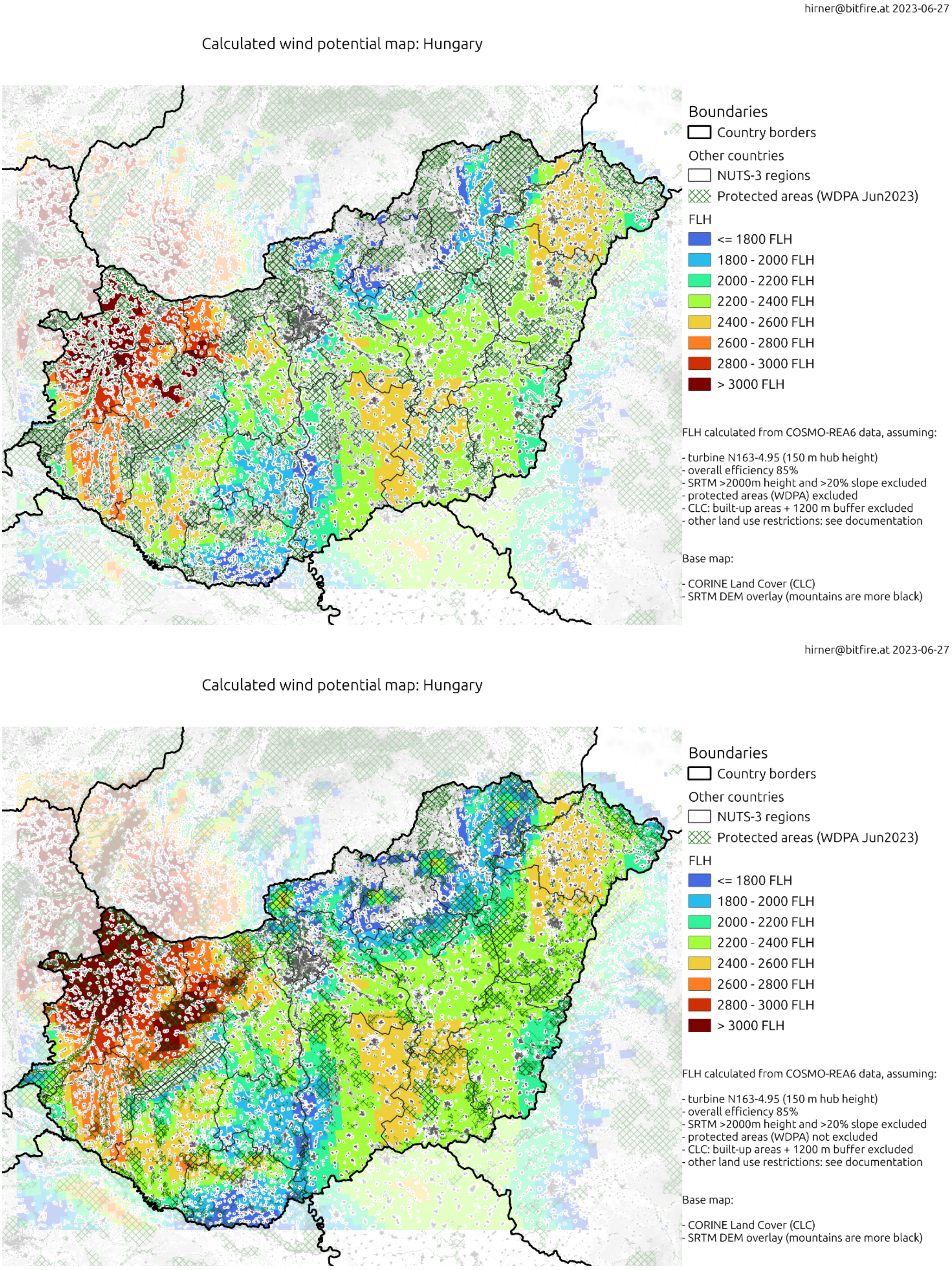


Figure 14: Wind maps for Hungary, indicating site qualities (expressed in full load hours) and by excluding (top) vs including (bottom) nature protection areas. Source: own analysis.

The technical details on wind potentials and average site qualities per region as discussed above are listed in Table 12 below. This table offers a breakdown of the technical potentials for wind power development in Hungary by NUTS-3 region, without consideration of further land use constraints for available areas and by excluding (left) or including (right) nature protection areas. As applicable from a graphical comparison of the upper (excluding nature protection areas) and the lower map (including nature protection areas) depicted in Figure 14, or, from the numbers listed in Table 12, nature protection has an impact on the feasible wind power development potential within those regions. Similar to Hungary overall, allowing for wind development also within nature protection areas would almost double the wind potential within those regions. Even from a techno-economic perspective this makes however hardly sense since already the constrained wind potential exceeds by far the domestic consumption.

Table 12: Breakdown of the technical potentials for wind power development in Hungary by NUTS-3 region, without consideration of further land use constraints for available areas and by excluding (left) or including (right) nature protection areas. Source: own analysis.

	Excl. Nature Protection Areas				**Incl. Nature Protection Areas**			
	Area potential	**Technical potential w/o land use constraints**			**Area potential**	**Technical potential w/o land use constraints**		
Region	total usable area [ha]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]	total usable area [ha]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]
Budapest	842	77	149	1,929	877	81	155	1,920
Veszprém	**113,599**	**10,452**	**29,727**	**2,844**	**249,852**	**22,987**	**65,294**	**2,840**
Győr-Moson-Sopron	**99,984**	**9,199**	**28,217**	**3,067**	**240,389**	**22,117**	**69,056**	**3,122**
Baranya	142,021	13,066	25,868	1,980	261,056	24,018	48,617	2,024
Somogy	**193,227**	**17,778**	**41,786**	**2,351**	**370,981**	**34,132**	**79,566**	**2,331**
Vas	**103,689**	**9,540**	**26,480**	**2,776**	**190,169**	**17,496**	**46,937**	**2,683**
Zala	**110,749**	**10,189**	**26,219**	**2,573**	**196,932**	**18,118**	**46,164**	**2,548**
Fejér	**179,008**	**16,469**	**38,511**	**2,338**	**266,252**	**24,496**	**58,384**	**2,383**
Komárom-Esztergom	**62,174**	**5,720**	**15,801**	**2,762**	**130,769**	**12,031**	**31,176**	**2,591**
Pest	159,082	14,636	32,952	2,251	346,574	31,886	71,037	2,228
Nógrád	62,219	5,724	10,553	1,843	97,237	8,946	16,717	1,869
Csongrád	**156,855**	**14,431**	**34,500**	**2,391**	**319,621**	**29,406**	**70,257**	**2,389**
Tolna	160,189	14,738	29,697	2,015	245,263	22,565	45,263	2,006
Hajdú-Bihar	**171,305**	**15,761**	**37,012**	**2,348**	**451,357**	**41,526**	**95,874**	**2,309**
Jász-Nagykun-Szolnok	260,051	23,926	54,849	2,292	397,983	36,616	83,262	2,274
Szabolcs-Szatmár-Bereg	**209,272**	**19,254**	**45,832**	**2,380**	**325,080**	**29,909**	**69,335**	**2,318**
Heves	37,693	3,468	6,274	1,809	141,649	13,032	24,775	1,901
Borsod-Abaúj-Zemplén	118,746	10,925	21,472	1,965	319,431	29,389	57,223	1,947
Bács-Kiskun	443,446	40,799	93,207	2,285	653,202	60,097	135,526	2,255
Békés	248,423	22,856	51,776	2,265	422,560	38,877	87,652	2,255
Hungary	**3,032,574**	**279,008**	**650,883**	**2,333**	**5,627,234**	**517,726**	**1,202,273**	**2,322**

If we limit the wind power development by applying further land use restrictions on those areas classified as being feasible for wind power development, we still end up with significant potentials for onshore wind development in Hungary. This is shown in Table 11 at the country level and in Table 13 at a regional level, following a least-cost allocation by giving preference to best sites within Hungary. A graphical illustration of the numbers listed in Table 13 is given by Figure 15, indicating the capacity potentials (top) and the corresponding average full load hours per region, again by including or excluding nature protection areas.

Table 13: Breakdown of the technical potentials for wind power development in Hungary by NUTS-3 region, with consideration of further land use constraints for available areas (via a least-cost allocation) and by excluding (left) or including (right) nature protection areas. Source: own analysis.

	Excl. Nature Protection Areas			**Incl. Nature Protection Areas**		
	Technical potential with land use constraints (Least-Cost)			**Technical potential with land use constraints (Least-Cost)**		
Region	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]
Budapest	20	38	1,944	20	38	1,942
Veszprém	**4,152**	**11,956**	**2,880**	**7,790**	**22,515**	**2,890**
Győr-Moson-Sopron	**4,824**	**14,871**	**3,083**	**10,249**	**32,098**	**3,132**
Baranya	3,277	6,580	2,008	5,187	10,624	2,048
Somogy	**5,413**	**12,791**	**2,363**	**8,887**	**20,889**	**2,350**
Vas	**3,768**	**10,689**	**2,837**	**6,131**	**17,208**	**2,806**
Zala	**3,028**	**7,841**	**2,590**	**5,126**	**13,196**	**2,574**
Fejér	**6,064**	**14,288**	**2,356**	**8,383**	**20,062**	**2,393**
Komárom-Esztergom	**2,512**	**6,946**	**2,765**	**4,111**	**10,958**	**2,666**
Pest	4,357	9,898	2,272	8,437	19,064	2,260
Nógrád	1,002	1,858	1,854	1,386	2,609	1,882
Csongrád	**5,515**	**13,179**	**2,389**	**10,701**	**25,564**	**2,389**
Tolna	3,991	8,102	2,030	5,509	11,166	2,027
Hajdú-Bihar	**5,862**	**13,810**	**2,356**	**12,929**	**29,983**	**2,319**
Jász-Nagykun-Szolnok	8,855	20,405	2,304	12,517	28,654	2,289
Szabolcs-Szatmár-Bereg	**6,217**	**14,851**	**2,389**	**8,916**	**20,883**	**2,342**
Heves	859	1,576	1,836	2,683	5,136	1,914
Borsod-Abaúj-Zemplén	2,883	5,800	2,012	5,938	11,746	1,978
Bács-Kiskun	12,542	28,887	2,303	16,899	38,505	2,278
Békés	8,408	19,113	2,273	13,429	30,443	2,267
Hungary	**93,548**	**223,479**	**2,389**	**155,229**	**371,341**	**2,392**

A closer look at the regional breakdown of technical capacity potentials and corresponding average full load hours shown in Figure 15 reveals that ten regions within Hungary can be classified as very good concerning wind site qualities. As discussed above, that top-ten list includes the regions Győr-Moson-Sopron, Veszprém, followed by Vas, Zala, Fejér, Komárom-Esztergom, Csongrád, Szabolcs-Szatmár-Bereg, Somogy and Hajdú-Bihar. Common among all these regions is that achievable full load hours of wind sites within are on average (well) above 2,350 hours per year. The technical potential for wind power development of all ten best regions sums up to 128.7 GW or 324.1 TWh, respectively, cf. Table 22. If we now apply further land use constraints and thereby assume a least-cost allocation for the whole of Hungary, then this would limit the technical potential to a bit more than a third, i.e., 47.4 GW or 121.2 TWh, respectively. However, even the smaller number in terms of generation potential is more than twice as high as the electricity consumption of the whole of Hungary at present (i.e., 49 TWh in 2021). Focussing on these areas may allow to better tackle one key barrier to an enhanced wind power uptake: the necessary grid expansion. Apart from the current hurdles in regulation, certain Hungarian stakeholders classify this as another barrier for a rapid up-take of this promising carbon-free energy carrier.

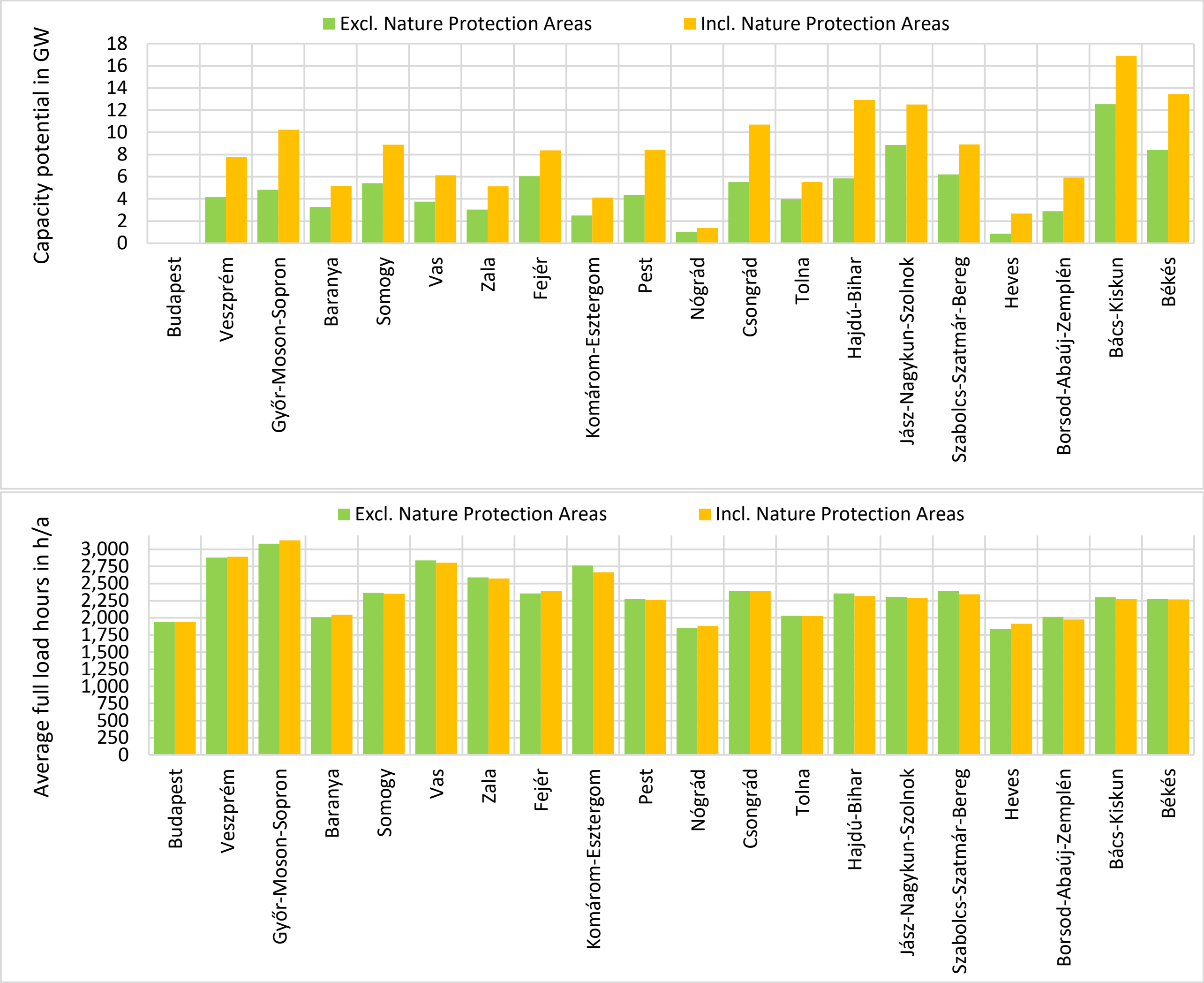


Figure 15: Breakdown of the technical potentials for wind power development in Hungary by NUTS-3 region, with consideration of further land use constraints for available areas (via a least-cost allocation) and by excluding or including nature protection areas. Expressed are capacity potentials (top) and average site qualities (full load hours) per region. Source: own analysis

Complementary to the above, Table 14 provides further insights on the distribution of the region-specific technical potentials among wind site classes, expressed by the respective range of full load hours. This is done under consideration of land use constraints, assuming again a least-cost allocation as well as by excluding nature protection areas.

Table 14: Breakdown by wind site class (i.e., full load hour ranges) of the region-specific technical potentials for wind power development in Hungary, expressed in capacity terms (MW), with consideration of land use constraints (least-cost allocation) and with exclusion of nature protection areas. Source: own analysis.

