COUNTRY REPORT BULGARIA

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

Client:

A study conducted on behalf of the European Climate Foundation.

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VIENNA, BUDAPEST, 30 NOVEMBER 2023

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

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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.

Vienna, Budapest, 2023.

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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 fueled 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 country report is dedicated to informing on **the approach and the results derived for Bulgaria**, informing on 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 is then dedicated to present the outcomes of the GIS-based analysis of wind power potentials in Bulgaria whereas Chapter 4 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.

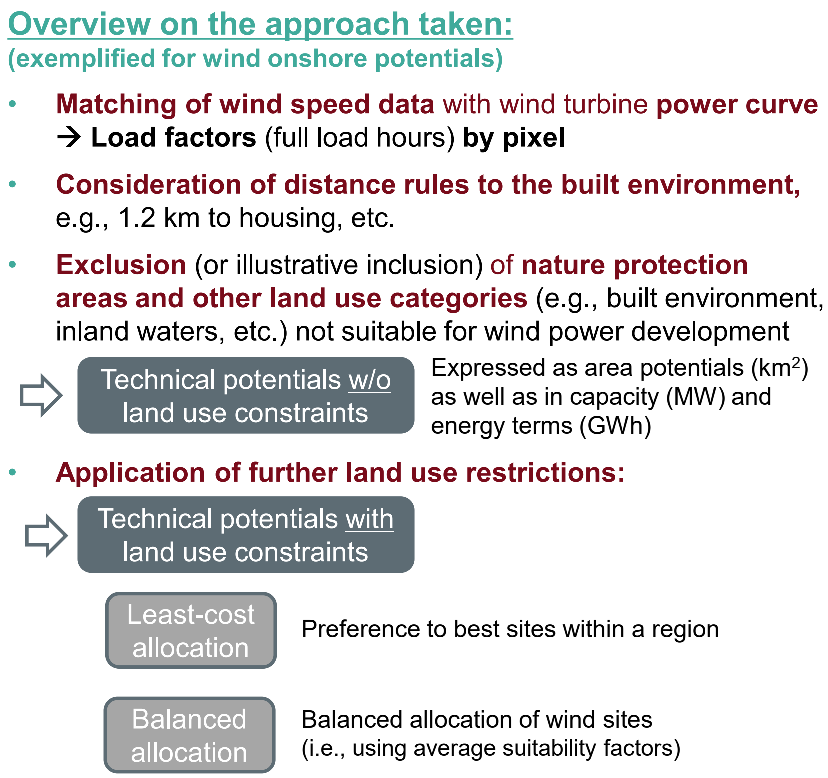


Figure 1: Overview on the approach taken for the assessment of wind potentials in the study region (exemplified for onshore wind)

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 – in the case of Bulgaria – 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). For Bulgaria these aspects, appear of relevance as identified in stakeholder consultations undertaken in prior. Apart from Bulgarian specifics 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 region.

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%

- 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:
  - 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-

[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.

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 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] 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

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 Bulgaria 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.

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). 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.

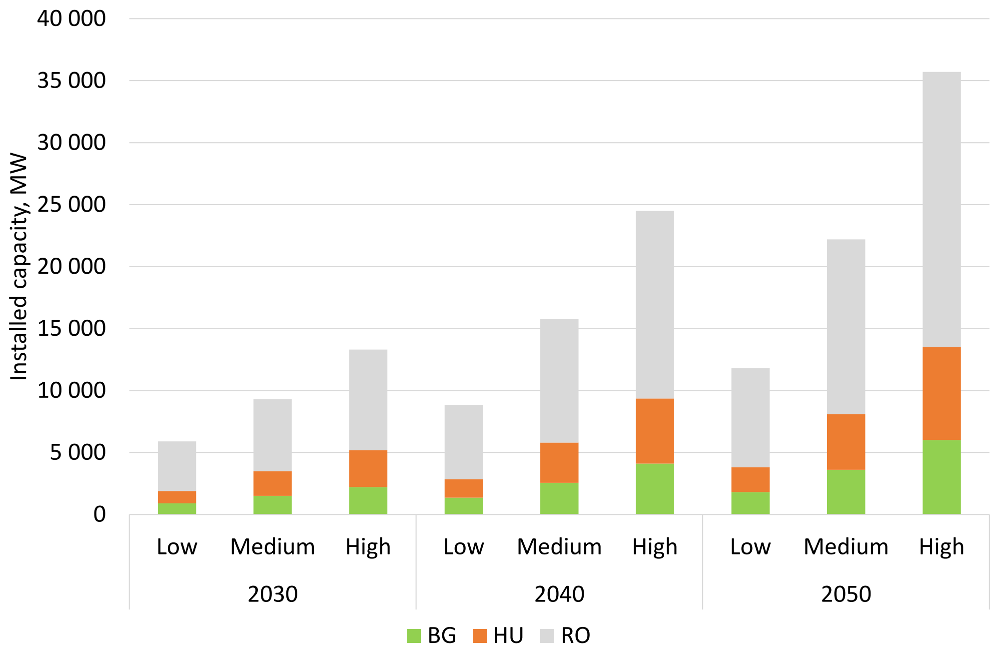


Figure 2: Wind installed capacities in the three analysed scenarios in the modelled years, MW

The outcomes of this complementary analysis are presented in Chapter 4 of this report, as a topical extension to inform on the outcomes and electricity market impacts of an enhanced wind uptake in future years. Please note that further details on the approach taken, specifically on assumptions can be found in the complementary technical background report, cf. Resch et al. (2023).

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 both 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. 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[4], 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 square km, corresponding to a capacity potential of 357.6 GW and a yearly electricity generation of 745.2 TWh.

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

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 3. 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.

