COUNTRY REPORT HUNGARY

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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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 country report is dedicated to informing on **the approach and the results derived for Hungary**, 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 Hungary 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.

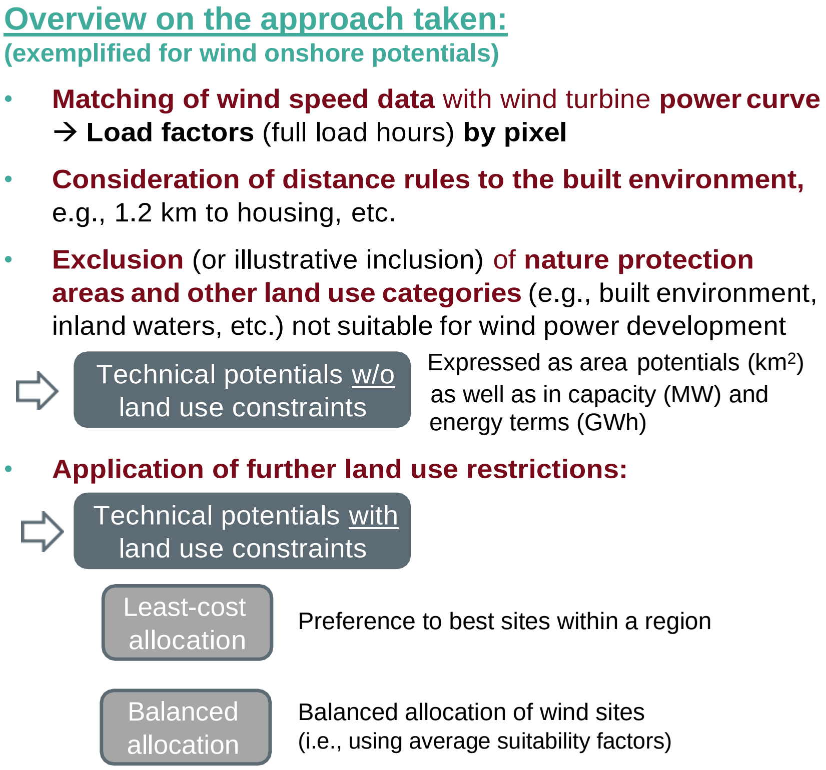

Figure 1: Overview on the approach taken for the assessment of wind potentials in the study region (exemplified for onshore wind)

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 Hungary – 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.

  Apart from Hungarian 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 the country, 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%

Complementary to the above, we also showcase the impact of excluding vs including nature protection areas into the classification of available areas for wind power development since that topic appeared of interest for stakeholder in Bulgaria and Romania

- 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.
      Specifically for Hungary, as part of the sensitivity analysis that reflects current (as of September 2023) legislative constraints, we also apply 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.
    - For offshore, being relevant at a regional context but not for Hungary, 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.

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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.

- 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-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 marked as “Including Nature Protection Areas”. Please note further that for onshore wind we generally exclude 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 as default, respecting that wind power development should not harm the local community via noise or shading, etc.

      Specifically for Hungary, as part of the 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).
    - 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 1,600 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 (as relevant for the Black Sea region in Bulgaria and Romania).

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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.

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, as relevant from a regional perspective for Bulgaria and Romania, the breakdown into 12 categories respects differences in water depth and distance to the shore, with impact on corresponding cost of electricity generation and wind farm design.

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.

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

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

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 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.

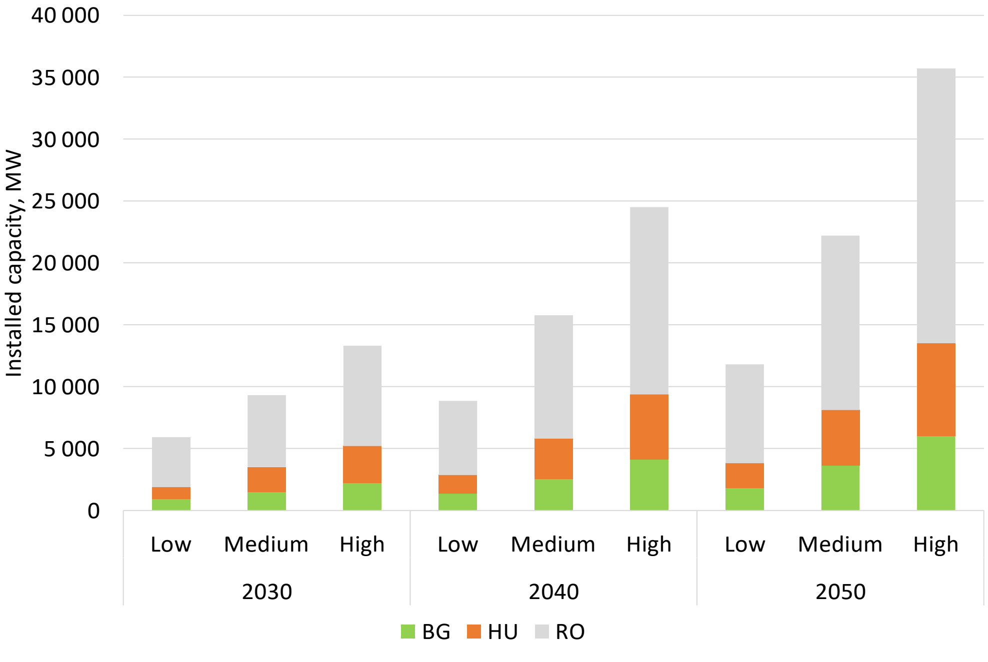

Figure 2: Wind installed capacities in the three analysed scenarios in the modelled years, MW

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 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 3.1) the results related to onshore wind within Hungary. Next to that, within section 3.2 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 3.3, illustrating the role wind power may be able take in future electricity supply within Hungary.

3.1 Wind potentials in Hungary

Looking at the geographical and topographical context as described in Wikipedia[4], 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.

3.1.1 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 2, 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 2: 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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[4] Cf. https://en.wikipedia.org/wiki/Geography_of_Hungary.