	Technical potential with land use constraints (least-cost) in capacity terms (in MW) in total (left column) and by wind site class, expressed by the range of respective full load hours (all other columns)										
Region	**all wind classes [MW]**	**flh 1600-1850 [MW]**	**flh 1850-2100 [MW]**	**flh 2100-2300 [MW]**	**flh 2300-2500 [MW]**	**flh 2500-2700 [MW]**	**flh 2700-2900 [MW]**	**flh 2900-3100 [MW]**	**flh 3100-3300 [MW]**	**flh3300-3500 [MW]**	**flh 3500-3800 [MW]**
Budapest	20	2	15	1	2	0	0	0	0	0	0
Veszprém	**4,152**	**0**	**68**	**170**	**12**	**708**	**1,183**	**1,174**	**385**	**364**	**86**
Győr-Moson-Sopron	**4,824**	**0**	**0**	**0**	**0**	**20**	**1,173**	**717**	**2,688**	**226**	**0**
Baranya	3,277	930	1,327	604	407	8	0	0	0	0	0
Somogy	**5,413**	**12**	**421**	**989**	**2,950**	**1,042**	**0**	**0**	**0**	**0**	**0**
Vas	**3,768**	**2**	**24**	**165**	**262**	**477**	**1,013**	**1,271**	**555**	**0**	**0**
Zala	**3,028**	**0**	**32**	**192**	**424**	**1,741**	**638**	**0**	**0**	**0**	**0**
Fejér	**6,064**	**0**	**194**	**2,633**	**2,114**	**653**	**330**	**119**	**21**	**0**	**0**
Komárom-Esztergom	**2,512**	**0**	**1**	**2**	**261**	**460**	**1,254**	**423**	**103**	**8**	**0**
Pest	4,357	84	681	1,190	2,199	203	0	0	0	0	0
Nógrád	1,002	547	283	172	0	0	0	0	0	0	0
Csongrád	**5,515**	**0**	**0**	**106**	**5,409**	**0**	**0**	**0**	**0**	**0**	**0**
Tolna	3,991	482	2,219	1,098	191	0	0	0	0	0	0
Hajdú-Bihar	**5,862**	**1**	**146**	**963**	**4,188**	**564**	**0**	**0**	**0**	**0**	**0**
Jász-Nagykun-Szolnok	8,855	16	501	2,245	6,094	0	0	0	0	0	0
Szabolcs-Szatmár-Bereg	**6,217**	**21**	**276**	**1,266**	**2,850**	**1,804**	**0**	**0**	**0**	**0**	**0**
Heves	859	476	253	129	0	0	0	0	0	0	0
Borsod-Abaúj-Zemplén	2,883	791	1,318	84	689	0	0	0	0	0	0
Bács-Kiskun	12,542	347	1,393	3,425	6,672	705	0	0	0	0	0
Békés	8,408	0	324	4,152	3,933	0	0	0	0	0	0
Hungary	**93,548**	**3,712**	**9,476**	**19,585**	**38,658**	**8,387**	**5,590**	**3,704**	**3,751**	**599**	**86**

4.1.3 Mapping with the grid infrastructure

A mapping exercise is finally conducted to indicate how identified promising areas for onshore wind power development match with the transmission grid infrastructure. We consequently add to the dataset an indicator that shows the average distance to the next grid node for feasible wind development areas, on average by region as well as on average for each available wind site class within a region, cf. Table 15. Thus, on average wind farms in Hungary are 26 km distant to the next grid node, with variations among individual sites but with comparatively small differences by wind site class.

Table 15: Average distance to the next transmission grid node of region-specific feasible wind development areas in Hungary, considering the technical potentials with land use constraints (least-cost allocation) and with exclusion of nature protection areas, expressed on average by region (left column) as well as by wind site class (all other columns). Source: own analysis.

Average distance of individual pixels to the next grid node (in km) on average (left column) and by wind site class, expressed by the range of respective full load hours (all other columns)

Region	all wind classes [km]	flh 1600-1850 [km]	flh 1850-2100 [km]	flh 2100-2300 [km]	flh 2300-2500 [km]	flh 2500-2700 [km]	flh 2700-2900 [km]	flh 2900-3100 [km]	flh 3100-3300 [km]	flh 3300-3500 [km]	flh 3500-3800 [km]
Budapest	7	4	8	4	3	0	0	0	0	0	0
Veszprém	**34**	**0**	**10**	**13**	**18**	**32**	**39**	**41**	**36**	**24**	**20**
Győr-Moson-Sopron	**29**	**0**	**0**	**0**	**0**	**35**	**25**	**26**	**32**	**38**	**0**
Baranya	26	25	27	26	25	25	0	0	0	0	0
Somogy	**31**	**28**	**26**	**30**	**31**	**32**	**0**	**0**	**0**	**0**	**0**
Vas	**22**	**39**	**33**	**17**	**15**	**15**	**23**	**22**	**32**	**0**	**0**
Zala	**34**	**0**	**53**	**51**	**43**	**31**	**28**	**0**	**0**	**0**	**0**
Fejér	**19**	**0**	**28**	**23**	**12**	**13**	**16**	**22**	**24**	**0**	**0**
Komárom-Esztergom	**18**	**23**	**23**	**13**	**13**	**15**	**19**	**20**	**27**	**26**	**0**
Pest	15	19	17	14	15	26	0	0	0	0	0
Nógrád	32	33	30	30	0	0	0	0	0	0	0
Csongrád	**27**	**0**	**0**	**22**	**27**	**0**	**0**	**0**	**0**	**0**	**0**
Tolna	29	20	30	31	29	0	0	0	0	0	0
Hajdú-Bihar	**28**	**13**	**20**	**36**	**27**	**15**	**0**	**0**	**0**	**0**	**0**
Jász-Nagykun-Szolnok	33	19	30	35	33	0	0	0	0	0	0
Szabolcs-Szatmár-Bereg	**23**	**10**	**13**	**31**	**19**	**26**	**0**	**0**	**0**	**0**	**0**
Heves	27	25	27	35	0	0	0	0	0	0	0
Borsod-Abaúj-Zemplén	20	17	22	26	20	0	0	0	0	0	0
Bács-Kiskun	42	18	38	45	43	34	0	0	0	0	0
Békés	27	0	28	26	28	0	0	0	0	0	0
Hungary	**26**	**21**	**26**	**27**	**24**	**25**	**25**	**26**	**30**	**29**	**20**

4.2 Sensitivity analysis: the impact of current legislation on the feasible wind potential

This section is dedicated to shed light on some key aspects concerning the possible future wind power uptake in Hungary: the impact of current legislation on the feasible wind power potential. More precisely, sensitivity analyses are performed on two key parameters affecting the applicable wind power potential in the country, namely distance rules (from the built environment) and details on the applied wind turbine design (i.e., hub height and/or rotor area in relation to generator size). For Hungary these aspects, i.e., restrictive distance rules and restrictions on the size of wind turbines, are of key relevance since both are barriers for an (enhanced) uptake of wind power at present.

4.2.1 The impact of current restrictive distance rules to the built environment

In our GIS modelling, built-up areas (incl. artificial surfaces like urban fabrics, industrial or commercial units, port areas, airports, construction sites, green urban areas, sport and leisure facilities) and infrastructure areas (incl. road and rail networks and associated land, mineral extraction sites, dump sites) are generally excluded from being a feasible area for wind power development. For the built-up areas a buffering of 1200 m is applied as default, respecting that wind power development should not harm the local community via noise or shading, etc. As part of this sensitivity analysis that reflects current (as of September 2023) legislative constraints, we also assess the impact of requiring larger distances to the built environment, ranging from 2400 m up to 12 km (current legislation).

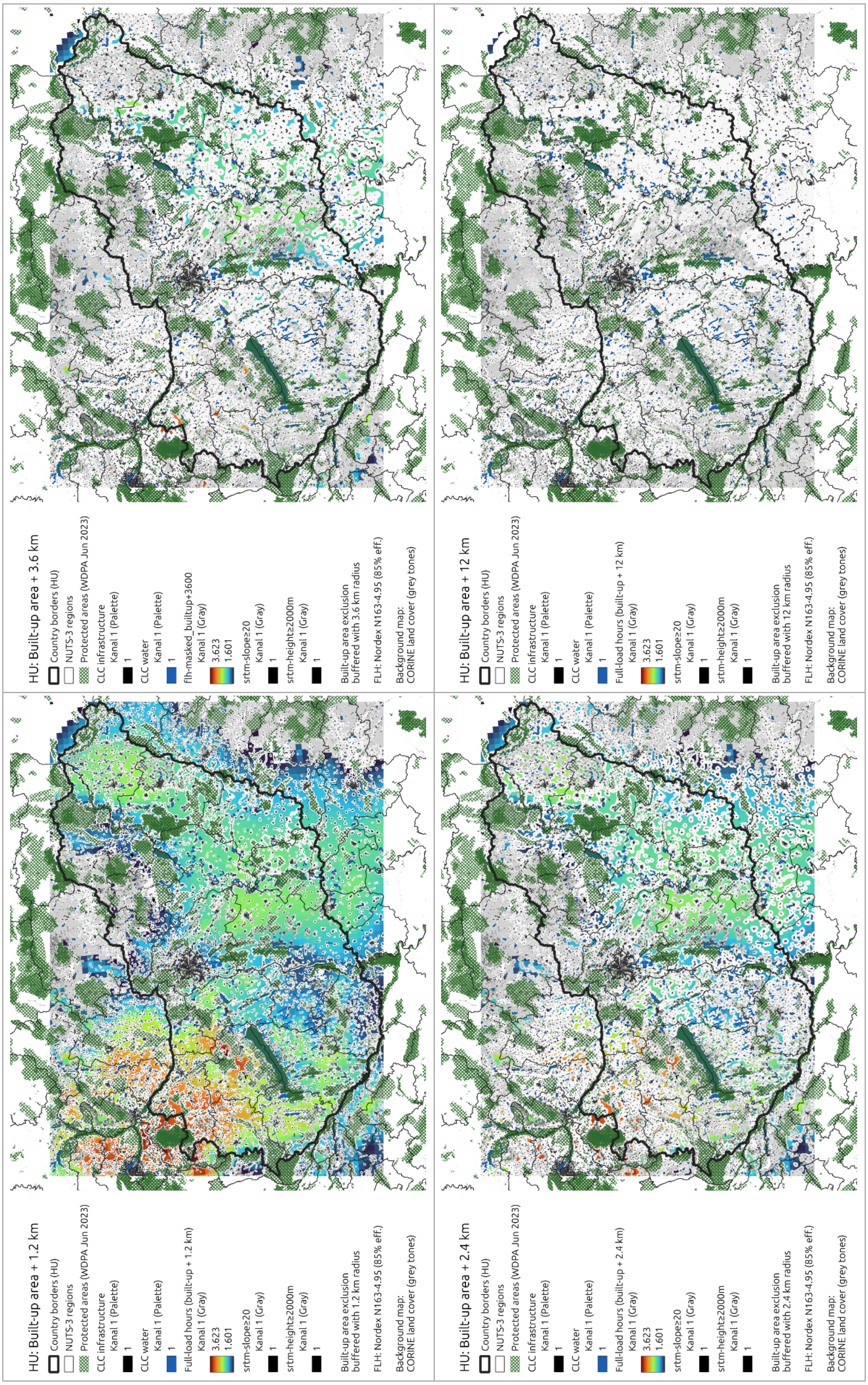


Figure 16: Wind maps for Hungary in dependence of the applied distance rules (to the built environment), indicating site qualities (expressed in full load hours) for feasible areas (excl. nature protection areas). Source: own analysis

Table 16: Sensitivity analysis on the technical potentials for onshore wind power development in Hungary in dependence of the applied distance rules (to the built environment), w/o (left) and with further land use constraints at feasible areas (via a least-cost allocation) (right), expressed in area, capacity and energy terms. Source: own analysis

Sensitivity analysis on the impact of distance rules	**Area potential**	**Technical potential w/o land use constraints**			**Technical potential with land use constraints (Least-Cost)**		
Distance (to built environment)	total usable area [ha]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]
1200 m (default)	3,032,574	279,008	650,883	2,333	93,548	223,479	2,389
2400 m	1,235,141	113,637	264,987	2,332	37,658	88,846	2,359
3600 m	388,945	35,784	83,662	2,338	11,918	28,012	2,350
4800 m	103,721	9,543	22,395	2,347	3,109	7,316	2,353
12000 m (current legislation)	0	0	0	n.a.	0	0	n.a.

The impact of applying more or less restrictive distance rules to the built environment on the feasible wind power potential in Hungary is illustrated in Figure 16. The four wind maps included in this depiction provide a graphical illustration of areas suitable for wind power development under varying distance rules. For each map the applied colour code marks the wind site qualities for feasible wind power development areas, expressed via on average achievable full load hours, using the underlying state-of-the-art onshore wind power turbine (cf. section 2.1.2). Complementary to the graphical illustration, Table 16 summarises the outcomes of the conducted sensitivity analysis on the impact of the applied distance rules. More precisely, this table lists the identified area, capacity and energy potentials in dependence of the underlying distance rule, ranging from 1.2 km (default assumption) to 12 km (current legislation). As default, we thereby list the technical potentials without (left columns) and with further land use constraints (right columns).

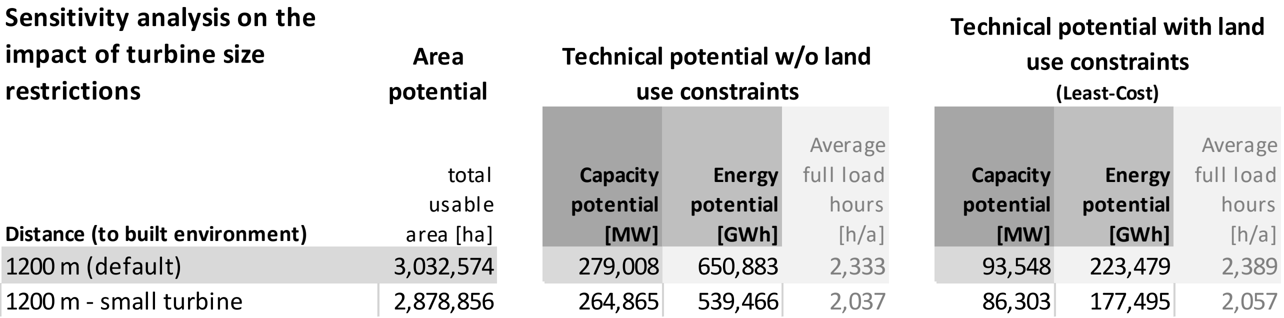
Remarkably, considering the current (as of September 2023) legislative practice, no wind power plant can be developed within Hungary. Loosing that restriction to 4.8 km or 3.6 km would allow for a limited uptake of wind power in future, i.e., 9.5 GW or 35.7 GW considering the technical potentials w/o further land use constraints, respectively. At a distance of 2.4 km the technical potential increases further to 113.6 GW whereas our default assumption (1.2 km as distance rule) allows for 279 GW as technical wind capacity potential.

Thus, the analysis makes clear that the current legislative practice on distance rules is *the* major hurdle for any future wind power uptake in Hungary. In practical terms, the requested distance of 12 km to the built environment would not allow for any wind power development in the country.

4.2.2 The impact of current size limits for wind turbines

Below we show the impact of limiting the size of a wind turbine on the feasible technical potential. As default our onshore wind turbine is the Nordex N163, characterised by a hub height of 150 m and a rotor diameter of 163 m. That turbine is equipped with a 4.95 MW electric generator. Reflecting the current (as of September 2023) legislative constraint implies to make use of a smaller wind turbine, i.e., a Gamesa G90/2000 with a hub height of 100 m, a rotor diameter of 90 m, and a 2 MW electric generator. Similar to above, Table 17 summarises the outcomes of the conducted sensitivity analysis on the impact of the applied size limits. More precisely, this table lists the identified area, capacity and energy potentials in dependence of the underlying turbine design, indicating the technical potentials without (left columns) and with further land use constraints (right columns).