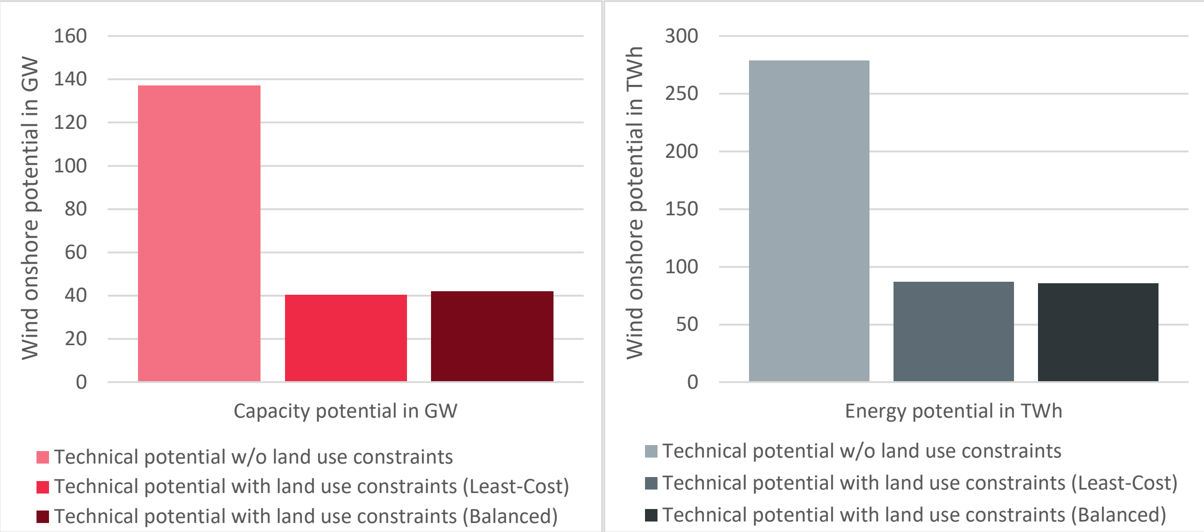
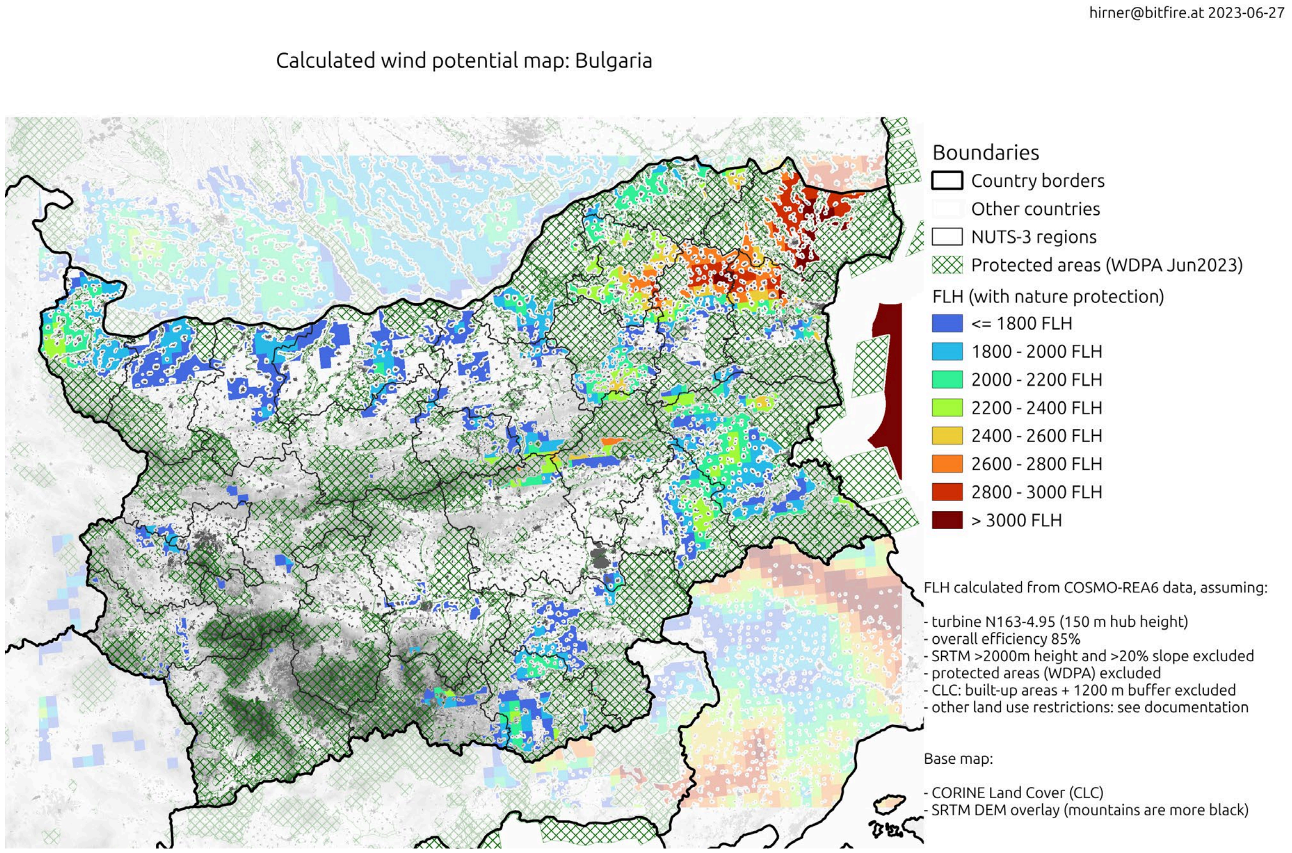


Figure 3: Technical potentials for onshore wind in Bulgaria, w/o and with (further) land use constraints (at feasible areas), expressed in capacity (left) and energy terms (right) for assessed allocation options (least-cost vs balanced). Source: own analysis.

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 4 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.