Table 2: 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 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 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 3, 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 3: 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 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 third of the unconstrained one.

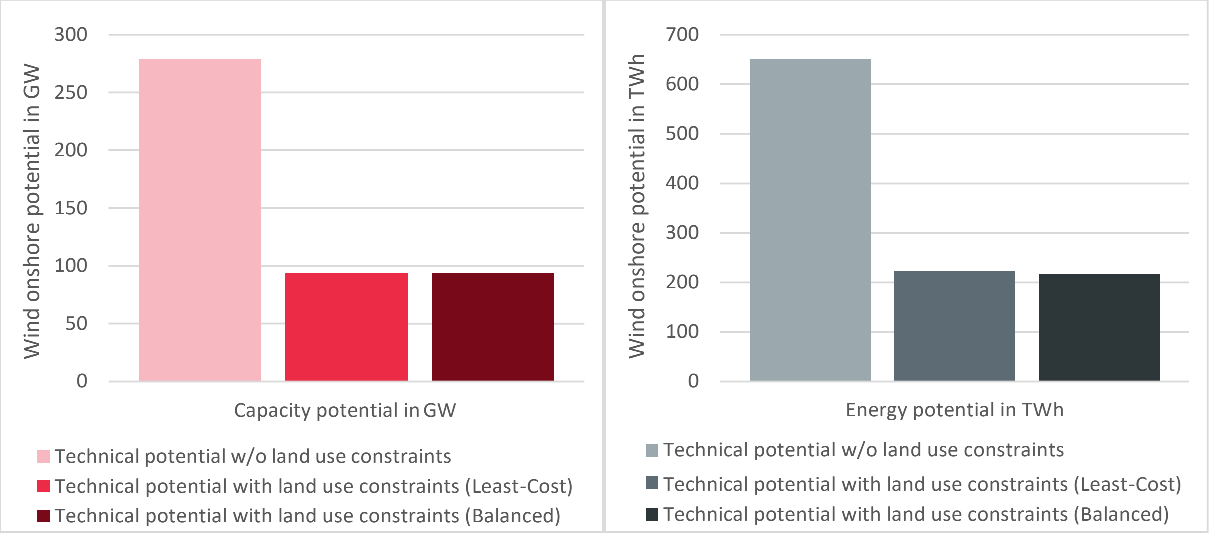


Figure 3: Technical potentials for onshore wind in Hungary, w/o and with (further) land use constraints (at feasible areas), expressed in capacity (left) and energy terms (right) for assessed allocation options (least-cost vs balanced). Source: own analysis.

3.1.2 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 4 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.

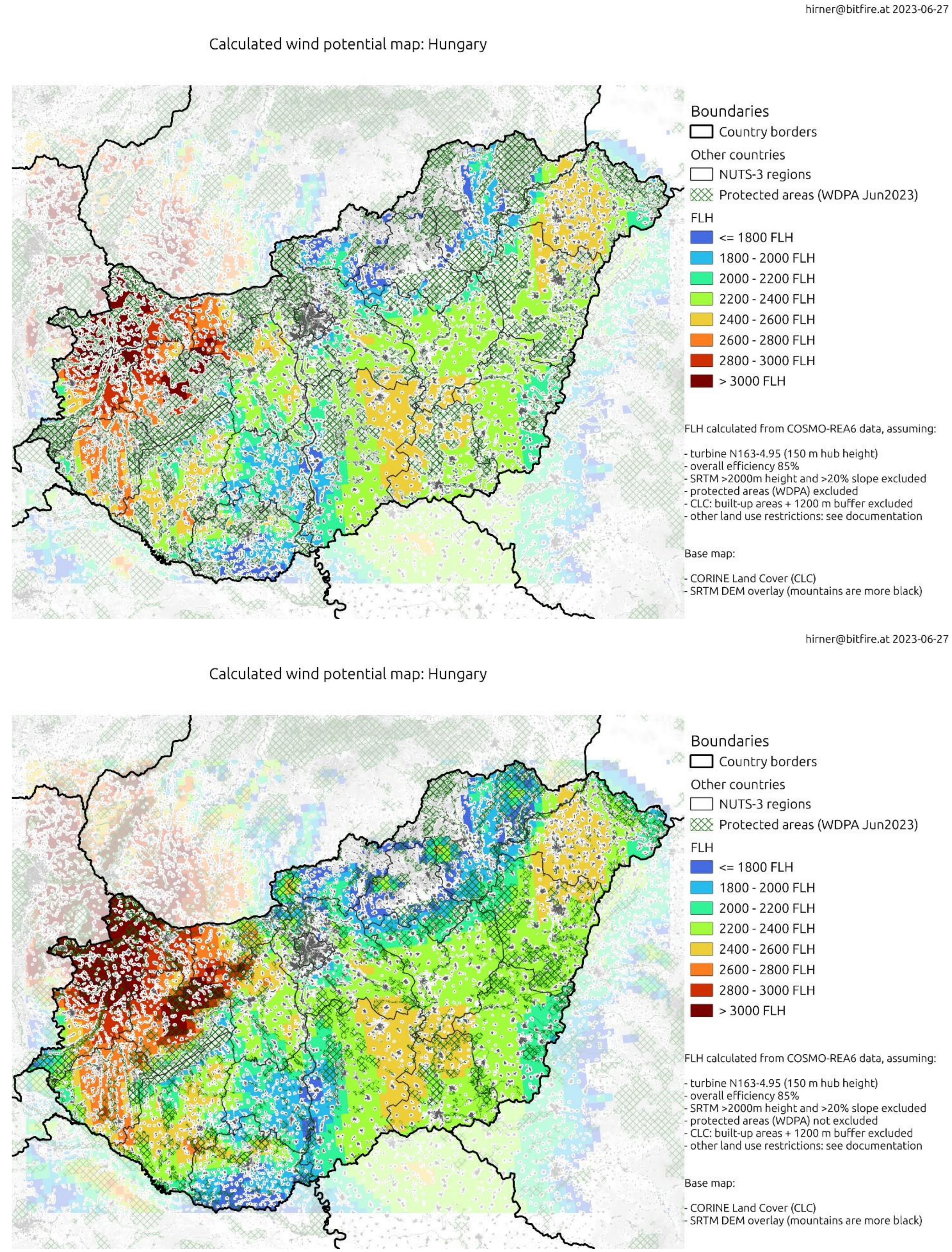


Figure 4: Wind maps for Hungary, indicating site qualities (expressed in full load hours) and by excluding (top) vs including (bottom) nature protection areas. Source: own analysis.