Table 17: Sensitivity analysis on the technical potentials for onshore wind power development in Hungary in dependence of the size limits of a wind turbine, w/o (left) and with further land use constraints at feasible areas (via a least-cost allocation) (right), expressed in area, capacity and energy terms. Source: own analysis



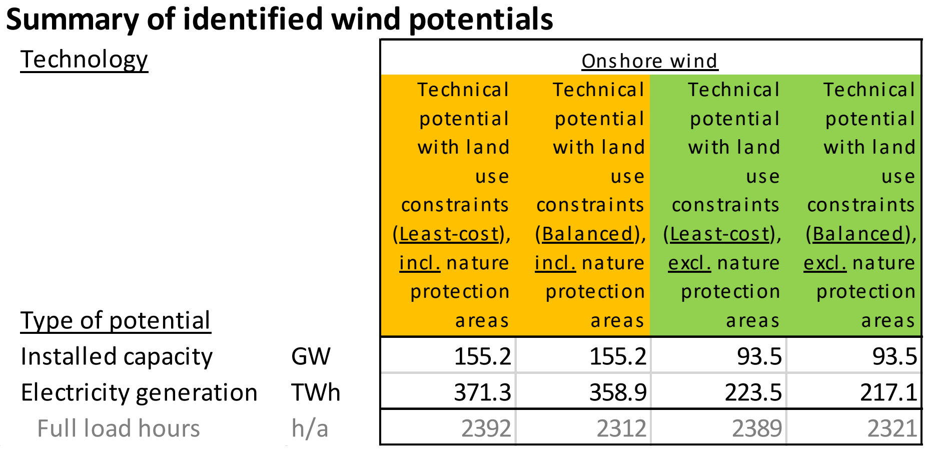
Sensitivity analysis on the impact of turbine size restrictions	**Area potential**	**Technical potential w/o land use constraints**			**Technical potential with land use constraints (Least-Cost)**		
Distance (to built environment)	total usable area [ha]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]
1200 m (default)	3,032,574	279,008	650,883	2,333	93,548	223,479	2,389
1200 m - small turbine	2,878,856	264,865	539,466	2,037	86,303	177,495	2,057

Apparently, the current size limit has a small impact on the capacity potential – i.e., considering the technical potential without further land use constraints the capacity potential declines from 279 to 265 GW. However, the size limit has more severe consequences on the economic feasibility of wind power development in Hungary. This is because the energy potential decreases more tremendously – i.e., from 651 to 539 TWh. This goes hand in hand with a decline of average full load hours – i.e., from 2,333 to 2,037 hours per year.

4.3 Brief summary of results & comparison with national energy planning

This section is dedicated to summarising the results of our GIS-based analysis of wind power development potentials in Hungary. To put them into perspective, we also undertake a comparison to the role of wind power in current energy planning. As starting point, Table 18 provides an overview on the identified technical potentials for wind power development in Hungary.

Table 18: Overview on identified technical potentials for wind power development in Hungary, with consideration of further land use constraints for available areas (via a least-cost or a balanced allocation) and by including (left) or excluding (right) nature protection areas. Source: own analysis.



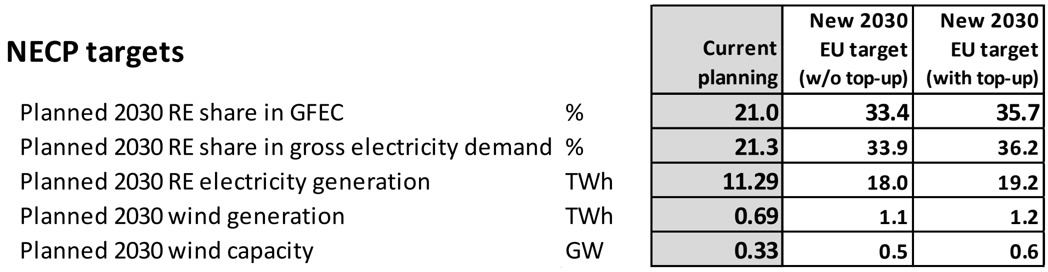
Summary of identified wind potentials

Technology		Onshore wind			
Type of potential		Technical potential with land use constraints (Least-cost), incl. nature protection areas	Technical potential with land use constraints (Balanced), incl. nature protection areas	Technical potential with land use constraints (Least-cost), excl. nature protection areas	Technical potential with land use constraints (Balanced), excl. nature protection areas
Installed capacity	GW	155.2	155.2	93.5	93.5
Electricity generation	TWh	371.3	358.9	223.5	217.1
Full load hours	h/a	2392	2312	2389	2321

Table 19 undertakes a comparison of 2030 deployment targets for wind power as well as renewables in general in Hungary. Here we show the planned renewable and wind power uptake according to current planning as indicated in the 2019 National Energy and Climate Plan (NECP) of Hungary (Republic of Hungary, 2019). Recently, all EU Member States agreed on a strengthening of the renewables ambition, given the urgency to combat climate change as well as to respond on the

Russian invasion of the Ukraine as well as the impact of that on Europe's gas, and, in consequence, also on electricity supply. To acknowledge that strengthening of the renewables ambition, all EU Member States, including Hungary, are currently revising their previous national energy planning. To indicate the implications on renewables in general as well as specifically on wind in energy planning, Table 19 contains deployment figures for both under the newly established EU framework on 2030 energy and climate targets. Note that these deployment figures for wind are purely indicative, derived by proportionally increasing wind in relation to the strengthened RES ambition.

Table 19: Comparison of 2030 deployment targets for wind power and renewables in general in Hungary according to current planning (left column) and under consideration of the newly established 2030 EU targets (all other columns). Sources: Republic of Hungary (2019) and own analysis.



NECP targets		Current planning	New 2030 EU target (w/o top-up)	New 2030 EU target (with top-up)
Planned 2030 RE share in GFEC	%	**21.0**	**33.4**	**35.7**
Planned 2030 RE share in gross electricity demand	%	**21.3**	**33.9**	**36.2**
Planned 2030 RE electricity generation	TWh	**11.29**	**18.0**	**19.2**
Planned 2030 wind generation	TWh	**0.69**	**1.1**	**1.2**
Planned 2030 wind capacity	GW	**0.33**	**0.5**	**0.6**

Finally, Figure 17 summarise all the above. More precisely, this graph shows the status quo of wind power development (as of 2021) and compares that with the 2030 deployment targets (both according to current planning and the possible implications on that from the strengthened RES ambition) as well as with the identified wind development potentials.

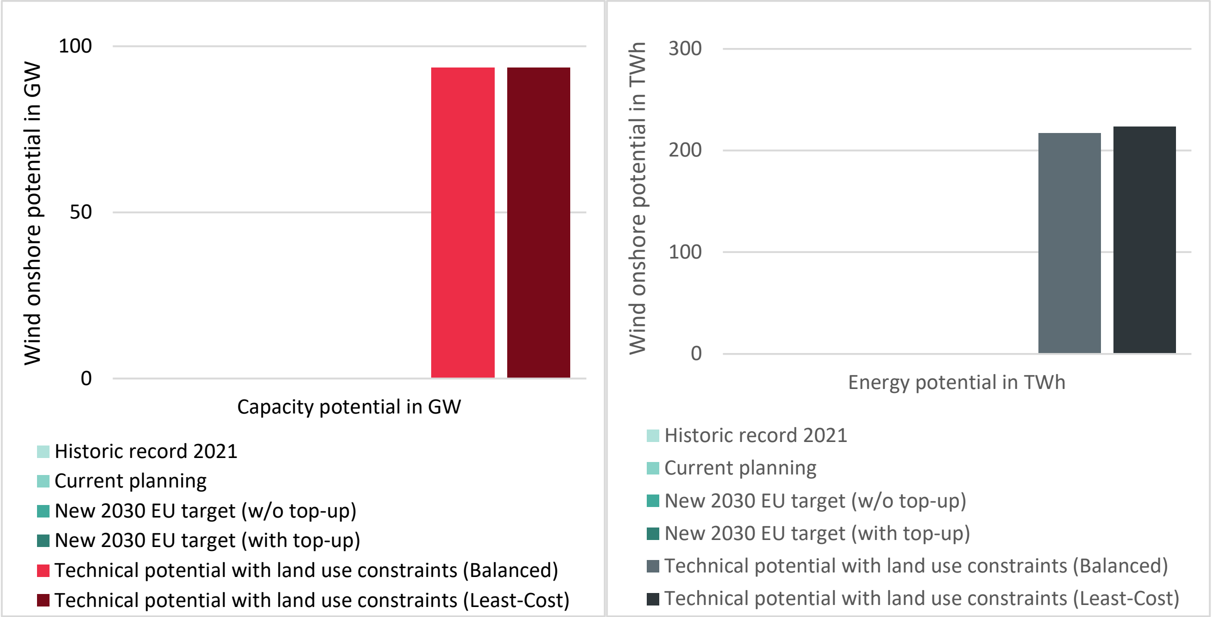


Figure 17: Wind energy at present and in future: Comparison of the status quo (2021), of 2030 deployment targets according to current planning (NECP) and under consideration of new 2030 EU targets as well as of identified technical potentials (with land use constraints). Sources: Eurostat (2023), Republic of Hungary (2019) and own analysis.

Apparently, we can conclude, considering the available wind resources in Hungary, there is sufficient room for enhancing the wind uptake in future years. At present, considering the 2019 NECP of Hungary (Republic of Hungary, 2019), there is no uptake of wind power planned at all. Within the subsequent economic analysis (cf. Chapter 7), the assumption was taken that the installed wind capacity may reach at least 1 GW by 2030 (according to the "low wind penetration" scenario). Hungary has, considering nature protection and land use constraints, a technical wind potential in the order of 93.5 GW – including some of the best wind sites in Central Europe. Thus, given the resources at hands, wind power deserves to take a much more prominent role in future energy planning. A strong uptake of the wind ambition should however go hand in hand with a strengthening of the power grid infrastructure, both at transmission and, where affected, also at the distribution grid level.

4.4 Brief consideration of economics

As a teaser for Chapter 7 that indicates the electricity market impacts of an enhanced wind uptake in future years within Hungary as well as within the neighbouring countries Bulgaria and Romania, we conclude our resource analysis with a snapshot on the economics of wind power. At the example of onshore wind, Figure 18 depicts so-called cost-resource curves of wind onshore for all countries within our study region, including apart from Hungary also Bulgaria and Romania. These cost-resource curves show the potentials for wind onshore, using technical least-cost potentials with consideration of land use and nature protection constraints, broken down by wind site class (i.e., by full load hours) on the horizontal axes. Lines are derived by complementing the data on the resources with information on the corresponding Levelized Cost of Electricity (LCOE), using typical assumptions for cost and financial parameter as listed below.

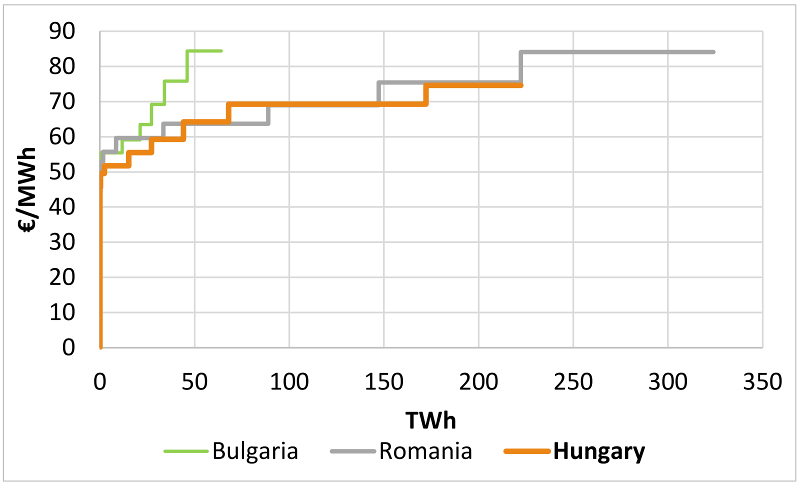


Figure 18: Cost-resource curves of wind onshore in the study region (using technical least-cost potentials with consideration of land use and nature protection constraints). Source: own analysis.

Note on the assumptions for LCOE calculation: Investment cost: 1,500 EUR/kW, O&M cost: 3% p.a. (of investment cost), Interest rate: 6.5%, Depreciation time: 20 years

The graph confirms the previous statement that Hungary offers promising wind sites at comparatively cheap cost, considering current prices on electricity wholesale markets. Wind power represents a carbon-free energy source and, consequently, could (and should) be used to meet large parts of the domestic electricity demand.

5 RESULTS OF THE GIS-BASED ANALYSIS OF WIND POTENTIALS IN ROMANIA

This chapter is dedicated to informing on the results of the GIS-based analysis of wind power potentials in Romania, comprising both wind development at the countryside (onshore) and in marine areas (offshore). Building on the approach described in the previous chapter, specifically section 5.1, we discuss subsequently the results related to onshore wind. Next to that results on offshore wind are presented briefly in section 5.2 (whereas Chapter 6 provides further insights on the underlying assessment). Finally, the study findings are put into a broader energy system context in section 5.3, illustrating the role wind may be able take in future electricity supply within Romania.

5.1 Onshore wind potentials

Looking at the topographical context as described in Wikipedia[7], Romania's natural landscape is almost evenly divided among mountains (31 percent), hills (33 percent), and plains (36 percent). In terms of size the country is the twelfth largest within Europe, covering an area of 238 thousand square km. The backbone of Romania is formed by the Carpathian Mountains, which reach elevations of more than 2,400 meters. The Carpathians extend over 1,000 km through the centre of the country, covering an area of 70,000 square km. These mountains are deeply fragmented by longitudinal and transverse valleys and crossed by several major rivers. Romania's lowest land is found on the northern edge of the Dobruja region in the Danube Delta. The delta is a triangular swampy area of marshes, floating reed islands, and sandbanks, where the Danube ends its trek of almost 3,000 km and divides into three frayed branches before emptying into the Black Sea.

5.1.1 Technical potentials at the national level

According to the GIS-based analysis conducted in this study, slightly less than a fourth of the country (i.e., 22.8% of the total area) appears suitable for onshore wind power development, considering constraints ranging from a techno-economic, a societal and a nature conservation perspective (i.e., by excluding nature protection areas) as described in section 2.1.2. If all identified sites being classified as feasible would actually be used for wind power development, an enormous technical potential for wind power occurs: Thus, as listed in Table 20, the country area suitable for wind power development comprises 54 thousand square km, corresponding to a capacity potential of 499 GW. That would allow to generate electricity in size of 1,047 TWh per year, reflecting average meteorological conditions. To put that into a perspective, Romania's gross electricity consumption amounted to 61 TWh in 2021. From a technical potential, Romania could generate more than seventeen times more electricity from onshore wind power than currently consumed. Apart from other barriers, a limiting factor to that is however the power grid infrastructure which is far from being ready to absorb these enormous amounts of electricity.

If one classifies nature protection areas as being suitable for wind power development, the technical potential increases further on, cf. Table 20: The area potential would then grow up to 85 thousand

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[7] Cf. https://en.wikipedia.org/wiki/Romania#Geography_and_climate and https://en.wikipedia.org/wiki/Topography_of_Romania.

square km, corresponding to a capacity potential of 784 GW and a yearly electricity generation of 1,680 TWh.

Table 20: Technical potentials for onshore wind power development in Romania, neglecting land use constraints (at feasible areas), expressed in area, capacity and energy terms. Source: own analysis.

	Area potential	**Technical potential w/o land use constraints**		
Scenario	total usable area [ha]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]
Excl. Nature Protection Areas	**5,421,656**	**498,812**	**1,047,422**	**2,100**
Incl. Nature Protection Areas	**8,524,566**	**784,291**	**1,679,550**	**2,141**

If we limit the wind power development by applying further land use restrictions on those areas classified as being feasible for wind power development, we still end up with significant potentials for onshore wind development in Romania as shown in Table 21. Doing so may maintain social acceptance of wind power in general, and it may also allow for a more rapid uptake in future years – once other barriers are removed. As discussed in section 2.1.1, two different variants are assessed:

- Balanced allocation: Balanced allocation of wind sites by using average suitability factors for agricultural (40%) and forestry areas (10%).
- Least-cost allocation: Preference to best sites within Romania, implying higher suitability factors as shown in Table 1 and, in turn, lower ones for less windy areas within the country.