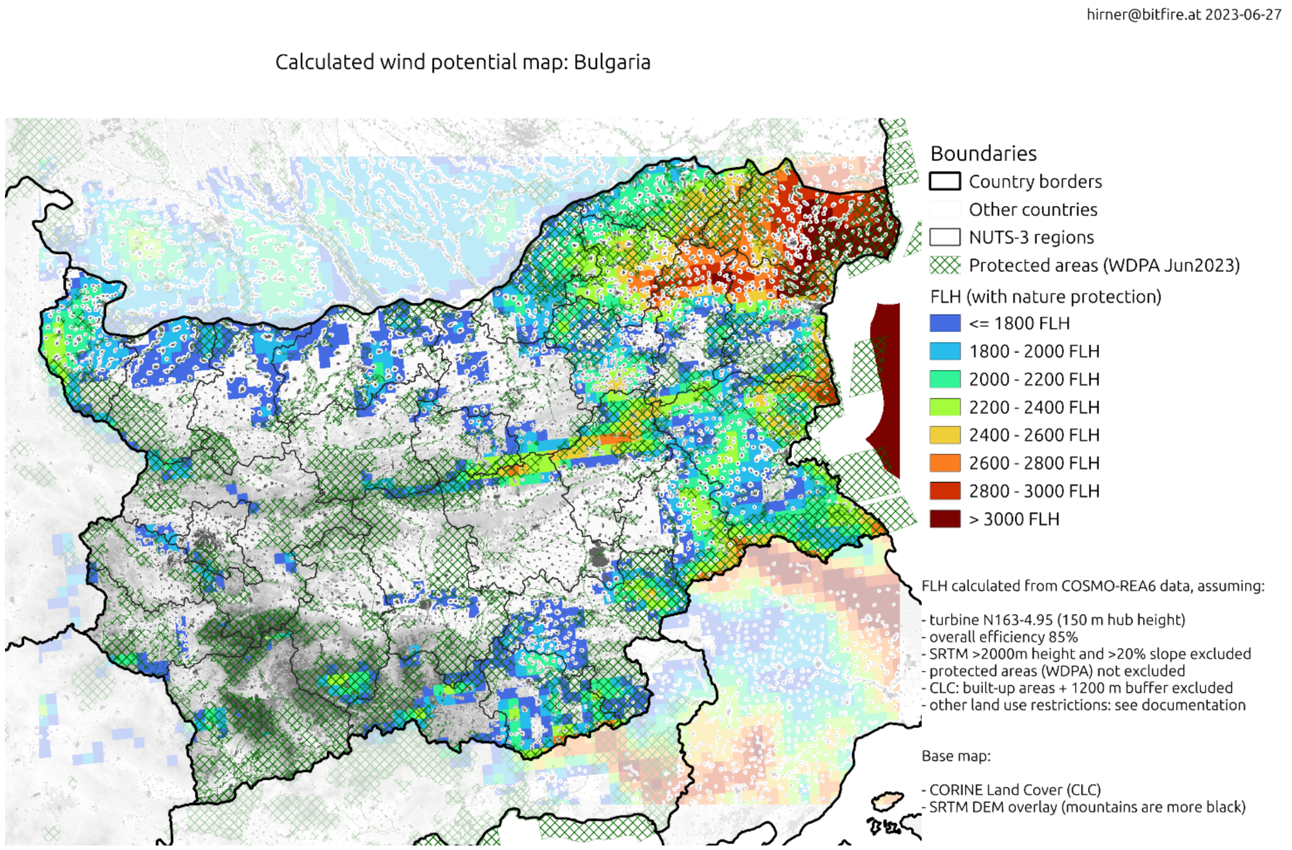


Figure 4: Wind maps for Bulgaria, indicating site qualities (expressed in full load hours) and by excluding (top) vs including (bottom) nature protection areas. Source: own analysis.

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 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 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 5, 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**

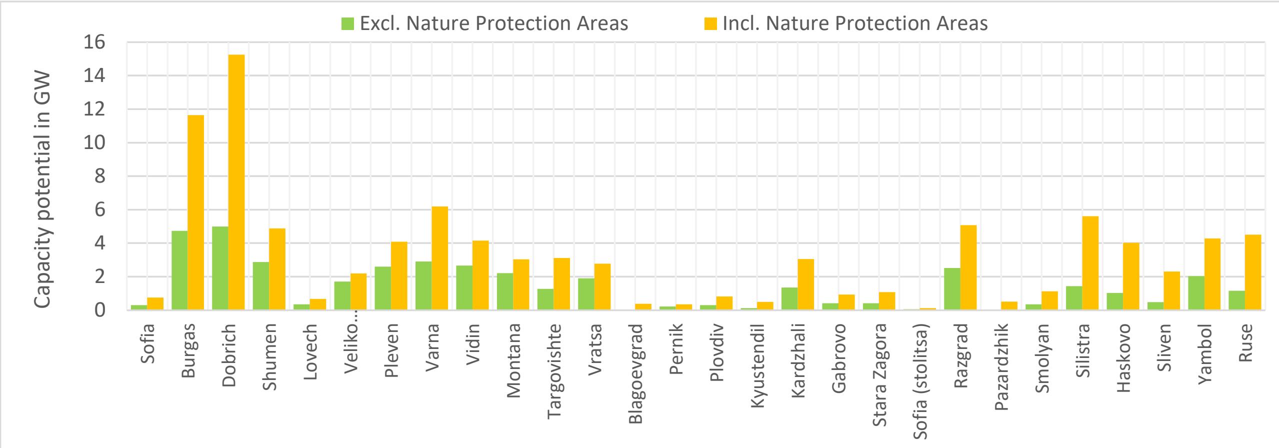
Complementary to the above, Table 6 provides further insights on the distribution of the region-specific technical potentials among wind site classes, expressed by the respective range of full load hours. This is done under consideration of land use constraints, assuming again a least-cost allocation 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 5 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.