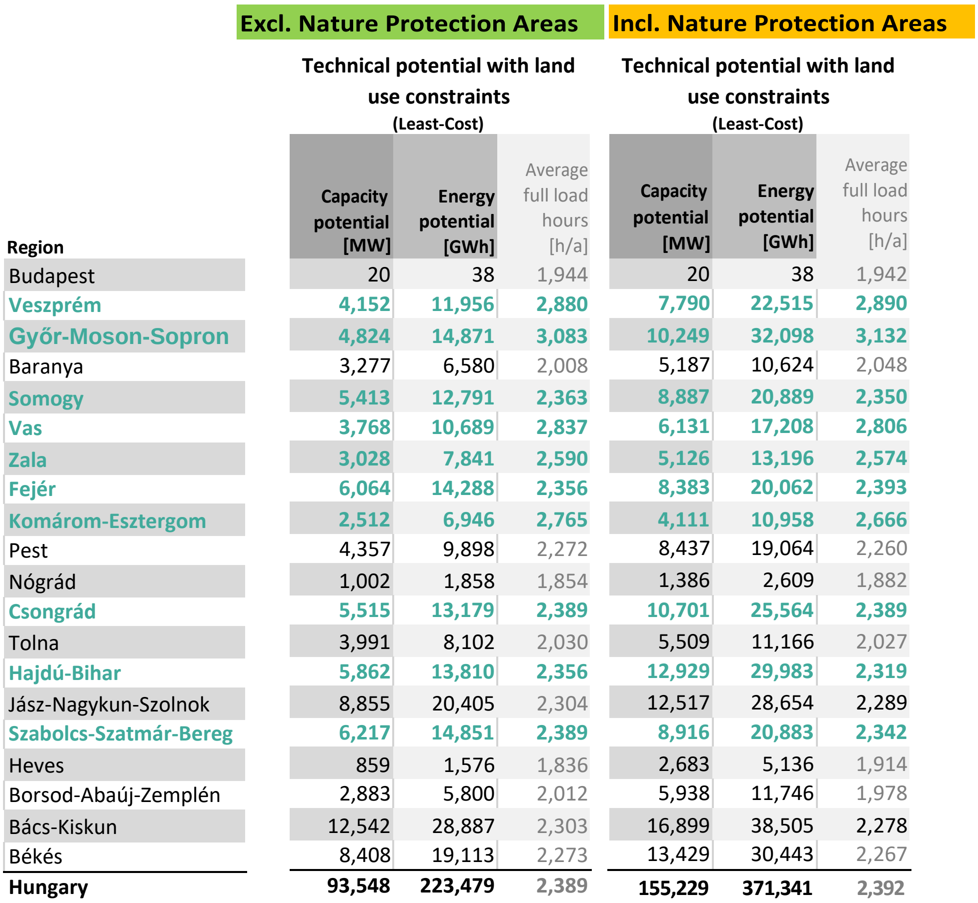
The technical details on wind potentials and average site qualities per region as discussed above are listed in Table 4 below. This table offers a breakdown of the technical potentials for wind power development in Hungary by NUTS-3 region, without consideration of further land use constraints for available 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 4, or, from the numbers listed in Table 4, 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 4: 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 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 Hungary. 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 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 5 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 4. 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.