According to Table 21, the identified technical potential for onshore wind in Romania, with consideration of (further) land use restrictions, amounts to ca. 166.5 GW – about one third of the unconstrained technical potential. The corresponding yearly electricity generation varies among both allocation options: following a balanced approach implies a yearly electricity generation in size of 355 TWh whereas the adoption of a least-cost allocation within each region increases the generation potential up to 364 TWh.

Table 21: Technical potentials for onshore wind power development in Romania, with (further) land use constraints (at feasible areas), expressed in capacity and energy terms for assessed allocation options (least-cost vs balanced). Source: own analysis.

	Technical potential with land use constraints (Least-Cost)			**Technical potential with land use constraints (Balanced)**		
Scenario	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]
Excl. Nature Protection Areas	**166,463**	**364,098**	**2,187**	**166,764**	**354,734**	**2,127**
Incl. Nature Protection Areas	**240,019**	**538,079**	**2,242**	**234,196**	**506,369**	**2,162**

A graphical illustration of the identified onshore wind development potentials in Romania is provided by Figure 19. From this graph the large differences between the technical potentials where all areas classified as suitable for wind power development (i.e., without land use constraints) would be used versus the smaller technical potentials derived by consideration of further land use restrictions. Thus, if only 40% of agricultural areas and 10% of forestry areas (not classified as nature protection areas) would be used, the technical potentials are reduced to about one third of the unconstrained one.

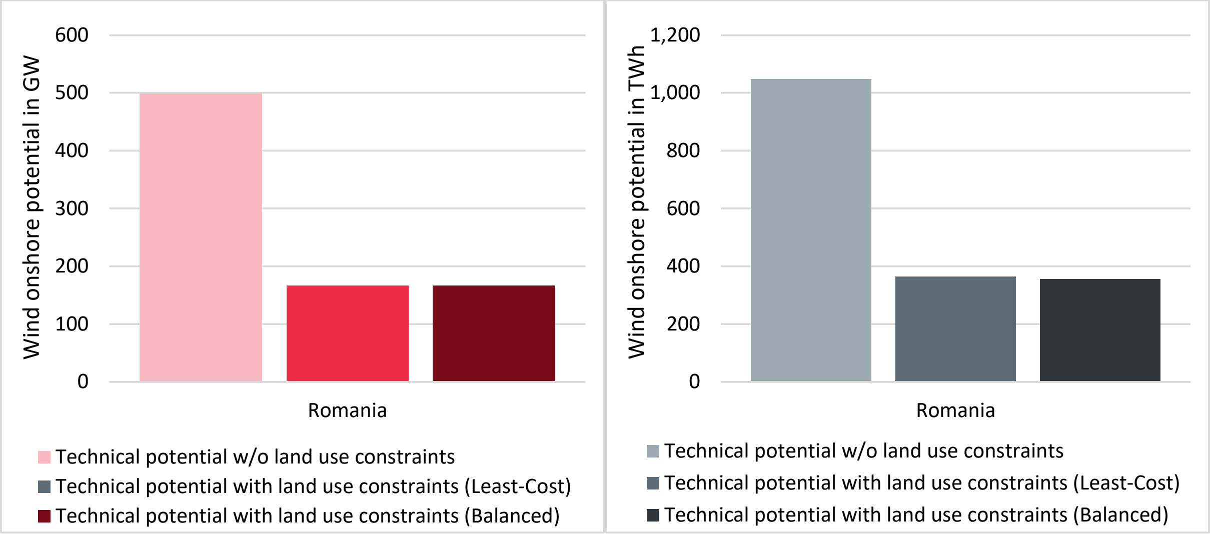
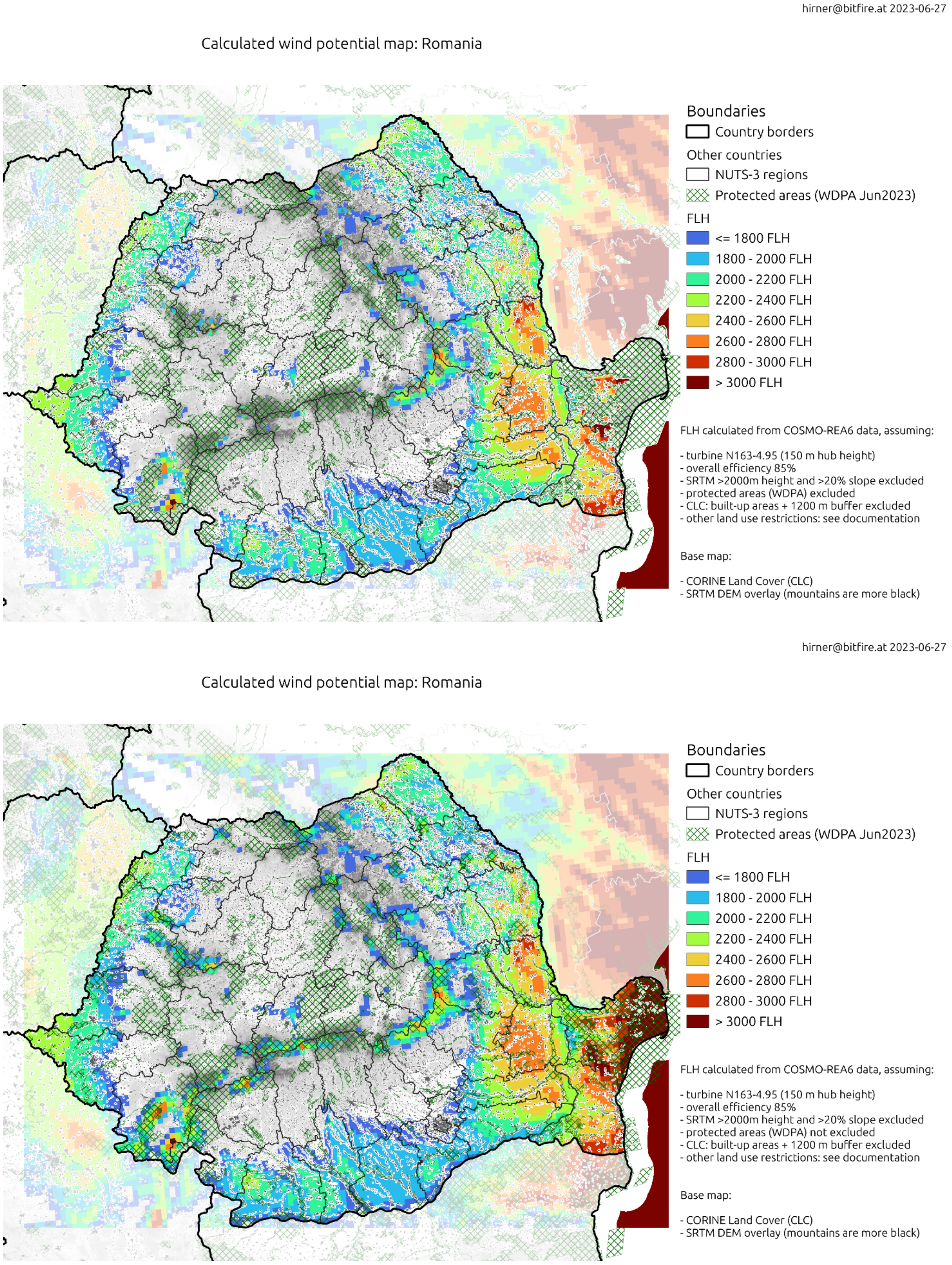


Figure 19: Technical potentials for onshore wind in Romania, w/o and with (further) land use constraints (at feasible areas), expressed in capacity (left) and energy terms (right) for assessed allocation options (least-cost vs balanced). Source: own analysis.

5.1.2 Technical potentials at the regional level

In accordance with the above, we now undertake a deep dive into the regions within Romania, presenting the outcomes of our GIS-based analysis of the onshore wind potentials at a regional level. In practical terms, we thereby follow the standardised NUTS-3 classification for the European Union and consequently undertake a breakdown of the results for the whole of Romania by region. In the case of Romania this implies to distinguish between 42 regions as applicable in the subsequent graphs and tables.

In this context, Figure 20 provides a graphical illustration of areas suitable for wind power development within Romania. More precisely, this figure shows wind maps for Romania, indicating for wind power development areas via a colour code that informs on corresponding wind site qualities, expressed via on average achievable full load hours, using the underlying state-of-the-art onshore wind power turbine (cf. section 2.1.2). This figure contains two graphs, the upper one shows the wind map excluding nature protection areas whereas to one at the bottom informs also on wind site qualities for those parts within nature protection areas. As applicable from these depictions, some of the best wind sites can be found in the eastern part of Romania, specifically where the Danube ends in the Black sea. Large parts of the region Tulcea but also of Constanţa are classified as nature protection areas which consequently reduces the wind power development potential there, supposing that those areas are not classified as suitable for wind power development. Despite of these constraints, the technical potential for wind power development is significant: these two regions alone have space for 33.8 GW of wind power, corresponding to a yearly electricity generation of 88.4 TWh – by far more than Romania consumes at present. There are however more regions within Romania that do offer promising wind conditions. If we expand the list to the five best regions within the country, in addition to Tulcea and Constanţa also Brăila, Galaţi and Ialomiţa have to be named. The technical potential for wind power sums then up to 98.9 GW or 249.2 TWh, respectively. Achievable full load hours of wind sites within these regions are on average (well) above 2,350 hours per year – this characterises also from a European perspective comparatively (very) good wind development areas.


hirner@bitfire.at 2023-06-27

Calculated wind potential map: Romania

FLH calculated from COSMO-REA6 data, assuming:

- turbine N163-4.95 (150 m hub height)
- overall efficiency 85%
- SRTM >2000m height and >20% slope excluded
- protected areas (WDPA) excluded
- CLC: built-up areas + 1200 m buffer excluded
- other land use restrictions: see documentation

Base map:

- CORINE Land Cover (CLC)
- SRTM DEM overlay (mountains are more black)

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Calculated wind potential map: Romania

FLH calculated from COSMO-REA6 data, assuming:

- turbine N163-4.95 (150 m hub height)
- overall efficiency 85%
- SRTM >2000m height and >20% slope excluded
- protected areas (WDPA) not excluded
- CLC: built-up areas + 1200 m buffer excluded
- other land use restrictions: see documentation

Base map:

- CORINE Land Cover (CLC)
- SRTM DEM overlay (mountains are more black)

Figure 20: Wind maps for Romania, indicating site qualities (expressed in full load hours) and by excluding (top) vs including (bottom) nature protection areas. Source: own analysis.

The technical details on wind potentials and average site qualities per region as discussed above are listed in Table 22 below. This table offers a breakdown of the technical potentials for wind power development in Romania by NUTS-3 region, without consideration of further land use constraints for available areas and by excluding (left) or including (right) nature protection areas.

Table 22: Breakdown of the technical potentials for wind power development in Romania by NUTS-3 region, without consideration of further land use constraints for available areas and by excluding (left) or including (right) nature protection areas. Source: own analysis.

	Excl. Nature Protection Areas				**Incl. Nature Protection Areas**			
	Area potential	**Technical potential w/o land use constraints**			**Area potential**	**Technical potential w/o land use constraints**		
Region	total usable area [ha]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]	total usable area [ha]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]
Braşov	33,558	3,087	5,722	1,853	63,521	5,844	11,097	1,899
Timiş	303,916	27,961	57,171	2,045	394,463	36,292	74,960	2,065
Teleorman	328,030	30,180	57,014	1,889	374,592	34,464	64,755	1,879
Covasna	37,215	3,424	6,825	1,993	60,925	5,605	10,975	1,958
Vaslui	195,981	18,031	39,968	2,217	256,567	23,605	52,660	2,231
Brăila	**245,113**	**22,551**	**57,128**	**2,533**	**344,818**	**31,725**	**80,386**	**2,534**
Prahova	57,449	5,286	10,491	1,985	80,258	7,384	14,902	2,018
Bucureşti	10	1	2	1,750	10	1	2	1,750
Arad	195,416	17,979	35,329	1,965	291,782	26,845	52,417	1,953
Caraş-Severin	171,006	15,733	31,854	2,025	374,827	34,485	71,351	2,069
Hunedoara	15,388	1,416	2,596	1,833	49,930	4,594	8,538	1,859
Sălaj	72,099	6,633	11,763	1,773	86,274	7,938	14,372	1,811
Gorj	645	59	105	1,772	58,697	5,400	11,080	2,052
Harghita	36,474	3,356	5,922	1,765	100,176	9,217	16,376	1,777
Neamţ	112,065	10,310	19,529	1,894	158,145	14,550	27,556	1,894
Maramureş	18,169	1,672	3,149	1,884	62,049	5,709	10,704	1,875
Satu Mare	146,267	13,457	27,666	2,056	179,994	16,560	34,205	2,066
Suceava	199,457	18,351	34,306	1,869	270,597	24,896	47,017	1,889
Ilfov	31,354	2,885	5,050	1,751	35,299	3,248	5,671	1,746
Dolj	305,296	28,088	55,327	1,970	433,222	39,858	77,070	1,934
Alba	11,173	1,028	1,867	1,816	33,130	3,048	5,576	1,829
Buzău	256,048	23,557	51,709	2,195	322,801	29,699	65,396	2,202
Constanţa	**287,225**	**26,426**	**69,310**	**2,623**	**487,218**	**44,826**	**116,338**	**2,595**
Cluj	16,770	1,543	2,916	1,890	66,038	6,076	11,573	1,905
Galaţi	**228,953**	**21,065**	**52,911**	**2,512**	**286,535**	**26,362**	**65,314**	**2,478**
Tulcea	**80,143**	**7,373**	**19,096**	**2,590**	**639,393**	**58,826**	**168,664**	**2,867**
Iaşi	149,156	13,723	27,190	1,981	235,163	21,636	43,212	1,997
Bihor	146,558	13,484	27,054	2,006	295,876	27,222	54,817	2,014
Vrancea	195,122	17,952	37,683	2,099	301,002	27,693	57,175	2,065
Giurgiu	156,883	14,434	27,002	1,871	212,822	19,580	36,278	1,853
Argeş	80,650	7,420	13,268	1,788	103,249	9,499	17,254	1,816
Bacău	188,814	17,372	33,782	1,945	235,834	21,698	42,069	1,939
Ialomiţa	**233,262**	**21,461**	**50,785**	**2,366**	**314,273**	**28,914**	**67,866**	**2,347**
Mureş	32	3	5	1,676	30,262	2,784	5,031	1,807
Sibiu	29,591	2,722	4,838	1,777	99,739	9,176	16,863	1,838
Olt	230,813	21,236	40,648	1,914	279,655	25,729	48,697	1,893
Mehedinţi	90,956	8,368	16,585	1,982	193,719	17,823	34,693	1,947
Vâlcea	10,627	978	1,784	1,825	47,805	4,398	8,657	1,968
Botoşani	199,402	18,346	38,384	2,092	252,065	23,191	48,525	2,092
Bistriţa-Năsăud	106	10	16	1,624	10,904	1,003	1,728	1,722
Călăraşi	305,993	28,152	60,761	2,158	373,176	34,334	73,096	2,129
Dâmboviţa	18,471	1,699	2,911	1,713	27,761	2,554	4,634	1,814
Romania	**5,421,656**	**498,812**	**1,047,422**	**2,100**	**8,524,566**	**784,291**	**1,679,550**	**2,141**

As state above, if we limit the wind power development by applying further land use restrictions on those areas classified as being feasible for wind power development, we still end up with significant potentials for onshore wind development in Romania. This is shown in Table 21 at the country level and in Table 23 at a regional level, following a least-cost allocation by giving preference to best sites within Romania. A graphical illustration of the numbers listed in Table 23 is given by Figure 21, indicating the capacity potentials (top) and the corresponding average full load hours per region, again by including or excluding nature protection areas.

Table 23: Breakdown of the technical potentials for wind power development in Romania by NUTS-3 region, with consideration of further land use constraints for available areas (via a least-cost allocation) and by excluding (left) or including (right) nature protection areas. Source: own analysis.