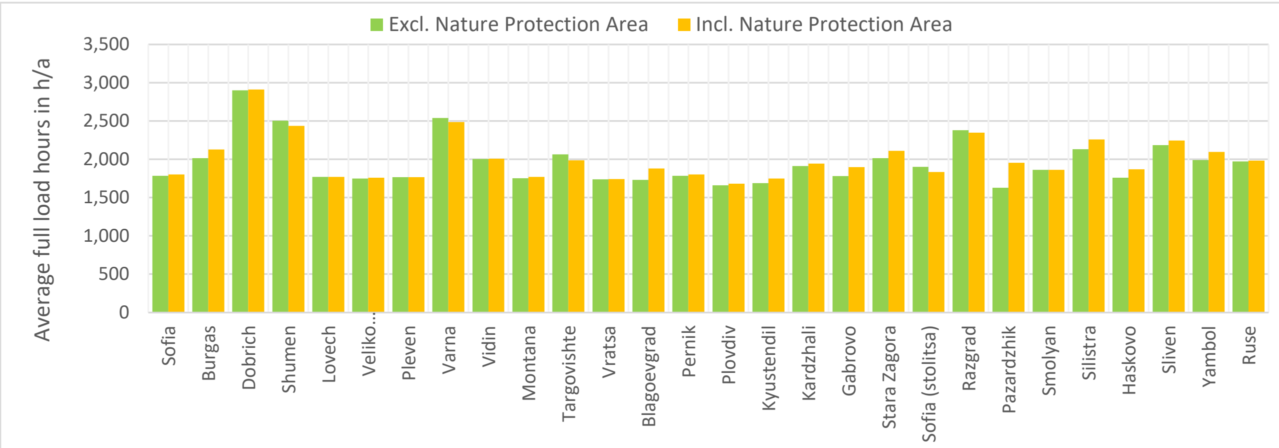


Figure 5: Breakdown of the technical potentials for wind power development in Bulgaria by NUTS-3 region, with consideration of further land use constraints for available areas (via a least-cost allocation) and by excluding or including nature protection areas. Expressed are capacity potentials (top) 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 (from a regional perspective)

This section 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. To put the identified offshore resources of Bulgaria into perspective, we include in addition to Bulgaria also Romania in our result assessment. In this context, Figure 6 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 (ex-pressed in full load hours) as well as nature protection areas and main shipping routes since both are types are excluded from the identification of potentials.

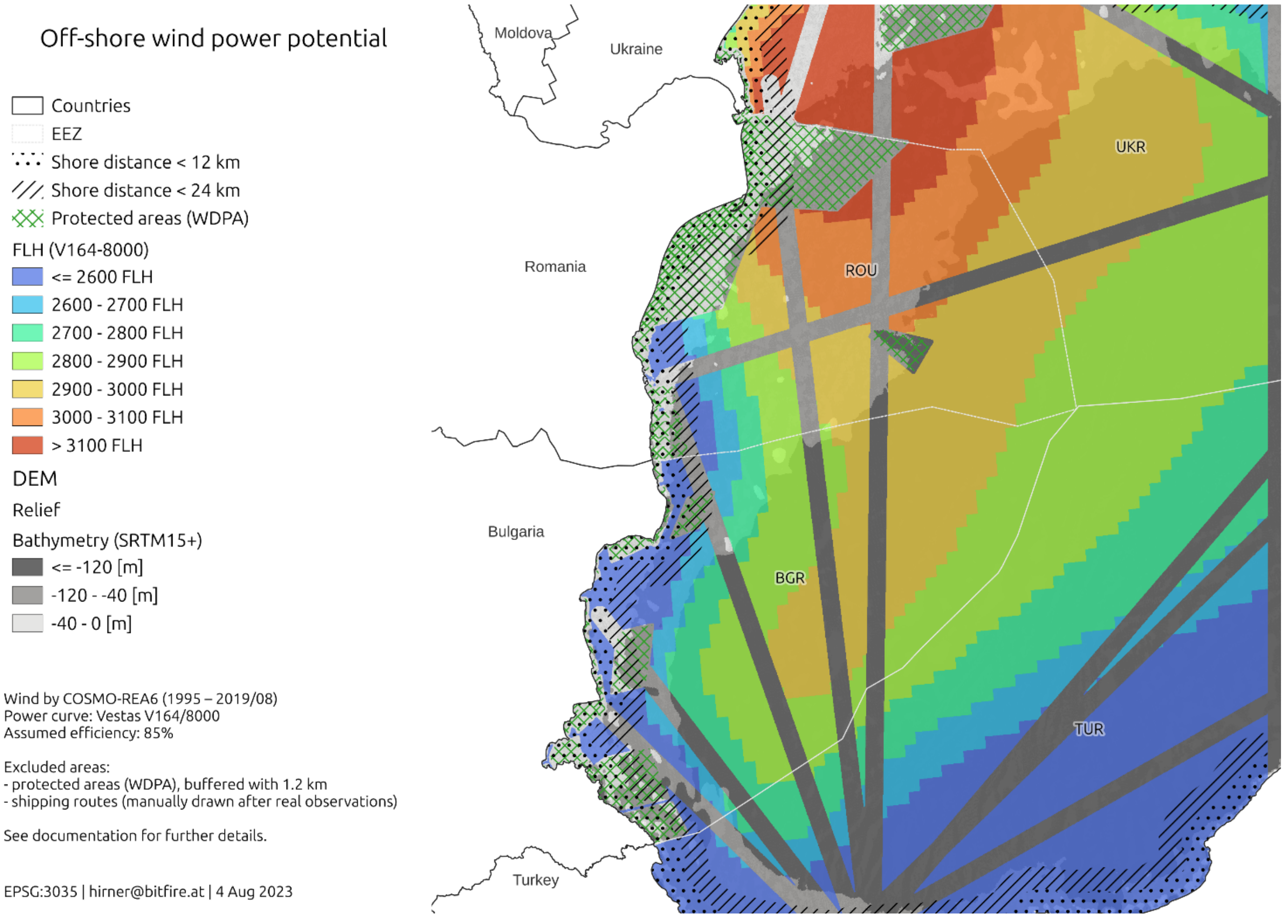


Figure 6: Wind energy at present and in future: Comparison of the status quo (2021), of 2030 deployment targets according to current planning (NECP) and under consideration of new 2030 EU targets as well as of identified technical potentials (with land use constraints)

Complementary to Figure 6 above, the results of our potential analysis are presented in table format below. Thus, Table 8 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 8) and, for sensitivity purposes to simplify the comparison with onshore sites, a typical onshore turbine (moderate generator, large rotor – at the bottom of Table 8). As applicable from these depictions, 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 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.

Table 8: 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 Table 8 above, 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 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.

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 9 provides an overview on the identified technical potentials for wind power development in Bulgaria, distinguishing between onshore (left) and offshore resources (right).

Table 9: 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 10: 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 10 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 10 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 7 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.