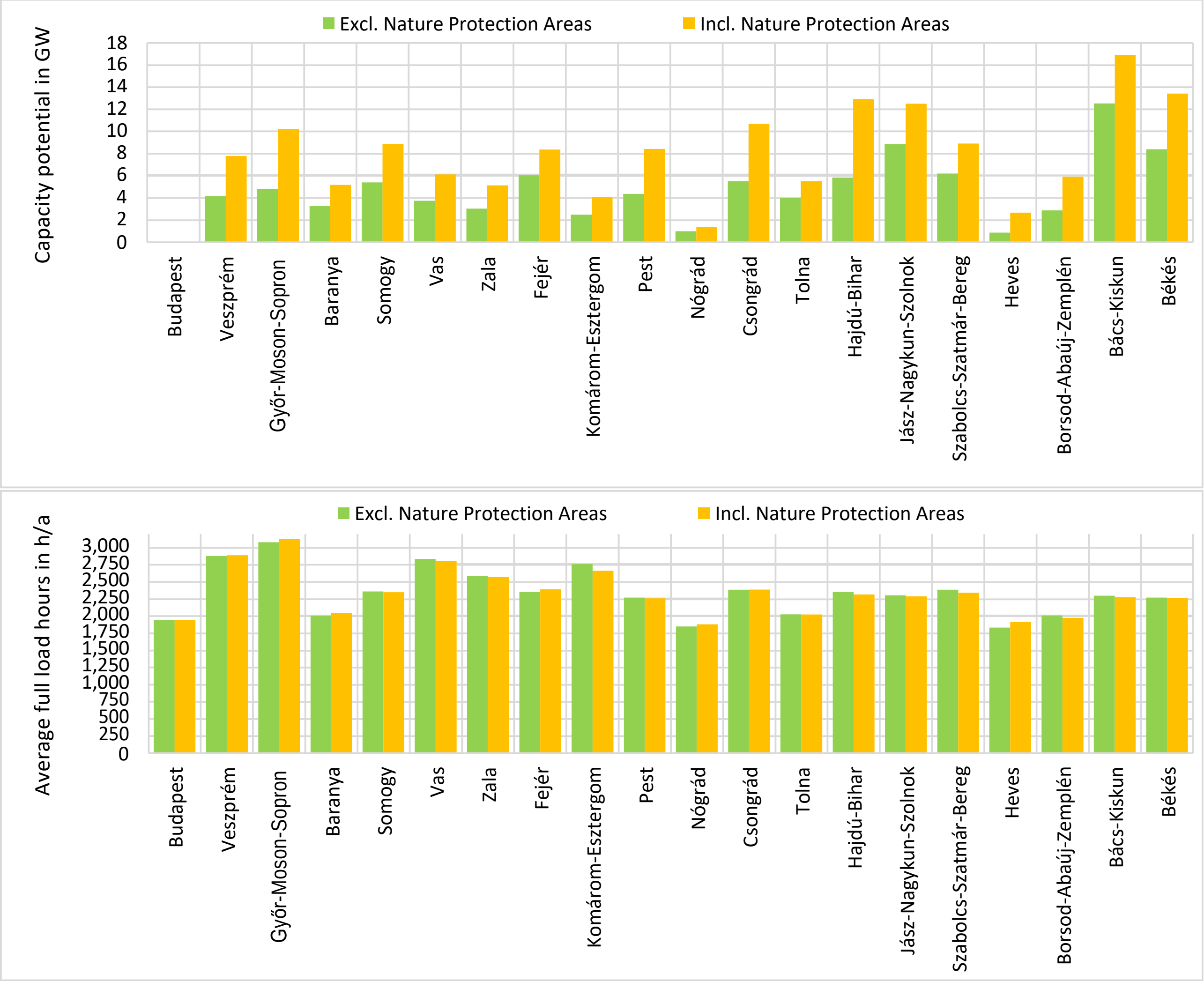


Figure 5: Breakdown of the technical potentials for wind power development in Hungary by NUTS-3 region, with consideration of further land use constraints for available areas (via a least-cost allocation) and by excluding or including nature protection areas. Expressed are capacity potentials (top) and average site qualities (full load hours) per region. Source: own analysis

Complementary to the above, Table 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 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**

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 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 7: 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**

3.2 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.

3.2.1 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).

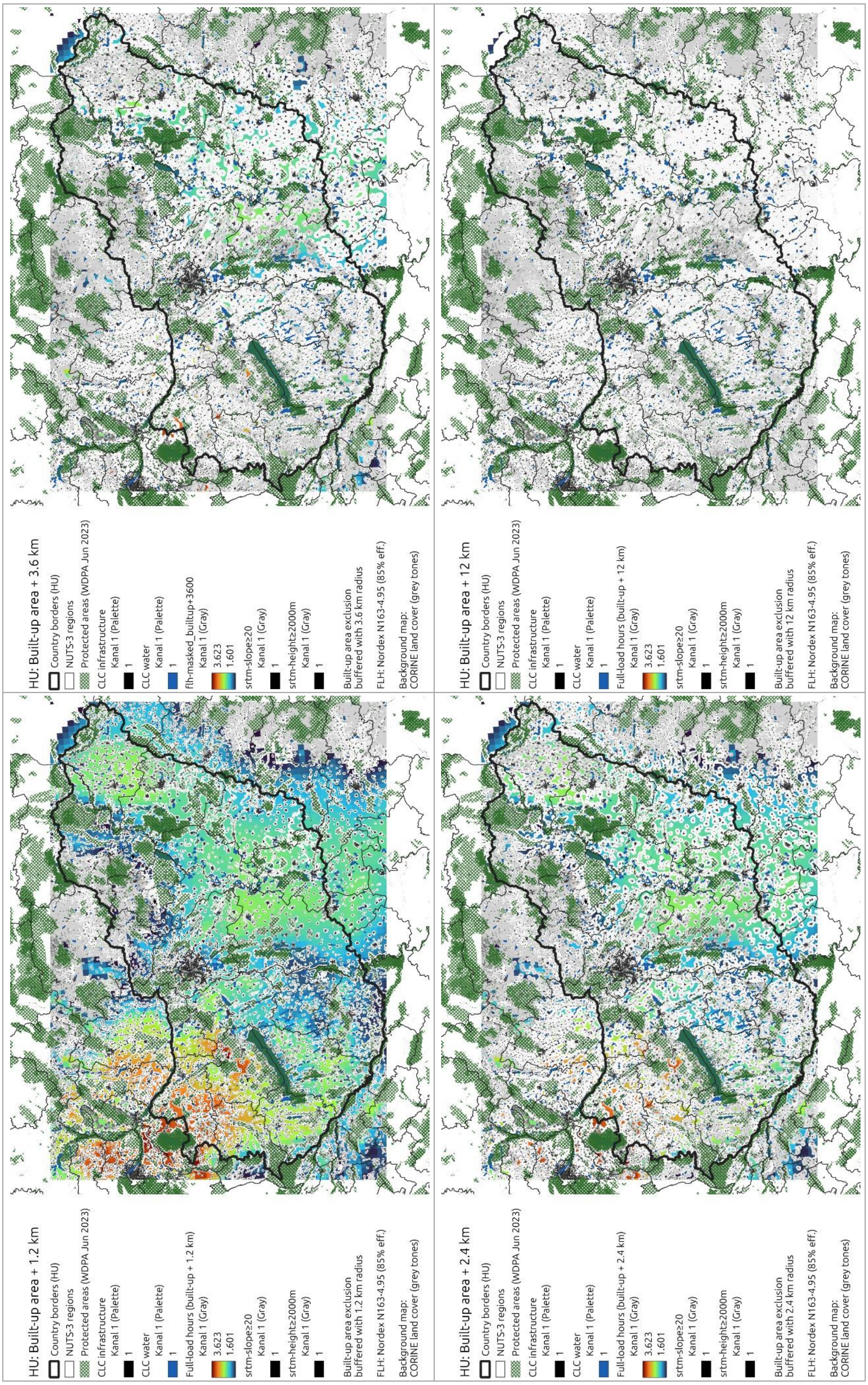


Figure 6: Wind maps for Hungary in dependence of the applied distance rules (to the built environment), indicating site qualities (expressed in full load hours) for feasible areas (excl. nature protection areas). Source: own analysis

Table 8: 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 6. 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 8 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).