	Excl. Nature Protection Areas			**Incl. Nature Protection Areas**		
	Technical potential with land use constraints (Least-Cost)			**Technical potential with land use constraints (Least-Cost)**		
Region	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]	**Capacity potential [MW]**	**Energy potential [GWh]**	Average full load hours [h/a]
Braşov	367	690	1,883	701	1,358	1,939
Timiş	10,112	21,023	2,079	13,242	27,792	2,099
Teleorman	10,125	19,166	1,893	11,215	21,157	1,886
Covasna	363	743	2,047	581	1,167	2,010
Vaslui	6,612	14,803	2,239	8,541	19,196	2,247
Brăila	**11,142**	**28,384**	**2,547**	**14,791**	**37,724**	**2,550**
Prahova	709	1,403	1,979	1,038	2,087	2,011
Bucureşti	0	0	1,750	0	0	1,750
Arad	5,709	11,482	2,011	8,404	16,733	1,991
Caraş-Severin	3,075	6,247	2,032	5,713	11,904	2,084
Hunedoara	149	274	1,846	449	851	1,894
Sălaj	1,491	2,649	1,776	1,707	3,086	1,808
Gorj	5	10	1,810	612	1,305	2,132
Harghita	298	526	1,767	838	1,496	1,785
Neamţ	2,112	4,164	1,972	2,793	5,507	1,972
Maramureş	229	434	1,895	626	1,191	1,904
Satu Mare	4,249	8,817	2,075	5,296	11,052	2,087
Suceava	3,158	6,170	1,954	4,184	8,236	1,969
Ilfov	784	1,374	1,753	835	1,461	1,751
Dolj	9,559	18,981	1,986	12,526	24,532	1,959
Alba	132	239	1,816	357	653	1,829
Buzău	7,882	17,863	2,266	9,494	21,579	2,273
Constanţa	**13,698**	**36,309**	**2,651**	**21,048**	**55,253**	**2,625**
Cluj	211	397	1,880	701	1,350	1,926
Galaţi	**9,840**	**24,878**	**2,528**	**11,864**	**29,631**	**2,498**
Tulcea	**3,703**	**9,792**	**2,644**	**22,870**	**66,221**	**2,896**
Iaşi	4,210	8,342	1,982	6,093	12,125	1,990
Bihor	3,950	8,034	2,034	7,214	14,817	2,054
Vrancea	4,915	10,769	2,191	6,376	13,785	2,162
Giurgiu	4,429	8,334	1,882	5,645	10,546	1,868
Argeş	2,135	3,837	1,797	2,387	4,318	1,809
Bacău	3,153	6,353	2,015	3,791	7,576	1,998
Ialomiţa	**9,685**	**23,222**	**2,398**	**12,347**	**29,440**	**2,384**
Mureş	0	0	1,676	228	415	1,822
Sibiu	627	1,105	1,763	1,497	2,710	1,810
Olt	6,952	13,391	1,926	8,006	15,298	1,911
Mehedinţi	2,604	5,164	1,983	4,383	8,598	1,962
Vâlcea	96	177	1,837	489	992	2,027
Botoşani	6,478	13,590	2,098	7,714	16,191	2,099
Bistriţa-Năsăud	1	1	1,624	81	141	1,736
Călăraşi	11,074	24,205	2,186	12,785	27,623	2,161
Dâmboviţa	442	753	1,705	556	979	1,759
Romania	**166,463**	**364,098**	**2,187**	**240,019**	**538,079**	**2,242**

Complementary to the above, Table 24 provides further insights on the distribution of the region-specific technical potentials among wind site classes, expressed by the respective range of full load hours. This is done under consideration of land use constraints, assuming again a least-cost allocation as well as by excluding nature protection areas.

Table 24: Breakdown by wind site class (i.e., full load hour ranges) of the region-specific technical potentials for wind power development in Romania, expressed in capacity terms (MW), with consideration of land use constraints (least-cost allocation) and with exclusion of nature protection areas. Source: own analysis.

	Technical potential with land use constraints (least-cost) in capacity terms (in MW) in total (left column) and by wind site class, expressed by the range of respective full load hours (all other columns)								
Region	**all wind classes [MW]**	**flh 1600-1850 [MW]**	**flh 1850-2100 [MW]**	**flh 2100-2300 [MW]**	**flh 2300-2500 [MW]**	**flh 2500-2700 [MW]**	**flh 2700-2900 [MW]**	**flh 2900-3100 [MW]**	**flh 3100-3300 [MW]**
Braşov	367	218	54	65	22	8			
Timiş	10112	1686	2916	4023	1487				
Teleorman	10125	1791	8334						
Covasna	363	57	205	51	12	38			
Vaslui	6612	84	1140	3122	1661	548	57		
Brăila	**11142**		**51**	**1032**	**2319**	**6465**	**1275**		
Prahova	709	260	190	128	132				
Bucureşti	0	0							
Arad	5709	1325	1885	2499					
Caraş-Severin	3075	1263	699	453	210	398	1	51	
Hunedoara	149	91	34	24					
Sălaj	1491	1104	369	18					
Gorj	5	4		1					
Harghita	298	233	65						
Neamţ	2112	548	1077	455	32				
Maramureş	229	81	104	44					
Satu Mare	4249	159	1926	2001	163				
Suceava	3158	841	1603	656	58				
Ilfov	784	717	67						
Dolj	9559	1590	5418	2551					
Alba	132	80	9	39	3				
Buzău	7882	822	904	2120	2659	1365	13		
Constanţa	**13698**		**168**	**383**	**2818**	**4213**	**4318**	**1456**	**342**
Cluj	211	117	63	2	30				
Galaţi	**9840**		**52**	**1084**	**3339**	**2953**	**2306**	**106**	
Tulcea	**3703**	**14**	**197**	**293**	**743**	**602**	**966**	**692**	**196**
Iaşi	4210	805	2727	460	207	11			
Bihor	3950	516	1701	1690	43				
Vrancea	4915	489	902	1814	1190	469	51		
Giurgiu	4429	1757	2672						
Argeş	2135	1532	604						
Bacău	3153	790	929	1362	72				
Ialomiţa	**9685**	**227**	**976**	**1213**	**3543**	**3726**			
Mureş	0	0							
Sibiu	627	495	131						
Olt	6952	1779	4687	485					
Mehedinţi	2604	570	1494	446	19	48		26	
Vâlcea	96	56	32	5		2			
Botoşani	6478	51	3659	2476	292				
Bistriţa-Năsăud	1	1							
Călăraşi	11074	326	3745	3246	3249	508			
Dâmboviţa	442	436		5					
Romania	**166,463**	**22,917**	**51,786**	**34,247**	**24,301**	**21,355**	**8,989**	**2,330**	**538**

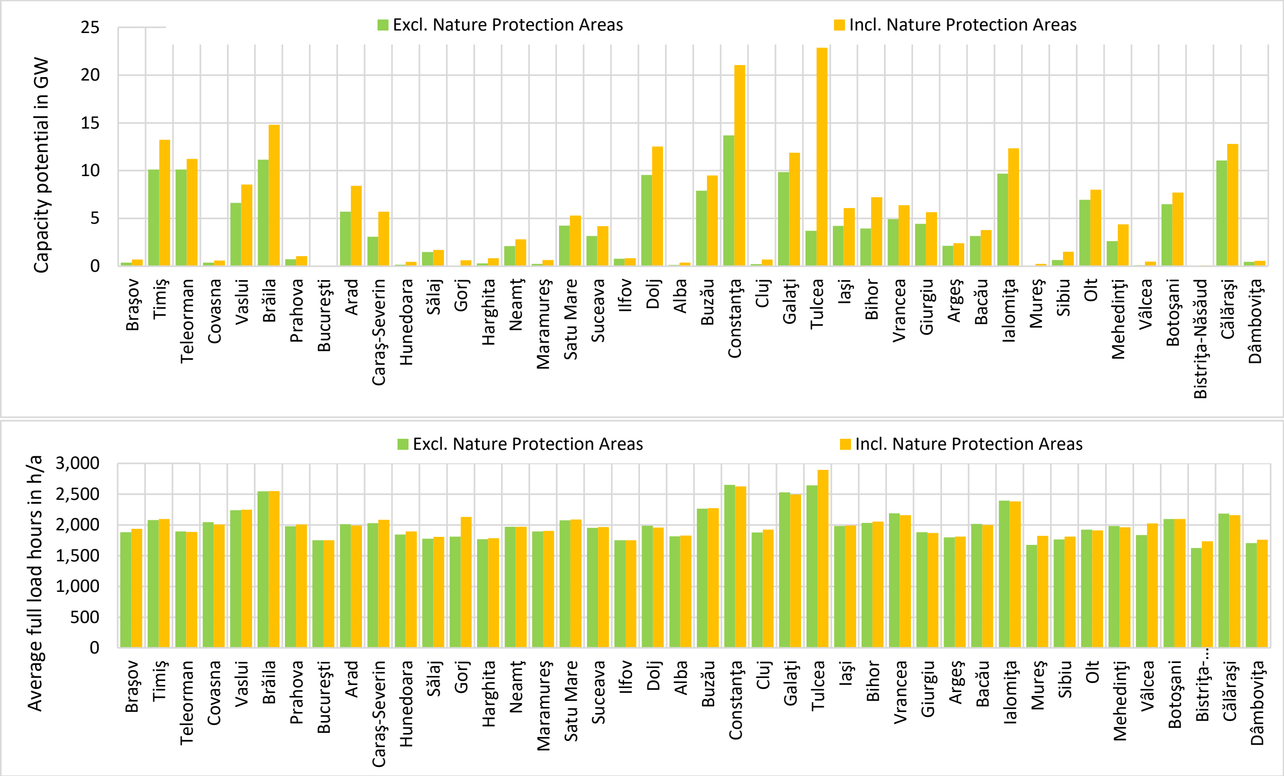


Figure 21: Breakdown of the technical potentials for wind power development in Romania by NUTS-3 region, with consideration of further land use constraints for available areas (via a least-cost allocation) and by excluding or including nature protection areas. Expressed are capacity potentials (top) and average site qualities (full load hours) per region. Source: own analysis

A closer look at the regional breakdown of technical capacity potentials and corresponding average full load hours shown in Figure 21 reveals that five regions within Romania can be classified as (very) good concerning wind site qualities. As discussed above, that top-five list includes the regions Tulcea, Constanţa, Brăila, Galaţi and Ialomiţa, and achievable full load hours of wind sites within these regions are on average (well) above 2,350 hours per year. The overall technical potential for wind power of all five regions together sums up to 98.9 GW or 249.2 TWh, respectively, cf. Table 22. If we now apply further land use constraints and thereby assume a least-cost allocation for the whole of Romania, then this would limit the technical potential to the half, i.e., 48.1 GW or 122.6 TWh, respectively. However, even the smaller number in terms of generation potential is twice as high as the electricity consumption of the whole of Romania at present. Focussing on these areas may allow to better tackle one key barrier to an enhanced wind power uptake: the necessary grid expansion. At present many Romanian stakeholders classify this as the central hurdle for a rapid uptake of this promising carbon-free energy carrier.

5.1.3 Mapping with the grid infrastructure

A mapping exercise is finally conducted to indicate how identified promising areas for onshore wind power development match with the transmission grid infrastructure. We consequently add to the dataset an indicator that shows the average distance to the next grid node for feasible wind development areas, on average by region as well as on average for each available wind site class within a region, cf. Table 25. Thus, on average wind farms in Romania are 30 km distant to the next grid node, with variations among individual sites but with hardly any differences by wind site class.

Table 25: Average distance to the next transmission grid node of region-specific feasible wind development areas in Romania, considering the technical potentials with land use constraints (least-cost allocation) and with exclusion of nature protection areas, expressed on average by region (left column) as well as by wind site class (all other columns). Source: own analysis.

Average distance of individual pixels to the next grid node (in km) on average (left column) and by wind site class, expressed by the range of respective full load hours (all other columns)

Region	all wind classes [km]	flh 1600-1850 [km]	flh 1850-2100 [km]	flh 2100-2300 [km]	flh 2300-2500 [km]	flh 2500-2700 [km]	flh 2700-2900 [km]	flh 2900-3100 [km]	flh 3100-3300 [km]
Braşov	24	25	25	18	29	34			
Timiş	31	29	22	31	60				
Teleorman	35	31	36						
Covasna	49	48	48	46	56	57			
Vaslui	30	24	29	32	29	23	56		
Brăila	**25**		**26**	**19**	**18**	**28**	**35**		
Prahova	31	34	32	28	30				
Bucureşti	6	6							
Arad	31	28	25	38					
Caraş-Severin	35	36	38	33	33	31	29	31	
Hunedoara	19	21	14	17					
Sălaj	19	18	22	33					
Gorj	12	11		14					
Harghita	36	36	36						
Neamţ	22	25	20	16	15				
Maramureş	39	45	38	32					
Satu Mare	23	17	18	29	37				
Suceava	47	59	37	33	38				
Ilfov	15	15	17						
Dolj	30	26	30	35					
Alba	22	21	13	26	22				
Buzău	34	28	32	33	37	40	57		
Constanţa	**20**		**21**	**20**	**14**	**17**	**26**	**31**	**5**
Cluj	19	21	17	20	19				
Galaţi	**37**		**56**	**37**	**34**	**37**	**43**	**61**	
Tulcea	**13**	**29**	**23**	**9**	**11**	**16**	**10**	**16**	**13**
Iaşi	30	23	32	32	34	33			
Bihor	30	31	27	32	40				
Vrancea	27	29	22	25	29	39	54		
Giurgiu	20	24	17						
Argeş	26	24	34						
Bacău	27	26	24	29	36				
Ialomiţa	**31**	**30**	**37**	**36**	**36**	**23**			
Mureş	53	53							
Sibiu	17	18	13						
Olt	30	26	31	50					
Mehedinţi	24	26	24	20	28	27		28	
Vâlcea	22	21	23	28		29			
Botoşani	55	39	53	60	51				
Bistriţa-Năsăud	90	90							
Călăraşi	27	23	30	26	23	27			
Dâmboviţa	41	41		40					
Romania	**30**	**30**	**28**	**30**	**32**	**31**	**39**	**34**	**9**

5.2 Offshore wind potentials

This section is dedicated to put, complementary to the analysis of onshore wind potentials, offshore wind power into the spotlight. It provides a brief overview on the results gained from our respective analysis whereas a detailed discussion is presented in Chapter 6. Offshore wind is according to past experiences less relevant for the Black Sea region but recently gaining key policy attention at the European as well as the national level. Specifically, for offshore wind, competing uses of the sea (e.g., main shipping routes, nature protection areas) are taken into consideration within our analysis, done by excluding related areas from the applicable resource base as a simplification.

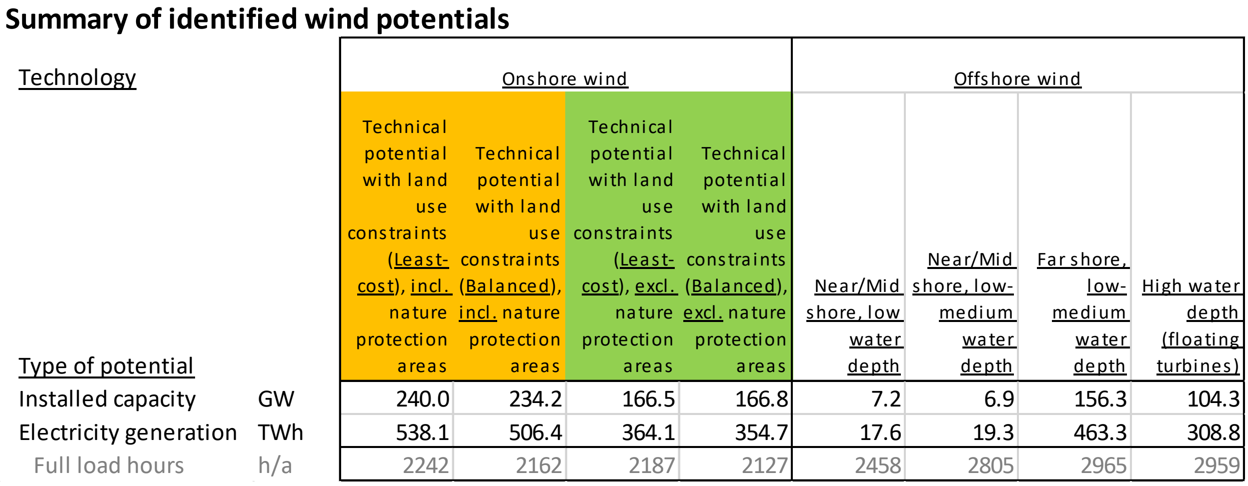
For offshore wind Romania has promising sites at hands but generally offshore comes at higher cost compared to onshore. For an offshore wind farm upfront investment cost are about 50% to 100% higher in comparison to onshore due to higher cost for the foundations and for grid connection. Thus, this needs to be compensated by better resource qualities.