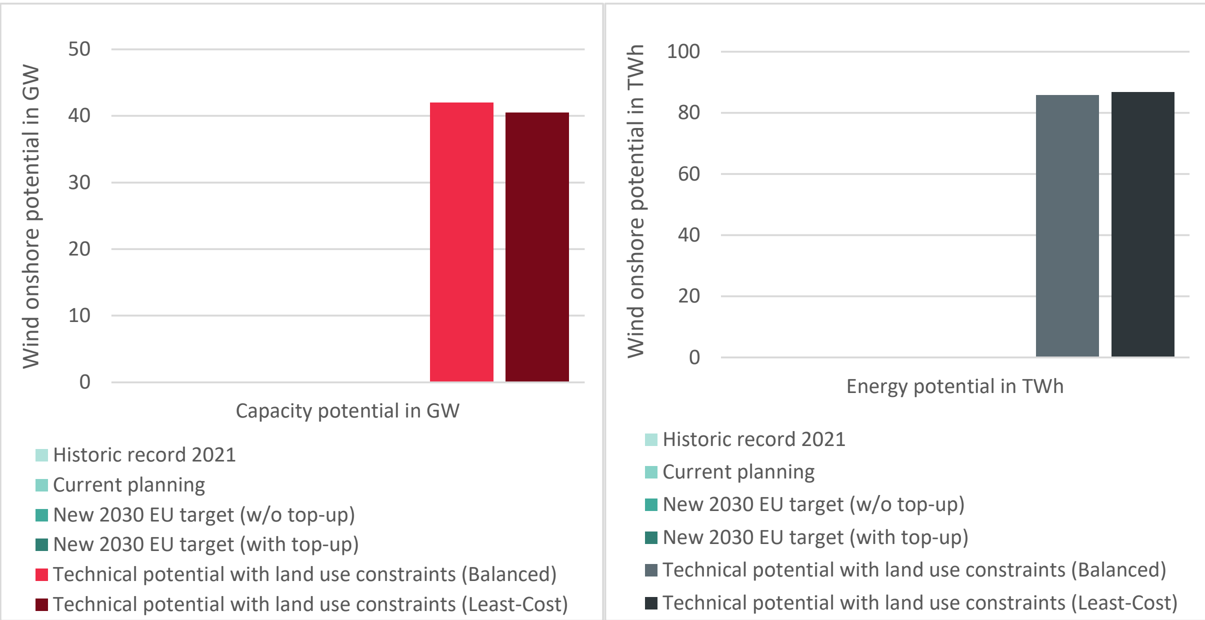


Figure 7: Wind energy at present and in future: Comparison of the status quo (2021), of 2030 deployment targets according to current planning (NECP) and under consideration of new 2030 EU targets as well as of identified technical potentials (with land use constraints). Sources: Eurostat (2023), Republic of Bulgaria (2020) and own analysis.

3.4 Brief consideration of economics

As a teaser for the next chapter that indicates the electricity market impacts of an enhanced wind uptake in future years within Bulgaria 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 8 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.

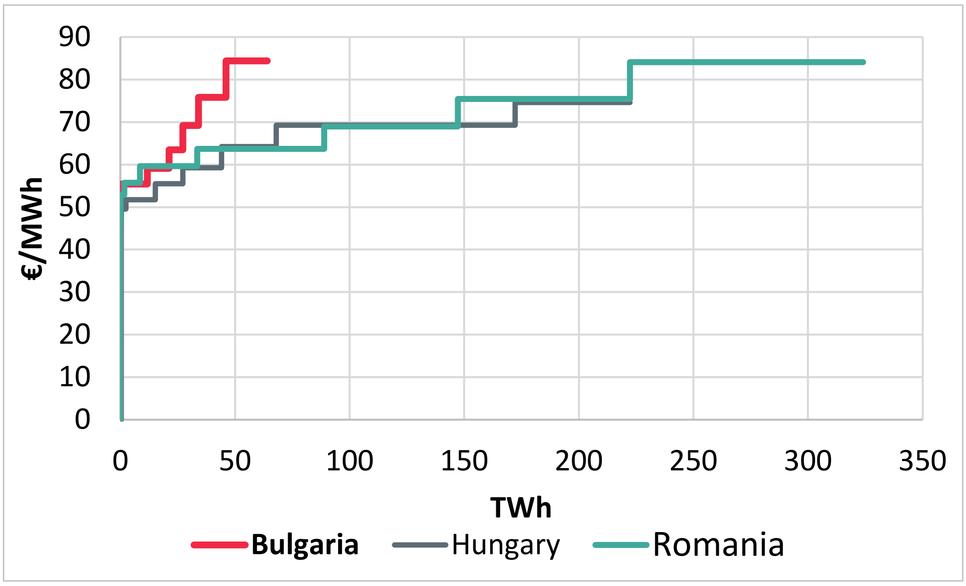


Figure 8: Cost-resource curves of wind onshore in the study region (using technical least-cost potentials with consideration of land use constraints). Source: own analysis

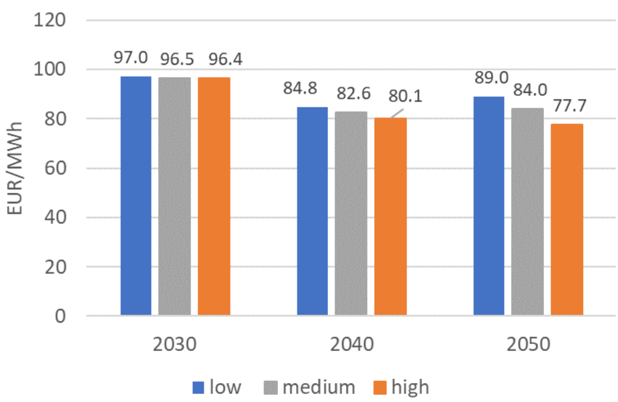
<u>Note on the assumptions for LCOE calculation:</u> Investment cost: 1,500 EUR/kW, O&M cost: 3% p.a. (of investment cost), Interest rate: 6.5%, Depreciation time: 20 years

4 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 outcomes of this analysis, with focus on Bulgaria. Further details on the aggregated results for the whole study region are applicable in the complementary technical report (cf. Resch et al., 2023) of the underlying study.

4.1 Wholesale electricity prices

Wholesale electricity prices follow a generally decreasing trend over time in all scenarios. Figure 9 shows the modelled wholesale electricity prices in the different scenarios (left) and the price differences in the low and high wind penetration scenarios compared to the moderate scenario (right). As expected, due to the merit order effect, the higher penetration of wind capacity reduces the wholesale price in Bulgaria in all modelled years. This price effect is moderate in 2030 (3.9 EUR/MWh between the low and high penetration scenarios), but increases significantly over the years, reaching 11.4 EUR/MWh in 2050. As the installed wind capacity in the three scenarios is much higher in 2050 than in 2030, the price difference is significantly higher in 2050. Wholesale electricity prices follow a generally decreasing trend over time in the high scenario, but in the medium and low cases, prices increase in 2050 compared to 2040.