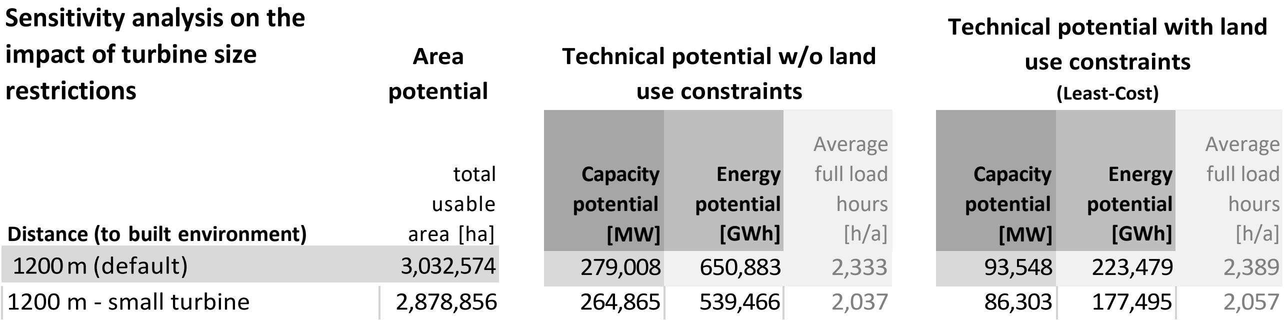
Remarkably, considering the current (as of September 2023) legislative practice, no wind power plant can be developed within Hungary. Loosing that restriction to 4.8 km or 3.6 km would allow for a limited uptake of wind power in future, i.e., 9.5 GW or 35.7 GW considering the technical potentials w/o 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.

3.2.2 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 8 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 9: 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



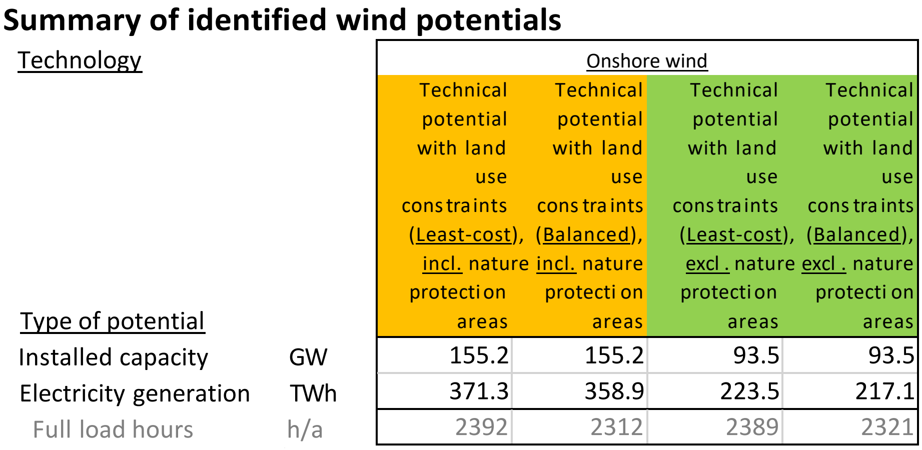
Sensitivity analysis on the impact of turbine size restrictions	**Area potential**	**Technical potential w/o land use constraints**			**Technical potential with land use constraints (Least-Cost)**		
Distance (to built environment)	total usable area [ha]	**Capacity potential [MW]**	**Energy potential [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.

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

Table 10: 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.

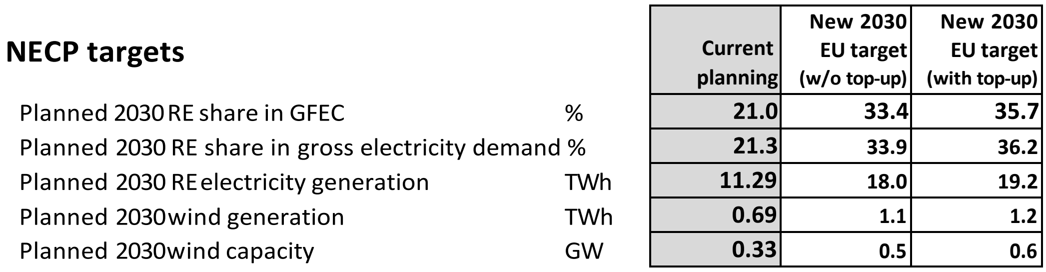


Summary of identified wind potentials

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 11 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 11 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 11: 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 6 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.