As applicable from the detailed description provided in Chapter 6, the overall technical potential for offshore wind in Romania is significant – i.e., 274.7 GW in capacity terms and 809.0 TWh in energy terms, respectively, when considering the standard offshore turbine for that purpose. Large parts of the most promising potentials are far-distant from the shore (cf. Table 26), at sites characterised by moderate water depth or at sites with high water depth whereby the latter would recommend using a floating turbine design.

5.3 Brief summary of results & comparison with national energy planning

This section is dedicated to summarising the results of our GIS-based analysis of wind power development potentials in Romania. To put them into perspective, we also undertake a comparison to the role of wind power in current energy planning. As starting point, Table 26 provides an overview on the identified technical potentials for wind power development in Romania, distinguishing between onshore (left) and offshore resources (right).

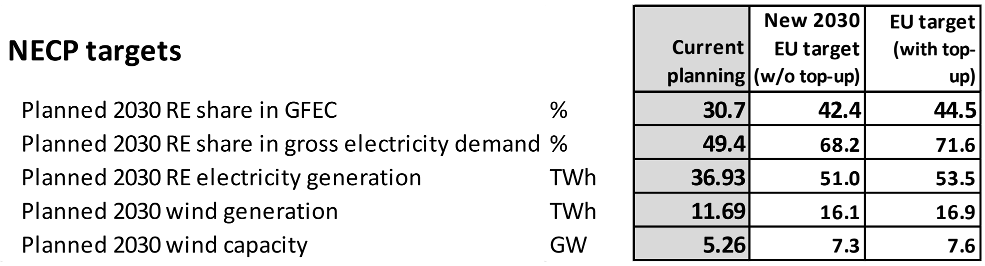
Table 26: Overview on identified technical potentials for wind power development in Romania, distinguishing between onshore (left) and offshore wind (right). Source: own analysis.



Summary of identified wind potentials

Technology		Onshore wind				Offshore wind			
Type of potential		Technical potential with land use constraints (Least-cost), incl. nature protection areas	Technical potential with land use constraints (Balanced), incl. nature protection areas	Technical potential with land use constraints (Least-cost), excl. nature protection areas	Technical potential with land use constraints (Balanced), excl. nature protection areas	Near/Mid shore, low water depth	Near/Mid shore, low-medium water depth	Far shore, low-medium water depth	High water depth (floating turbines)
Installed capacity	GW	240.0	234.2	166.5	166.8	7.2	6.9	156.3	104.3
Electricity generation	TWh	538.1	506.4	364.1	354.7	17.6	19.3	463.3	308.8
Full load hours	h/a	2242	2162	2187	2127	2458	2805	2965	2959

Table 27: Comparison of 2030 deployment targets for wind power and renewables in general in Romania according to current planning (left column) and under consideration of the newly established 2030 EU targets (all other columns). Sources: Republic of Romania (2019) and own analysis.



NECP targets		**Current planning**	**New 2030 EU target (w/o top-up)**	**EU target (with top-up)**
Planned 2030 RE share in GFEC	%	**30.7**	**42.4**	**44.5**
Planned 2030 RE share in gross electricity demand	%	**49.4**	**68.2**	**71.6**
Planned 2030 RE electricity generation	TWh	**36.93**	**51.0**	**53.5**
Planned 2030 wind generation	TWh	**11.69**	**16.1**	**16.9**
Planned 2030 wind capacity	GW	**5.26**	**7.3**	**7.6**

Table 27 above undertakes of comparison of 2030 deployment targets for wind power as well as renewables in general in Romania. Here we show the planned renewable and wind power uptake according to current planning as indicated in the 2019 National Energy and Climate Plan (NECP) of Romania (Republic of Romania, 2019). Recently, all EU Member States agreed on a strengthening of the renewables ambition, given the urgency to combat climate change as well as to respond on the Russian invasion of the Ukraine as well as the impact of that on Europe's gas, and, in consequence, also on electricity supply. To acknowledge that strengthening of the renewables ambition, all EU Member States, including Romania, are currently revising their previous national energy planning. To indicate the implications on renewables in general as well as specifically on wind in energy planning, Table 27 contains deployment figures for both under the newly established EU framework on 2030 energy and climate targets. Note that these deployment figures for wind are purely indicate, derived by proportionally increasing wind in relation to the strengthened RES ambition.

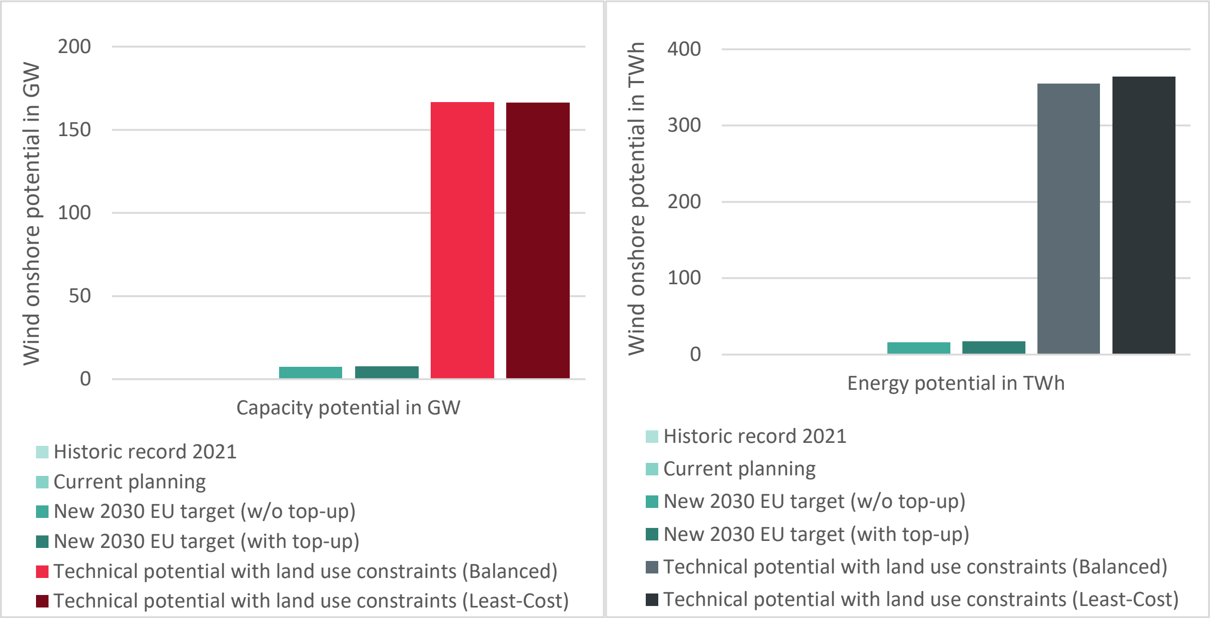


Figure 22: Wind energy at present and in future: Comparison of the status quo (2021), of 2030 deployment targets according to current planning (NECP) and under consideration of new 2030 EU targets as well as of identified technical potentials (with land use constraints). Sources: Eurostat (2023), Republic of Romania (2019) and own analysis.

Finally, Figure 22 summarises all the above. More precisely, this graph shows the status quo of wind power development (as of 2021) and compares that with the 2030 deployment targets (both according to current planning and the possible implications on that from the strengthened RES ambition) as well as with the identified wind development potentials, here exemplified for onshore wind only. Apparently, we can conclude that when considering the available wind resources in Romania that there is sufficient room for enhancing the wind uptake in future years. Given the resources at hands, wind power deserves to take a more prominent role in future energy planning in Romania. Any strengthening of the wind ambition should however go hand in hand with a strengthening of the power grid infrastructure, both at transmission and, where affected, also at the distribution grid level.

5.4 Brief consideration of economics

As a teaser for the next chapter that indicates the electricity market impacts of an enhanced wind uptake in future years within Romania as well as within the neighbouring countries Bulgaria and Hungary, we conclude our resource analysis with a snapshot on the economics of wind power. At the example of onshore wind, Figure 23 depicts so-called cost-resource curves of wind onshore for all countries within our study region, including apart from Romania also Bulgaria and Hungary. These cost-resource curves show the potentials for wind onshore, using technical least-cost potentials with consideration of land use and nature protection constraints, broken down by wind site class (i.e., by full load hours) on the horizontal axes. Lines are derived by complementing the data on the resources with information on the corresponding Levelized Cost of Electricity (LCOE), using typical assumptions for cost and financial parameter as listed below. The graph confirms the previous statement that Romania offers promising wind sites at comparatively cheap cost, considering current prices on electricity wholesale markets.

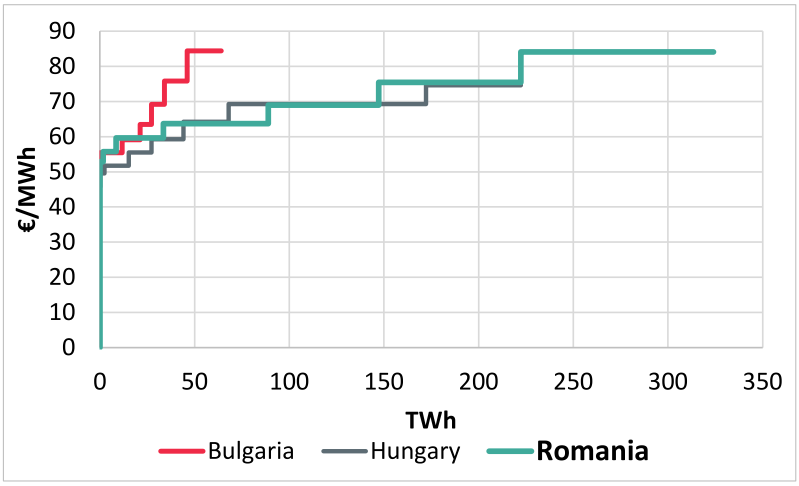
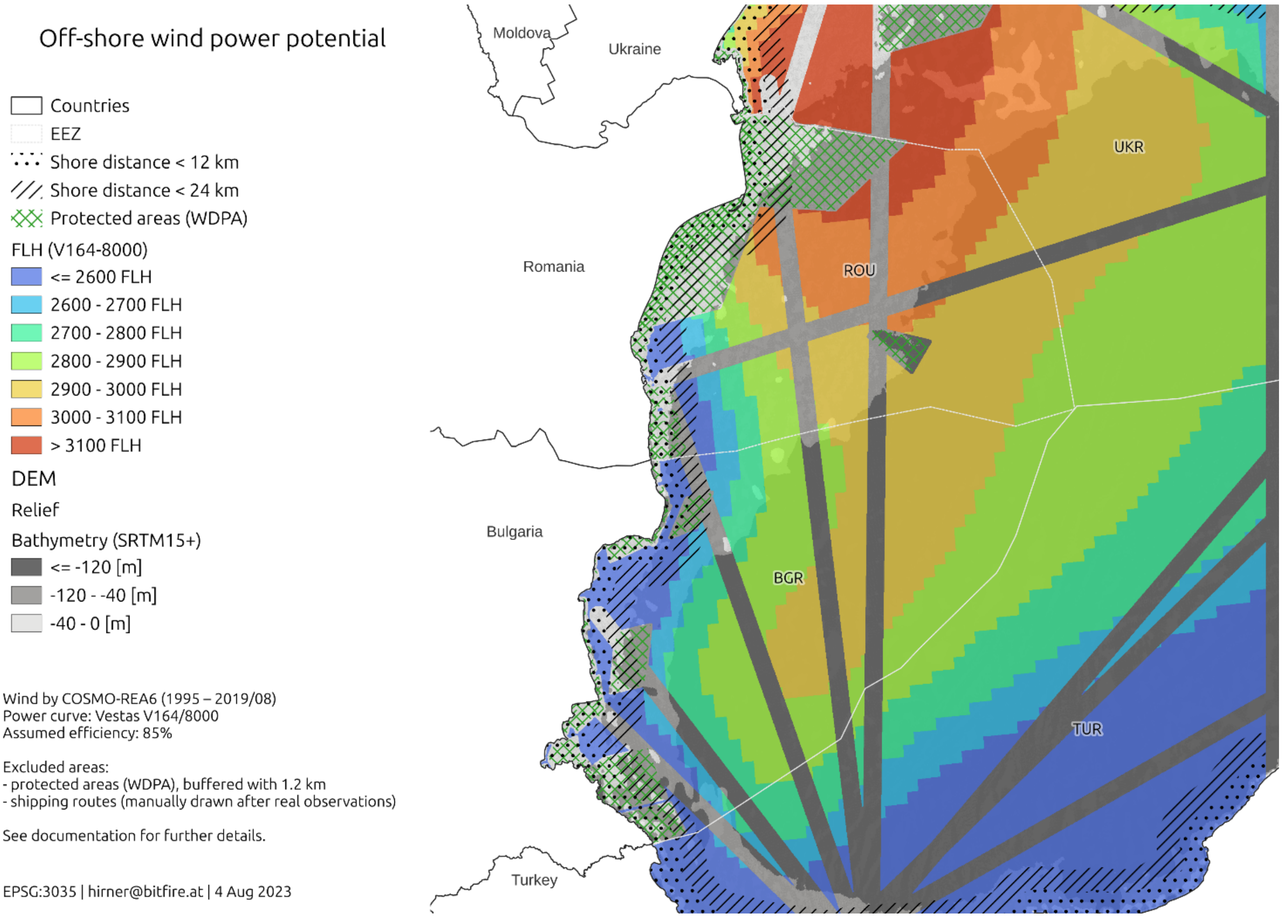


Figure 23: Cost-resource curves of wind onshore in the study region (using technical least-cost potentials with consideration of land use and nature protection constraints). Source: own analysis.

Note on the assumptions for LCOE calculation: Investment cost: 1,500 EUR/kW, O&M cost: 3% p.a. (of investment cost), Interest rate: 6.5%, Depreciation time: 20 years

6 RESULTS ON OFFSHORE WIND POTENTIALS FROM A REGIONAL PERSPECTIVE

This Chapter is dedicated to put, complementary to the analysis of onshore wind potentials, offshore wind power into the spotlight. Offshore wind is according to past experiences less relevant for the Black Sea region but recently gaining key policy attention at the European as well as the national level. Specifically, for offshore wind, competing uses of the sea (e.g., main shipping routes, nature protection areas) are taken into consideration within our analysis, done by excluding related areas from the applicable resource base as a simplification. In this context, Figure 24 provides a graphical illustration of applicable offshore potentials. More precisely, this graph provides an offshore wind map for the Black Sea region of Bulgaria and Romania, indicating site qualities (expressed in full load hours) as well as nature protection areas and main shipping routes since both area types are excluded from the identification of potentials.



Wind by COSMO-REA6 (1995 – 2019/08)
Power curve: Vestas V164/8000
Assumed efficiency: 85%

Excluded areas:
- protected areas (WDPA), buffered with 1.2 km
- shipping routes (manually drawn after real observations)

See documentation for further details.

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Figure 24: Offshore wind map for the Black Sea region of Bulgaria and Romania, indicating site qualities (expressed in full load hours) as well as nature protection areas and main shipping routes (both being excluded from the identification of potentials). Source: own analysis.

Complementary to Figure 24, the results of our potential analysis are presented in table format below. Thus, Table 28 provides an overview on the technical potentials for offshore wind power development in Bulgaria and Romania, with indication of area, capacity and energy potentials as well as site qualities (full load hours), classified according to water depth and distance to the shore, using a standard offshore turbine (large generator, large rotor – at the top of Table 28) and, for sensitivity purposes to simplify the comparison with onshore sites, a typical onshore turbine (moderate generator, large rotor – at the bottom of Table 28).

Table 28: Overview on the technical potentials for offshore wind power development in Bulgaria and Bulgaria, with indication of area, capacity and energy potentials as well as site qualities (full load hours), classified according to water depth and distance to the shore, using a standard offshore turbine (large generator, large rotor – top) and a typical onshore turbine (moderate generator, large rotor – bottom). Source: own analysis.