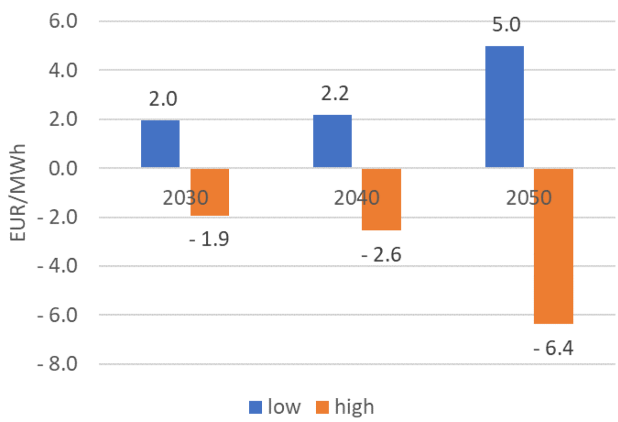


Figure 9: Bulgarian Baseload electricity prices in the different scenarios, €/MWh

4.2 Wind market value

As shown on the left-hand side of Figure 10, the market value of wind decreases with increasing capacities due to the merit-order effect and cannibalisation. The market value of wind is higher than the baseload price in all modelled years and scenarios (ranging between 101-107% of the baseload price). This wind price premium over average prices increases over time in all scenarios from 1-1.5% in 2030 to 4-7% in 2050.

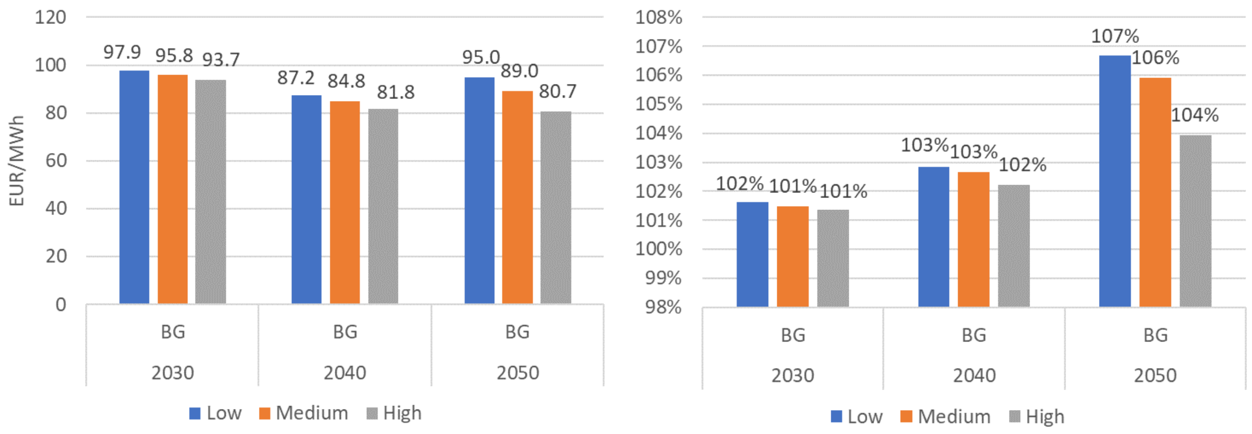


Figure 10: Wind Market value in Bulgaria in the three analysed scenarios, €/MWh (left) and % compared to baseload prices

4.3 PV market value

Similar to the wind market value, the PV market value also decreases over time in all scenarios, from 73-80 EUR/MWh in 2030 to 30-34 EUR/MWh in 2050. However, the PV market value is always lower than the baseload market prices: the PV market value factor is around 80% in 2030, decreasing to 40% in 2050. The change in the PV market value due to the different wind capacity deployment is not significant: the larger wind deployment has a slightly negative impact on the PV market value.

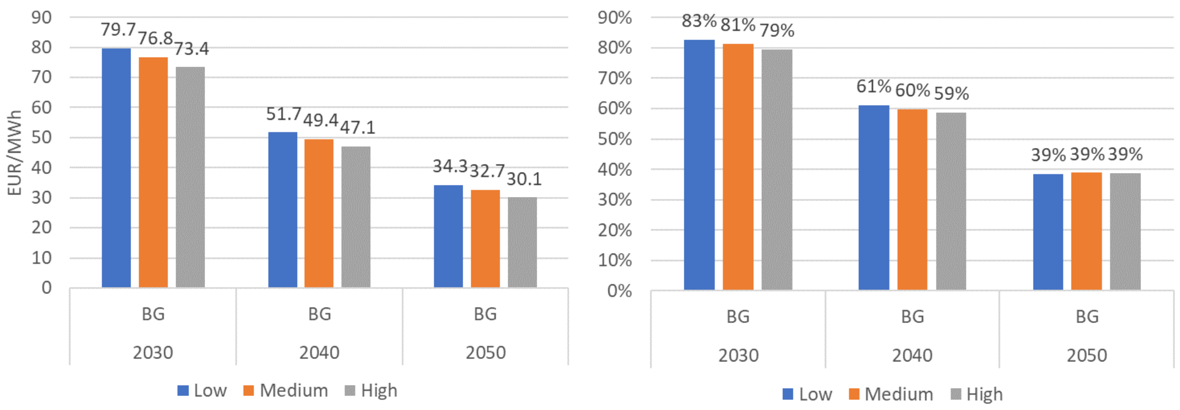


Figure 11: PV Market value in Bulgaria in the three analysed scenarios, €/MWh (left) and % compared to baseload prices

4.4 RES curtailment

The RES curtailment in Bulgaria is negligible in 2030 and 2040 but increases in 2050 and varies considerably depending on the wind penetration: in the low wind penetration scenario it accounts for only 2.5% of the total PV and wind generation but reaches almost 4.5% in the high penetration scenario.