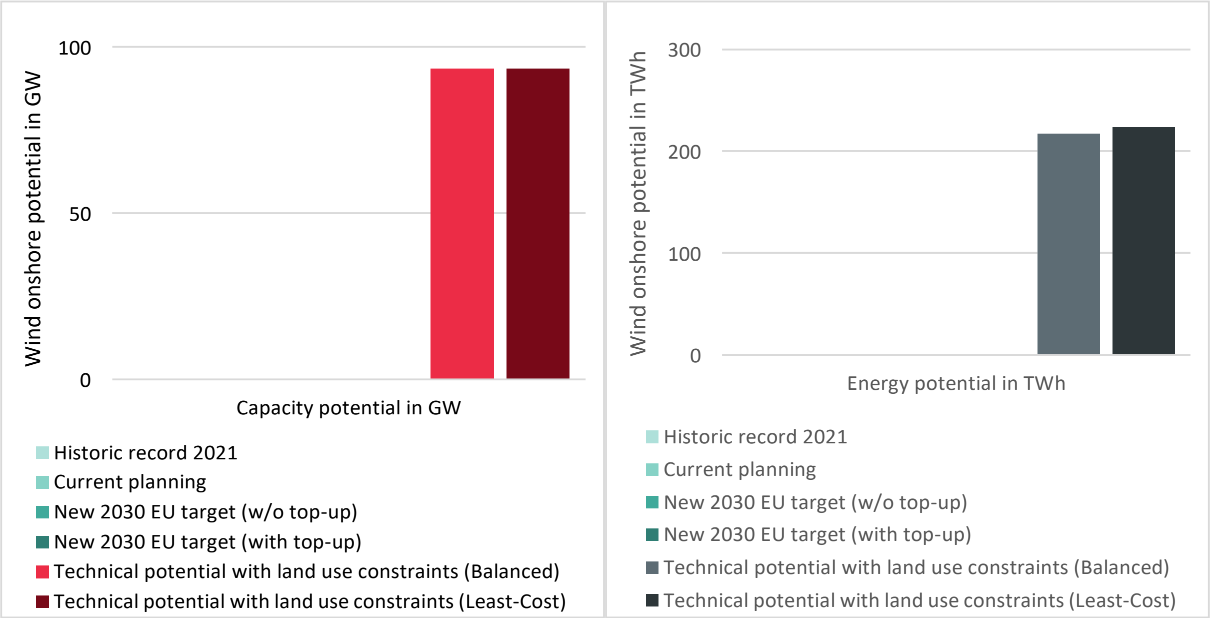


Figure 7: Wind energy at present and in future: Comparison of the status quo (2021), of 2030 deployment targets according to current planning (NECP) and under consideration of new 2030 EU targets as well as of identified technical potentials (with land use constraints). Sources: Eurostat (2023), Republic of 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 4), 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.

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 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 8 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.

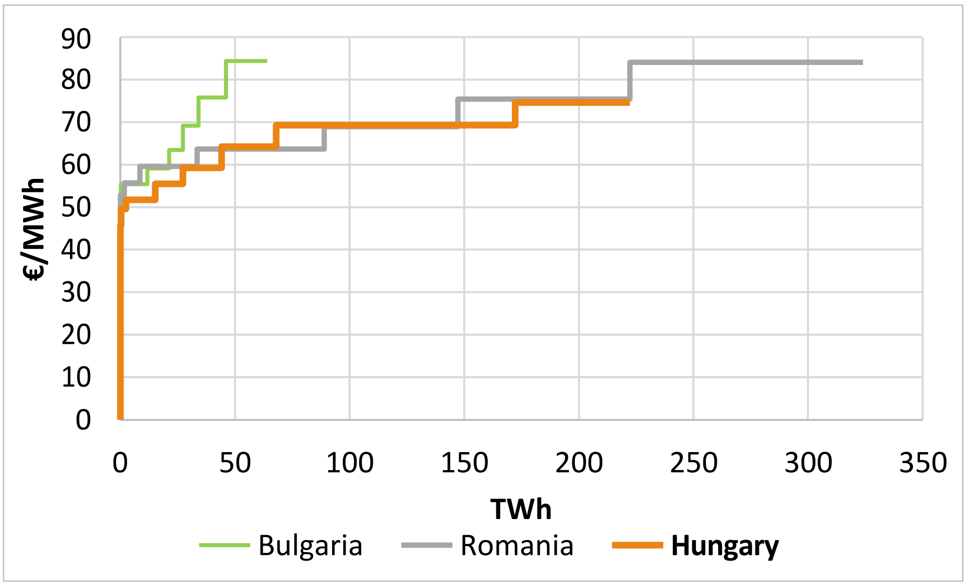


Figure 8: Cost-resource curves of wind onshore in the study region (using technical least-cost potentials with consideration of land use and nature protection constraints). Source: own analysis.

<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

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.

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 in further detail, 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. As described in section 2.2, assumptions taken in this respect for Hungary are as follows:

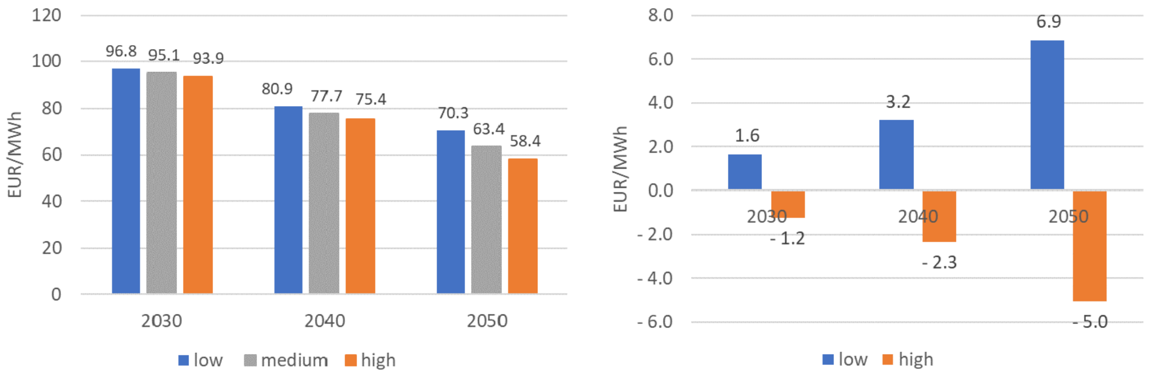
- The “low wind penetration” scenario implies an increase of wind deployment from at present (2021) 0.3 GW to 1.0 GW by 2030, increasing steadily further up to 2.0 GW by 2050.
- In contrast to the above, in the “high wind penetration” scenario a significantly stronger uptake of wind power is presumed, 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.

The sections below inform on the outcomes of this analysis, with focus on Hungary. 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 Hungary in all modelled years. This price effect is moderate in 2030 (2.9 EUR/MWh between the low and high penetration scenarios), but increases significantly over the years, reaching 11.9 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 all scenarios.

Figure 9: Hungarian 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 capacity due to the merit-order effect and cannibalisation. The market value of wind is higher than the baseload price in most of the modelled years and scenarios (ranging between 101-104% of the baseload price). The only exception is the high penetration scenario in 2050 where the market value factor is 99%. The price premium of wind generation relative to average prices increases from 2030 to 2040 but decreases between 2040 and 2050 in all scenarios.