Wind turbine specification:

VESTAS V164/8000

Generator size	8	MW
Rotor diameter	164	m
Area for one turbine	0.54	km2
MW per km2	14.7	MW/km2

GIS-based analysis of potentials for offshore wind energy

	Country:	Bulgaria				Romania			
Water depth (z, in m)	distance from shore (1 km)	Area potential (km2)	Capacity potential (MW)	Full load hours (h/a)	Energy Potential (GWh)	Area potential (km2)	Capacity potential (MW)	Full load hours (h/a)	Energy potential (GWh)
-40 ≤ z	d < 12	464	6,818	2,222	15,150	186	2,728	2,336	6,372
	12 ≤ d < 24	600	8,819	2,195	19,357	303	4,444	2,533	11,257
	24 ≤ d	168	2,463	2,632	6,483	335	4,914	2,754	13,531
-80 ≤ z < -40	d < 12	380	5,575	2,427	13,530	17	247	3,051	754
	12 ≤ d < 24	628	9,228	2,507	23,137	452	6,636	2,796	18,555
	24 ≤ d	1,564	22,968	2,671	61,350	7,216	105,985	2,939	311,538
-120 ≤ z < -80	d < 12	0	0	0	0	0	0		0
	12 ≤ d < 24	181	2,659	2,570	6,832	0	0		0
	24 ≤ d	1,582	23,241	2,690	62,527	3,089	45,374	3,046	138,209
z < -120	d < 12	0	0	0	0	0	0		0
	12 ≤ d < 24	34	505	2,453	1,238	0	0		0
	24 ≤ d	19,121	280,857	2,882	809,502	7,104	104,341	2,959	308,784
TOTAL Area		34,709				29,587			
USABLE Area		24,722	363,133	2,806	1,019,105	18,700	274,670	2,945	809,001

Wind turbine specification:

Nordex N163-4.95

Generator size	4.95	MW
Rotor diameter	163	m
Area for one turbine	0.54	km2
MW per km2	9.2	MW/km2

GIS-based analysis of potentials for offshore wind energy

	Country:	Bulgaria				Romania			
Water depth (z, in m)	distance from shore (1 km)	Area potential (km2)	Capacity potential (MW)	Full load hours (h/a)	Energy Potential (GWh)	Area potential (km2)	Capacity potential (MW)	Full load hours (h/a)	Energy potential (GWh)
-40 ≤ z	d < 12	958	8,810	2,704	23,826	186	1,709	3,100	5,298
	12 ≤ d < 24	651	5,987	2,881	17,248	303	2,783	3,305	9,198
	24 ≤ d	168	1,543	3,389	5,228	335	3,078	3,529	10,863
-80 ≤ z < -40	d < 12	398	3,661	3,135	11,477	17	155	3,847	596
	12 ≤ d < 24	628	5,780	3,251	18,793	452	4,157	3,572	14,846
	24 ≤ d	1,564	14,386	3,431	49,357	7,216	66,385	3,718	246,836
-120 ≤ z < -80	d < 12	2	18	2,407	44	0	0		0
	12 ≤ d < 24	181	1,665	3,310	5,512	0	0		0
	24 ≤ d	1,582	14,558	3,450	50,227	3,089	28,421	3,830	108,865
z < -120	d < 12	0	2	2,362	6	0	0		0
	12 ≤ d < 24	34	316	3,183	1,006	0	0		0
	24 ≤ d	19,121	175,919	3,663	644,370	7,104	65,356	3,751	245,174
TOTAL Area		34,709				29,587			
USABLE Area		25,287	232,645	3,555	827,095	18,700	172,044	3,730	641,676

As applicable from these depictions, for offshore wind both Bulgaria and Bulgaria have promising sites at hands but generally offshore comes at higher cost compared to onshore. For an offshore wind farm upfront investment cost are about 50% to 100% higher in comparison to onshore due to higher cost for the foundations and for grid connection. Thus, this needs to be compensated by better resource qualities.

To sum up on the identified offshore wind potentials, the overall technical potential for offshore wind in Bulgaria is significant – i.e., 363.1 GW in capacity terms and 1,019.1 TWh in energy terms, respectively, when considering the standard offshore turbine for that purpose. Accordingly, Romania also offers a significant technical potential for offshore wind development – i.e., 274.7 GW in capacity terms and 809.0 TWh in energy terms, respectively, when considering the standard offshore turbine for that purpose. For both countries large parts of the most promising potentials are far-distant from the shore at sites characterised by moderate water depth or at sites with high water depth whereby the latter would recommend using a floating turbine design.

The outcomes of our offshore wind potential assessment are comparable but larger in magnitude compared previous assessments conducted in this topical context, cf. Energy Policy Group (2020) in the case of Romania. Differences in the results are a consequence of differing geographical boundaries and underlying assumptions concerning wind power densities.

7 RESULTS OF THE ASSESSMENT OF ELECTRICITY MARKET IMPACTS OF AN ENHANCED WIND DEPLOYMENT

This chapter is dedicated to informing on the results gained from the assessment of an enhanced wind deployment within our study region, including Bulgaria, Hungary, and Romania. As outlined in section 2.2, a model-based electricity market analysis is conducted, showcasing electricity market impacts of future wind power deployment in the study region. More precisely, three scenarios are analysed, with varying assumptions on the assumed wind power uptake, ranging from a low to a high wind penetration scenario. The sections below inform on the details on the aggregated results for the whole study region.

7.1 Wholesale electricity prices

Wind penetration has a high effect on baseload prices. Due to the merit order effect, the higher the wind penetration, the lower the wholesale price. It is also important to note that the increase in wind penetration in each country also has an effect outside the country. For this reason, we show changes in wholesale electricity price in the wider region, not only for the three countries assessed.

In the middle of Figure 25, we depict the baseload electricity price development in the moderate scenario, on the left side the low penetration scenario is compared to the moderate, while on the right side the high wind penetration is compared to the moderate scenario. In the upper part the 2030 case is shown, and in the bottom the 2050 case.

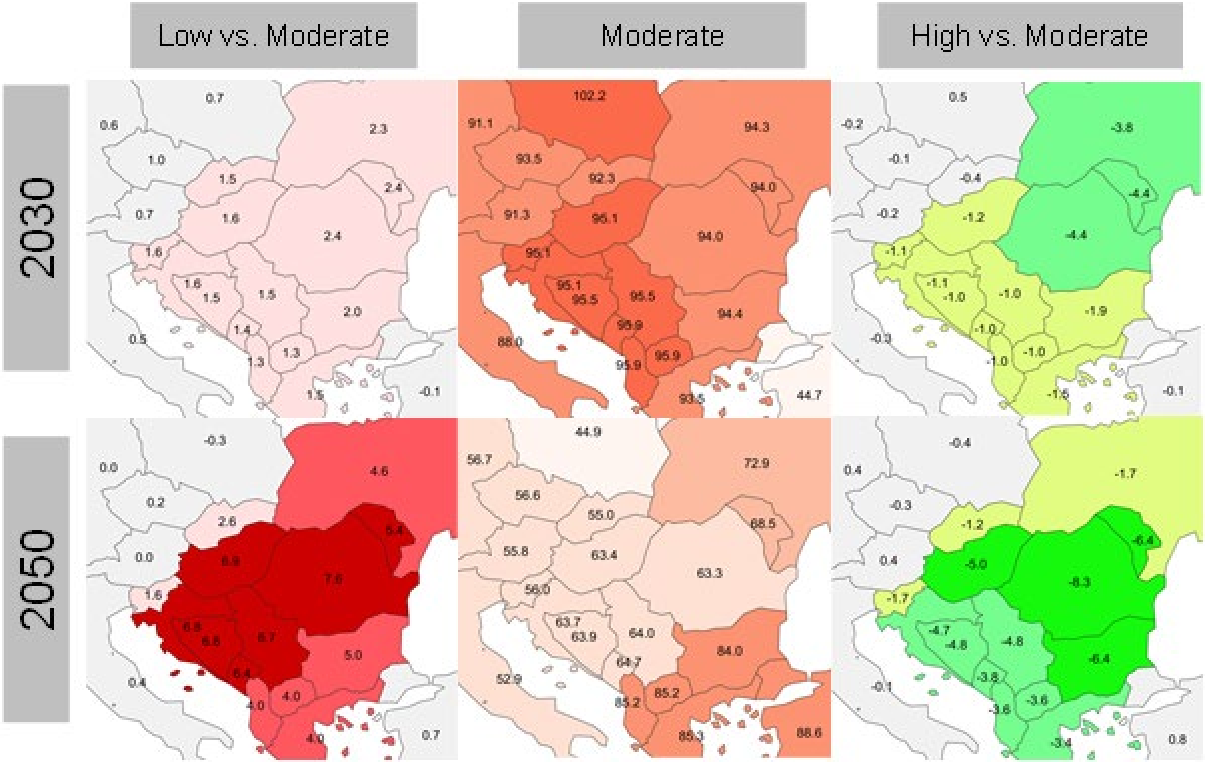

Figure 25: Wholesale electricity baseload prices in the moderate scenario, and changes to it in the high and low scenario, €/MWh

In 2030, the price differences between the countries in the region are small, with the exception of Turkey, where we assume that Turkey will not adopt the EU ETS, which means that the marginal costs of the Turkish power plants are much lower.

In the low scenario the price increases by 1.5-2 €/MWh in the countries of South-East Europe. The effect is also visible in the West-European countries. The largest effect is in Romania (+2.4 €/MWh), while the smallest of the three countries is in Hungary (1.6€/MWh). In the High scenario, the price drop is very high (-4.4 €/MWh) in Romania (and in Ukraine and Moldova), while it is much smaller (~1.0-1.5€/MWh) in the other SEE countries.

In the Moderate scenario, the Region is divided into different subregions in 2050: Bulgaria, Greece, Albania, North Macedonia and Turkey are the most expensive, but the price level is still below the 2030 level. Northern to this region the baseload price is around 20€/MWh cheaper, due to the fact that this region is closer to the relatively cheap Western-European countries. As the wind installed capacities in the three scenarios are much higher in 2050 than in 2030, the price difference is higher. In the southern sub-region, the price increase is around 4-5€/MWh, while in the other part of the SEE region (where the baseload price is the lowest) the price increase is around 6-8 €/MWh. The picture is not so clear in the high scenario concerning the price developments. The largest price decrease is in Romania (where the baseload price is one of the cheapest in the region), while Hungary and Bulgaria are at similar levels (-5–6.4€/MWh).

7.2 Wind market value

In 2030, the wind market value is very close to the baseload electricity prices in the whole region in all three scenarios. In 2050 the differences are larger. In most of the countries, including the three assessed countries, the wind market value is higher than the baseload electricity prices in the moderate scenario. However, the tendencies in the low and high wind scenarios are similar to the baseload price trend, but the change is higher in most of the countries, as can be seen in Figure 26.

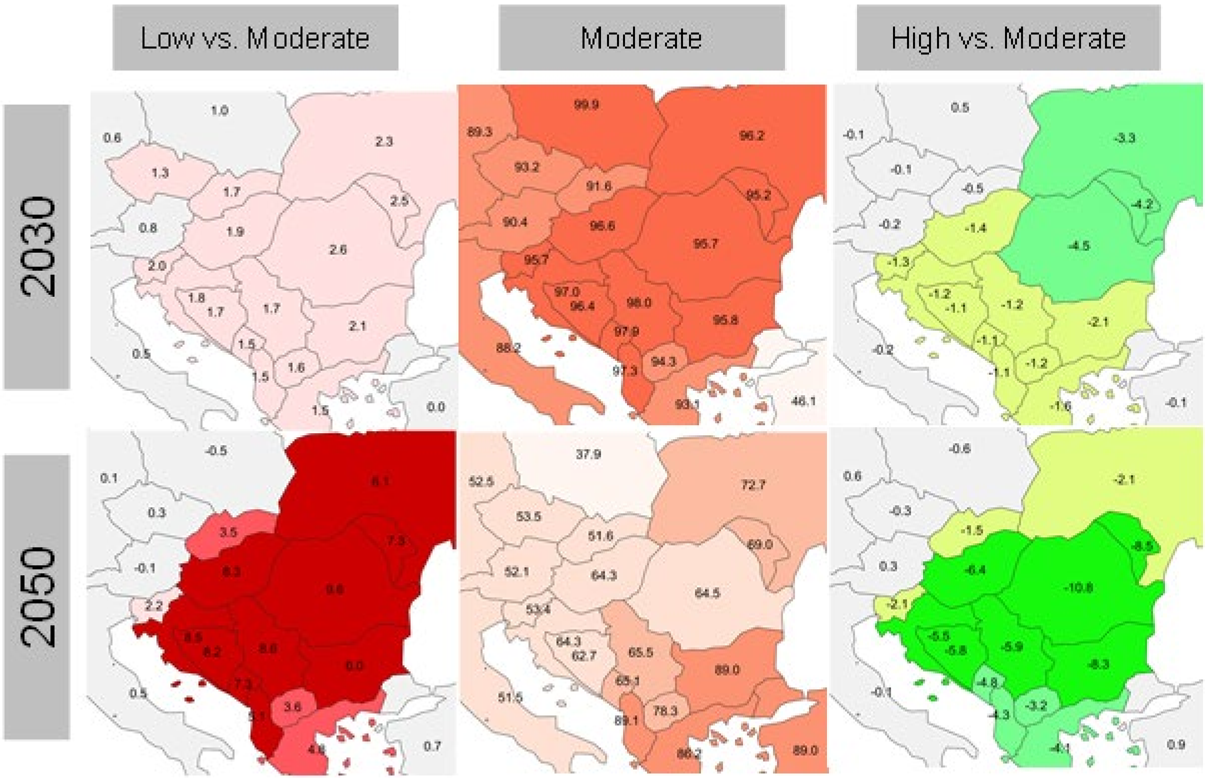

Figure 26: Wind market value in the moderate scenario, and changes to it in the high and low scenario, €/MWh

Figure 27 compares the changes in the baseload electricity price, wind market value and PV market value with the Moderate scenario. In 2030, according to the modelling results, the PV market value changes are the most significant for all the three countries in both scenarios. However, all changes remain below 5 €/MWh (~ 5%).

In 2050 we see a completely different picture when comparing the two market values (MV in next figure) and the baseload electricity price. In all scenarios, the wind market value is most affected, usually between 5-10 €/MWh, while the baseload electricity price changes a little less. It is interesting that the change in PV market value is less significant. This is due to the low PV market value in all scenarios. In the moderate scenario in 2050 the PV market value is around 30 €/MWh in all countries, while the baseload electricity price is 60-80 €/MWh.