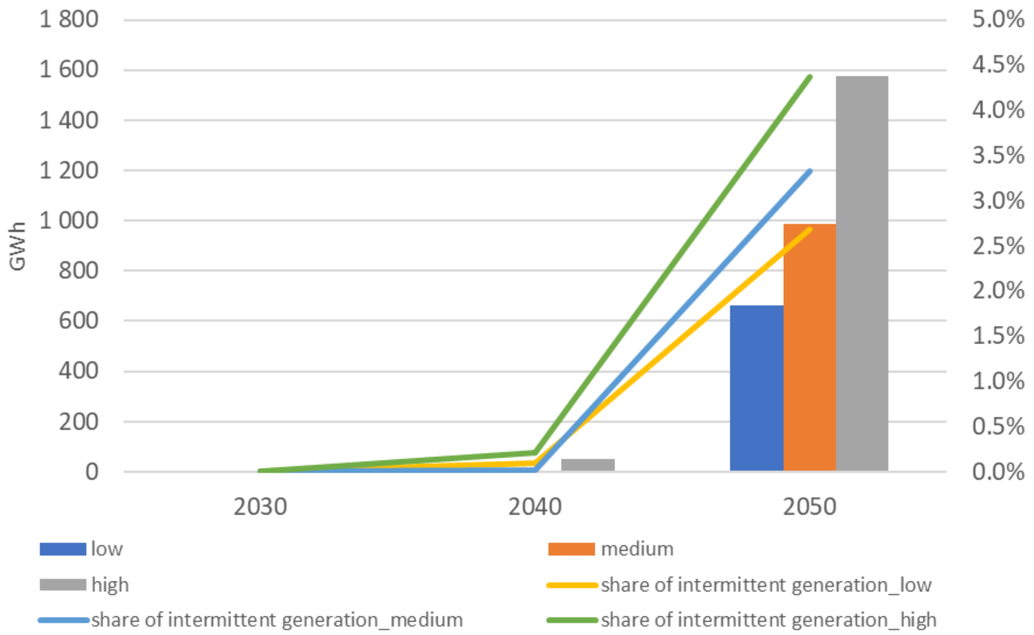


Figure 12: RES curtailment (GWh) and share of intermittent generation (%) in Bulgaria in the three analysed scenarios

4.5 Electricity mix

Higher wind penetration in the region mainly affects Bulgaria's net export ratio, with the country exporting significantly more electricity in the high wind penetration scenario than in low scenario in all modelled years.

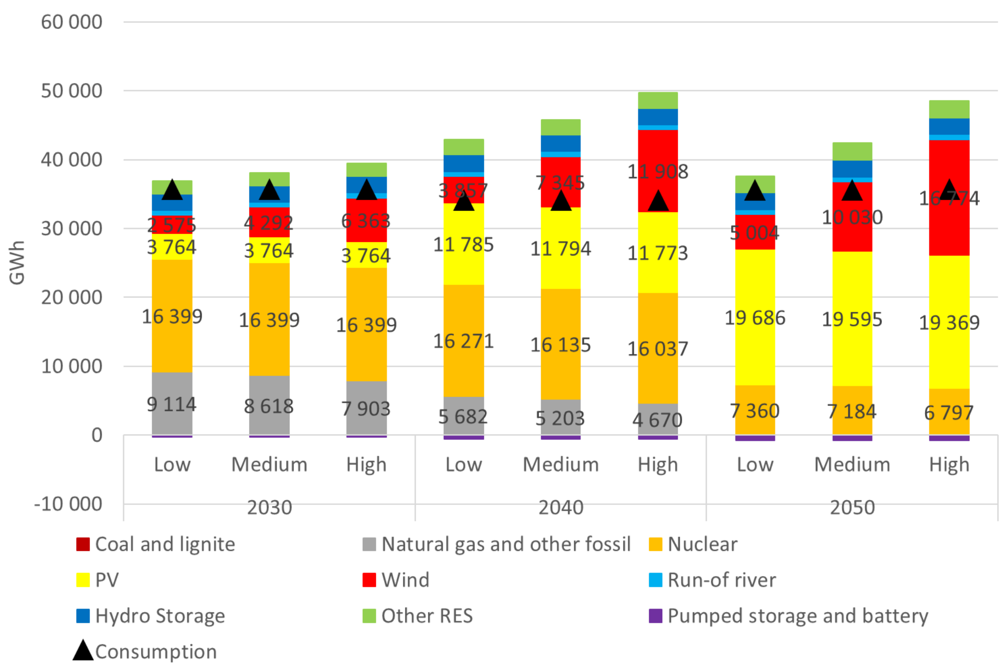


Figure 13: Electricity generation mix and consumption in Bulgaria in the three analysed scenarios, Gwh

Wind deployment has a smaller impact on Bulgarian generation in 2030 and 2040, with the production based mainly on natural gas decreasing as more wind is present, while nuclear and PV generation is slightly lower in 2050.

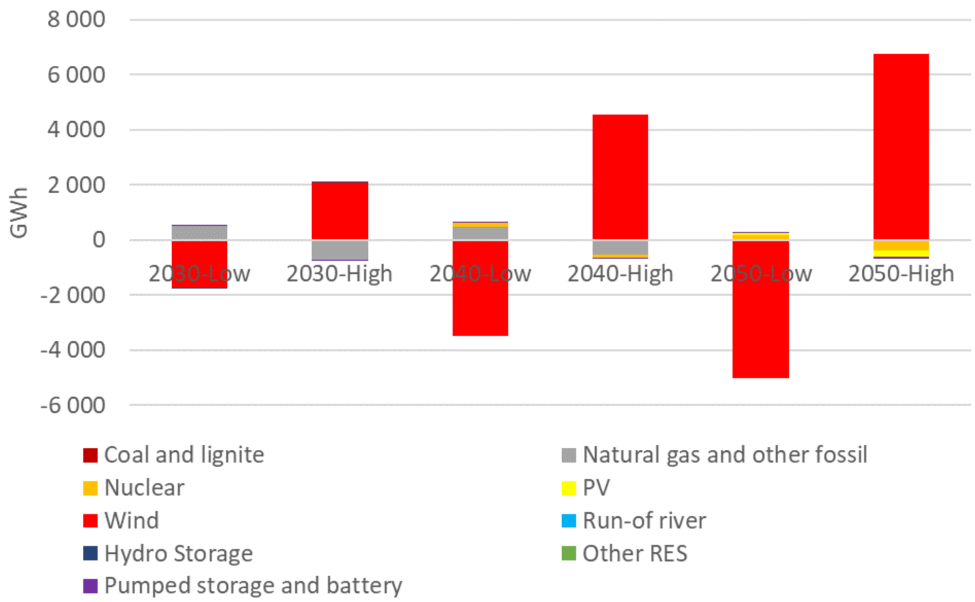


Figure 14: Change of electricity generation from the different technologies compared to moderate wind capacities scenario, GWh