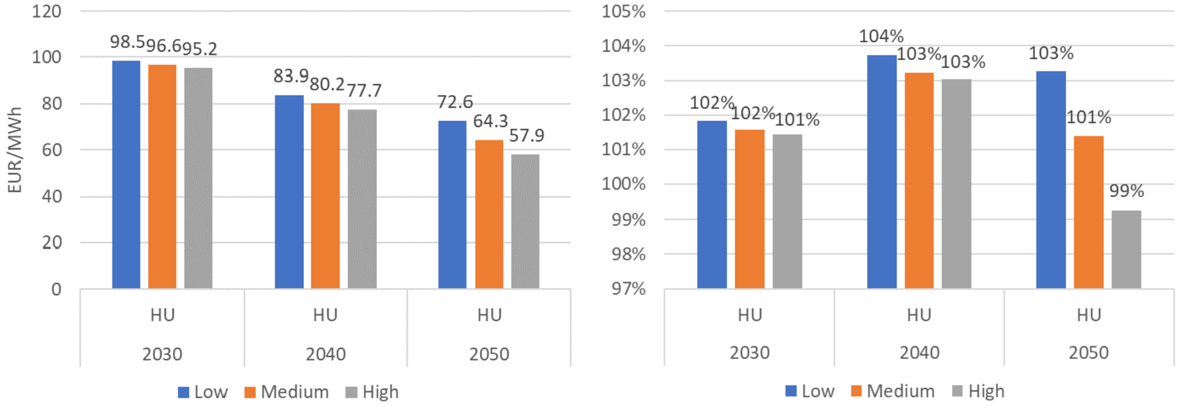


Figure 10: Wind Market value in Hungary in the three analysed scenarios, €/MWh (left) and % compared to base-load prices

4.3 PV market value

Similar to the wind market value, the PV market value also decreases over time in all scenarios, from 74-78 EUR/MWh in 2030 to 25-28 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 around 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.

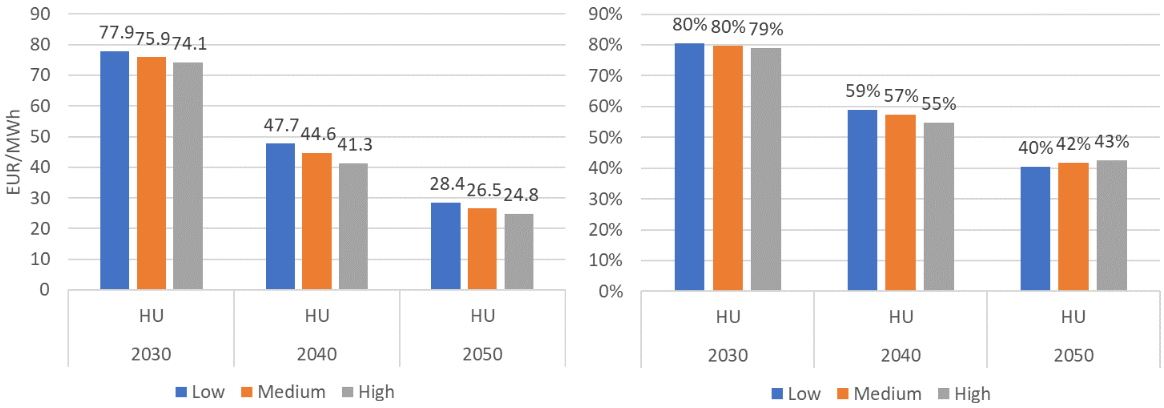


Figure 11: PV Market value in Hungary in the three analysed scenarios, €/MWh (left) and % compared to baseload prices

4.4 RES curtailment

The RES curtailment in Hungary 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 3% of the total PV and wind generation but rises to over 5% in the high penetration scenario.

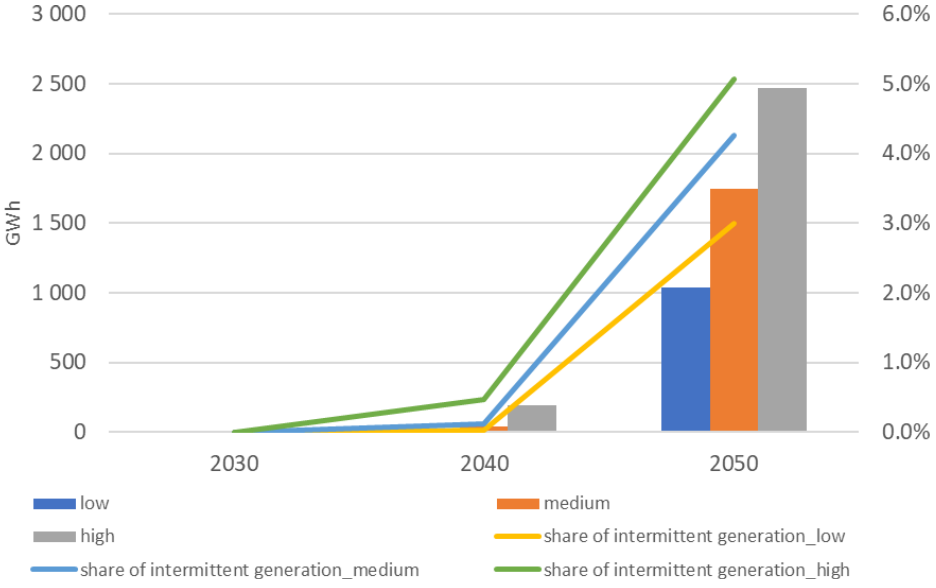


Figure 12: RES curtailment (GWh) and share of intermittent generation (%) in Hungary in the three analysed scenarios

4.5 Electricity mix

Higher wind penetration in the region mainly affects Hungary's the net import ratio, with the country importing significantly less electricity in the high wind penetration scenario than in low scenario in all modelled years.