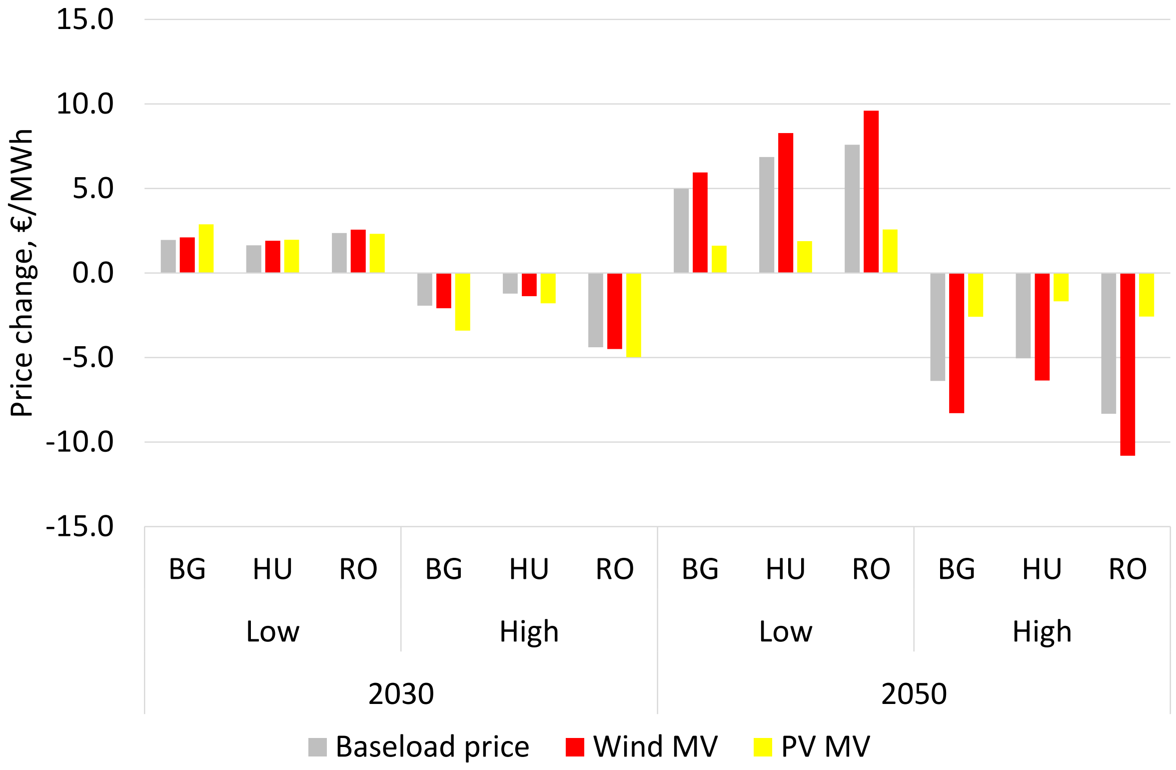

Figure 27: Baseload electricity prices, wind MV and PV MV changes compared to the moderate scenario, €/MWh

The results indicate an important difference in the changing Market values of PV and wind generation. While in case of wind generation the cannibalisation effect is less dominant, so the change in wind market value is in a similar range then the change in the baseload price, leaving the real value of the wind generation at the general wholesale price levels. There is still a cross-effect of the higher wind generation on PV, it further reduces the PV market value, but to a more limited extent, due to the fact that PV market values are already low in the scenarios. The main driver in these price development trends is the production pattern: wind tend to produce at a more equalized pattern if the generation is looked at a more aggregated regional level, while PV capacities produce at the same daily periods reducing the corresponding price.

7.3 Electricity mix

In the following, we analyse the changes in the electricity mix compared to the Moderate scenario for the three countries, and another category “other”, which consists of the other modelled countries (see Figure 28). In 2030 the total wind generation in the low scenarios is almost 10 TWh lower than in the Moderate scenario. This is mainly replaced by natural gas (6.5 TWh) of which only 1.5 TWh is in the three countries. Coal and lignite-based generation also increases by around 2.2 TWh, almost entirely from outside the three countries. The tendencies are really the same in the high scenario. The higher wind generation leads to lower natural gas and coal production.

Due to the fact, that in 2050 the share of coal-based generation is much smaller, the changes in wind generation have a limited impact on coal generation. While in 2030 nuclear generation is not affected by changes in wind generation, this is not the case in 2050. An increase in total wind generation of 33 TWh, reduces nuclear generation by 11 TWh, of which 3.3 TWh is in Romania. It is also interesting that in both the low and the high case, the changes in wind generation are substituted by 75-80 % outside the three countries, resulting in increased imports.

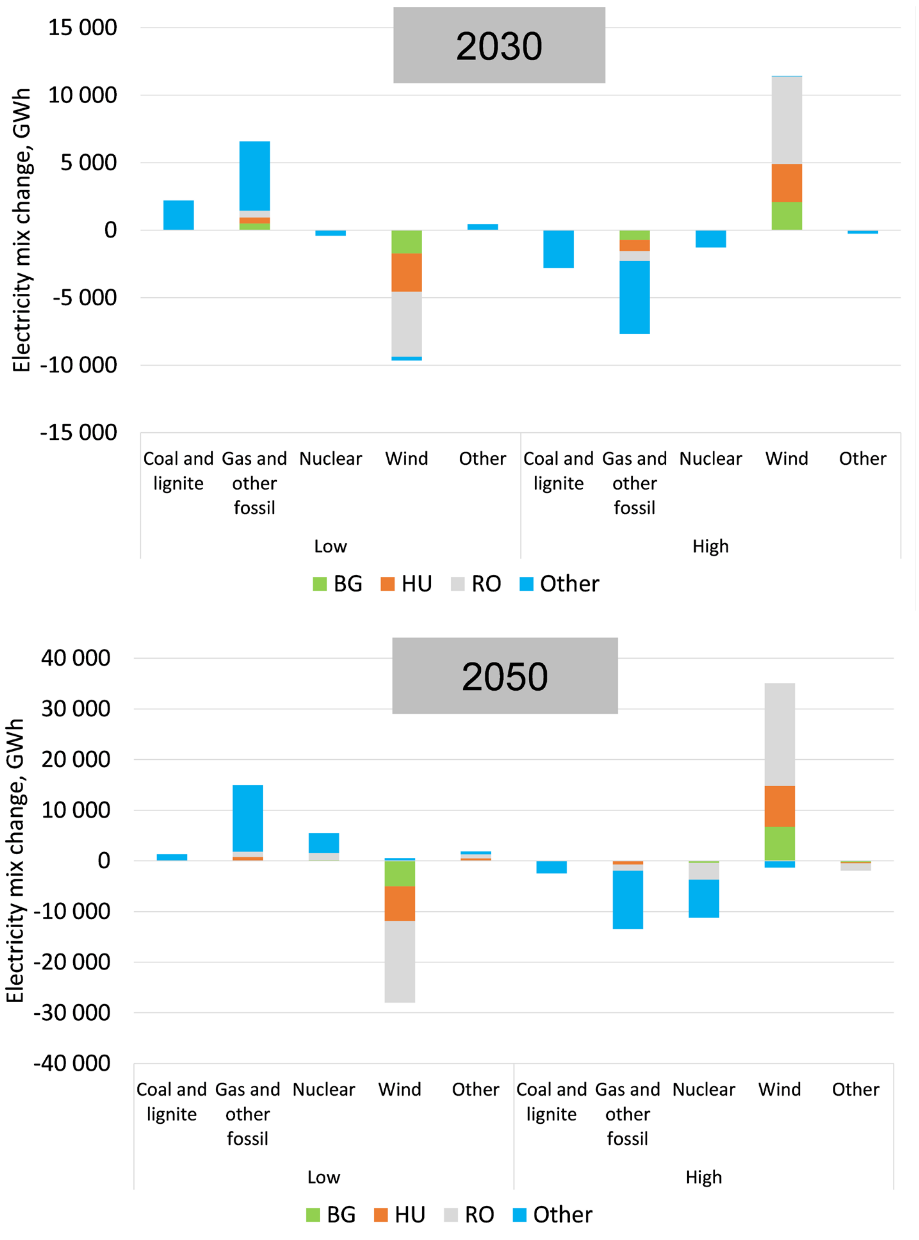

Figure 28: Electricity mix changes compared to the moderate scenario by 2030 and 2050, GWh

7.4 CO_2 emissions

In this section we analyse the changes in the CO_2 emissions compared to the Moderate scenario for the three countries, as can be seen in Figure 29. In 2030, the total difference in wind generation is -9.6 TWh and +11.4 TWh, resulting in changes in CO_2 emissions of +4.6 Mt and -5.6 Mt. This means that 1 MWh of additional wind generation reduces CO_2 emissions by 0.47-0.5 Mt. In 2050, the total difference in wind generation is -27.4 TWh and +33.7 TWh, resulting in changes in CO2 emissions of +6.3 Mt and -6.8 Mt. The result is a much smaller CO_2 reduction: 1 MWh of additional wind generation reduces CO_2 emissions by only 0.20-0.23 Mt. This is because the share of coal/lignite generation changes much less in 2050 than in 2030.

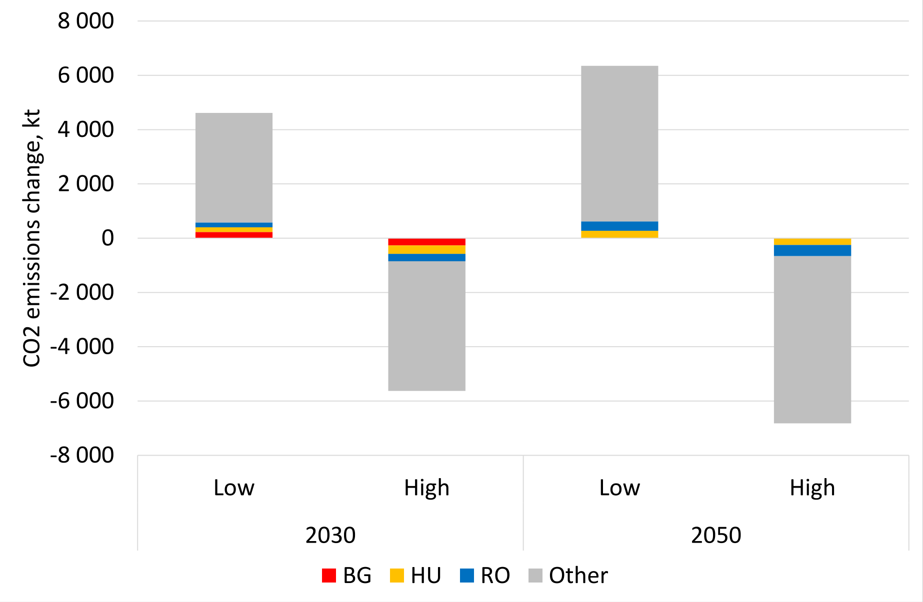

Figure 29: CO_2 emissions changes compared to the moderate scenario, kt

7.5 RES curtailment

In 2030 the change in RES curtailment is negligible (see Figure 30), but in 2050 the RES curtailment changes are significant, in the low scenario the RES curtailment decreases by 4 TWh, while in the high scenario, it increases the curtailment need by +6 TWh. These figures represent 14-20 % of the wind generation production changes. Most of the RES curtailment changes are in Romania – where the wind changes are the highest -, followed by the “other” countries. Hungarian and Bulgarian RES producers are less impacted by curtailment.

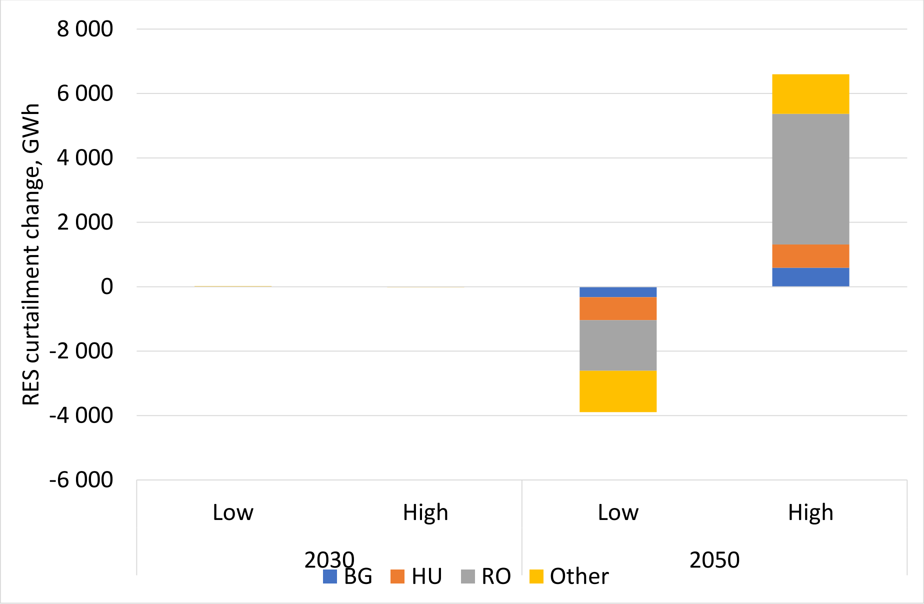

Figure 30: RES curtailment changes compared to the moderate scenario, GWh

8 CONCLUDING REMARKS

The overall potential for both onshore and offshore wind in our study region, including Bulgaria, Hungary, and Romania, is significant in energetic terms, by far exceeding the current level of overall electricity consumption at a regional level.

A closer look at the regional breakdown of the technical onshore wind potentials and of corresponding wind resources in Bulgaria allows for identifying at least five regions within the country that can be classified as (very) good concerning wind site qualities. That top-five list includes the regions Dobrich, Varna, Shumen, Razgrad and Silistra. The overall technical potential for wind power of all these five regions together is very high, even with consideration of land use and nature protection constraints it sums up to 14.7 GW or 38.1 TWh, respectively. This is nearly as high as the electricity consumption of the whole of Bulgaria at present. Focussing on these areas may allow to better tackle one key barrier to an enhanced wind power uptake: the necessary grid expansion. At present many Bulgarian stakeholders classify this as the central hurdle for a rapid uptake of this promising carbon-free energy carrier.

For Hungary the regional breakdown of the technical onshore wind potentials and of corresponding wind resources shows at least ten regions within Hungary that can be classified as very good concerning wind site qualities, including Győr-Moson-Sopron, Veszprém, followed by Vas, Zala, Fejér, Komárom-Esztergom, Csongrád, Szabolcs-Szatmár-Bereg, Somogy and Hajdú-Bihar. Common among all these regions is that achievable full load hours of wind sites are on average (well) above 2,350 hours per year. The technical potential in those regions sums up to 47.4 GW or 121.2 TWh, respectively, even with consideration of land use and nature protection constraints. This is more than twice as high as the electricity consumption of the whole country at present (i.e., 49 TWh in 2021). Focussing on these areas may allow to better tackle one other barrier to an enhanced wind power uptake: the necessary grid expansion. At present certain Hungarian stakeholders classify this as a hurdle for a rapid uptake of this promising carbon-free energy carrier.

Apart from grid constraints, there are however more severe hurdles applicable in Hungary at present. Those stem from the current (as of September 2023) legislative practice on distance rules as well as on size restrictions for wind turbines. The performed sensitivity analyses make clear that the current legislative practice on distance rules is *the* major hurdle for any future wind power uptake in Hungary: the requested distance of 12 km to the built environment would not allow for any wind power development in the country. Additionally, the current size limit (i.e., 2 MW as upper limit for a wind power generator, combined with a hub height of at maximum 100 m) negatively affects the economic viability of wind power in the country.

For Romania the regional breakdown of the technical onshore wind potentials and of corresponding wind resources indicates at least five regions within Romania that can be classified as (very) good concerning wind site qualities. That top-five list includes the regions Tulcea, Constanţa, Brăila, Galaţi and Ialomiţa. The overall technical potential for wind power of all these five regions together is enormous, even with consideration of land use and nature protection constraints it sums up to 48.1 GW or 122.6 TWh, respectively. This is twice as high as the electricity consumption of the whole of Romania at present. Focussing on these areas may allow to better tackle one key barrier to an enhanced wind power uptake: the necessary grid expansion. At present many Romanian stakeholders classify this as the central hurdle for a rapid uptake of this promising carbon-free energy carrier. Care should however be taken in wind planning to minimise negative social and environmental impacts. Avoiding negative impacts on biodiversity appears thereby of key relevance since specifically the Danube delta and other parts of the country serve as nature protected habitats for bird's breeding etc.

Apart from onshore wind, there are even more significant offshore resources applicable in the Black Sea region. Thus, for offshore wind both Bulgaria and Romania have promising sites at hands but generally offshore comes at higher cost compared to onshore. For an offshore wind farm up-front investment cost are currently about 50% to 100% higher in comparison to onshore due to higher cost for the foundations and for grid connection. Thus, this needs to be compensated by better resource qualities.

Taking a closer look at the role of wind power in Bulgaria, Hungary and Romania at present and in current energy planning, we can conclude that there is sufficient room for enhancing the wind uptake in future years. Given the resources at hands, including some of the best wind sites in Central Europe, wind power deserves to take a much more prominent role in future energy planning within all of the assessed countries. A strong uptake of the wind ambition should however go hand in hand with a strengthening of the power grid infrastructure, both at transmission and, where affected, also at the distribution grid level.

The assessment of market impacts as well as the brief consideration of economics for wind power confirm the above. Thus, Bulgaria, Hungary and Romania offer promising wind sites at comparatively cheap to moderate cost, considering current prices on electricity wholesale markets. The expectable market impacts are generally promising since an enhanced wind uptake may go hand in hand with a decrease of wholesale prices in all three countries and it will be beneficial for their combat against climate change, causing a further decline of carbon emissions in future years.

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