4.6 Balancing Reserve capacity mix

With higher installed wind capacity, the reserve requirement in Bulgaria is higher in all years and scenarios in both the upward and downward directions. In the downward direction, the share of wind capacity in reserves increases as more wind capacity is installed. Wind substitutes natural gas and other RES (PV and hydro storage) in 2030 and natural gas in 2040 in the downward direction. On the other hand, the share of natural gas capacity increases in the upward direction. In 2050 the additional reserve capacity need is provided by wind and other RES (PV and hydro) in the downward direction and by hydro in the upward direction.

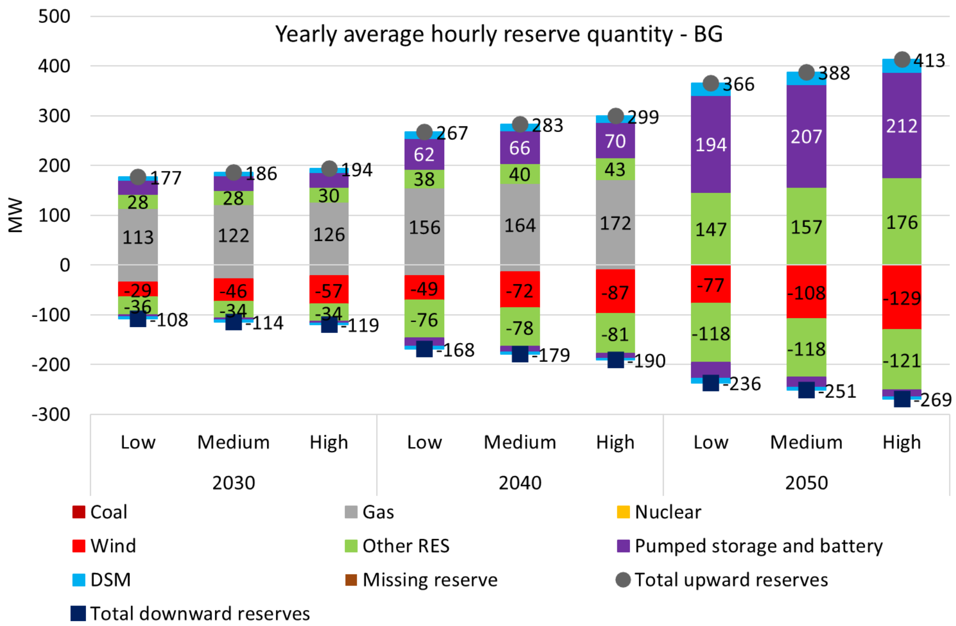


Figure 15: Composition of reserve capacities in the different scenarios, MW

4.7 CO_2 emissions

The CO_2 emission of Bulgaria decreases over time, and a carbon neutral electricity system is achieved by 2050. More wind capacity in the region tends to reduce Bulgaria's CO_2 emissions by around 500 kt in both 2030 and 2040 comparing the low and high scenarios.

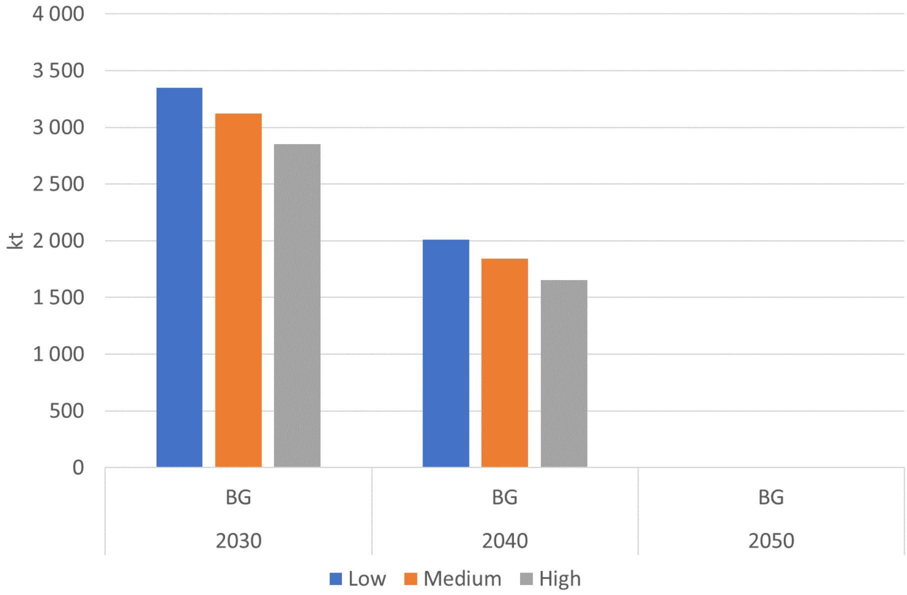


Figure 16: CO_2 emissions in the different scenarios, kt

5 CONCLUDING REMARKS

The overall potential for both onshore and offshore wind in Bulgaria is significant in energetic terms, by far exceeding the current level of overall electricity consumption. A closer look at the regional breakdown of the technical onshore wind potentials and of corresponding wind resources allows for identifying at least five regions within Bulgaria 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.

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 at present (0.7 GW) and in current energy planning (0.95 GW until 2030 according to the 2019 National Energy and Climate Plan of Bulgaria (Republic of Bulgaria, 2019)), we can conclude 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.

The assessment of market impacts as well as the brief consideration of economics for wind power confirm the above. Thus, Bulgaria offers promising wind sites at comparatively 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 Bulgaria and it will be beneficial for Bulgaria's combat against climate change, causing a further decline of carbon emissions in future years.

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