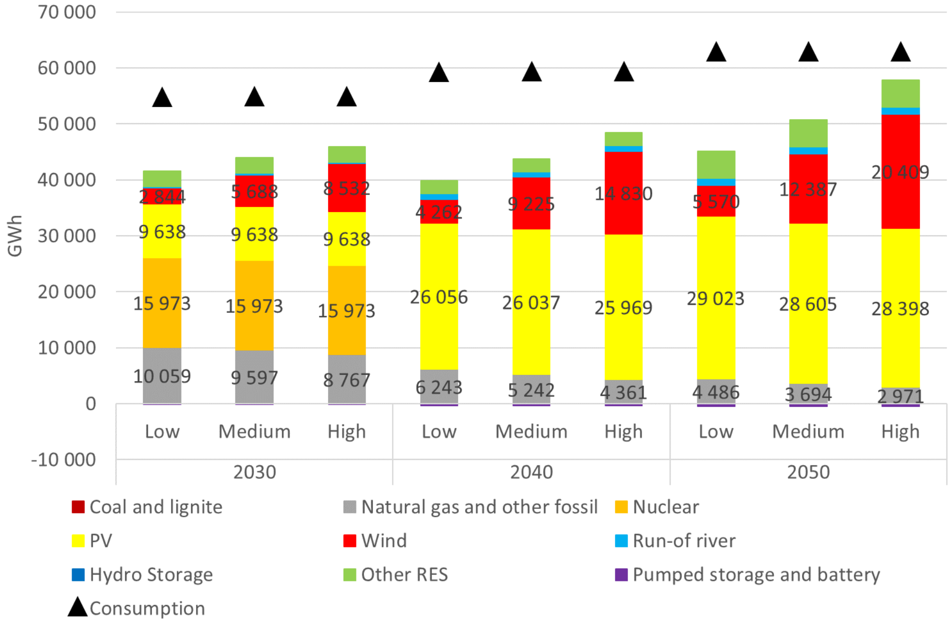


Figure 13: Electricity generation mix and consumption in Hungary in the three analysed scenarios, GWh

Wind deployment has an increasing impact on Hungarian generation over time, with the production based mainly on natural gas decreasing as more wind is available, while PV generation is also slightly affected in 2050.

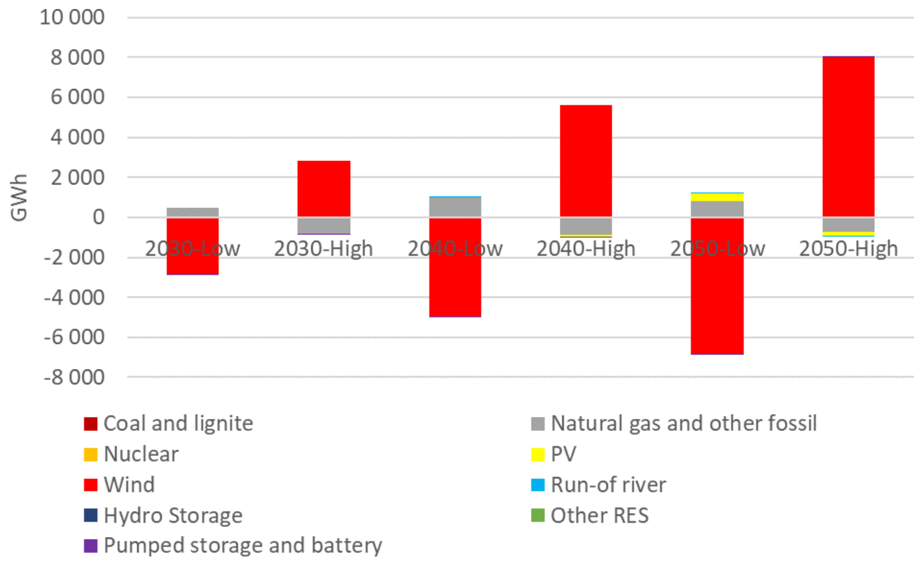


Figure 14: Change of electricity generation from the different technologies compared to moderate wind capacities scenario, GWh

4.6 Balancing Reserve capacity mix

With higher installed wind capacity, the reserve requirement in Hungary 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. In the downward direction, wind mainly substitutes natural gas in all modelled years. This increased capacity is partly provided by wind itself, but other RES (in case of Hungary it is PV) reserve capacities are also growing. In the upward direction, the additional reserve capacity needs due to higher wind penetration are mainly covered by natural gas at the beginning of the period and by batteries and DSM in 2050.

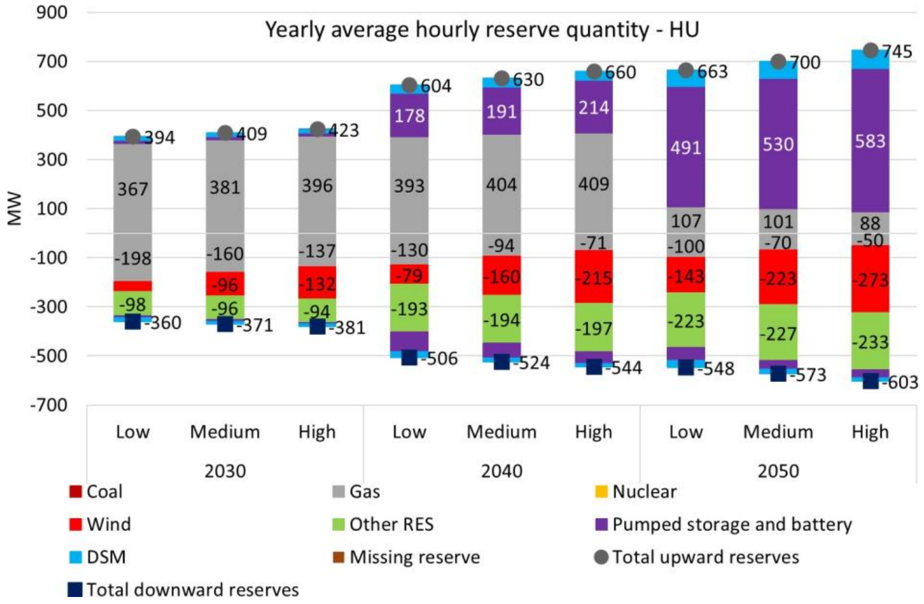


Figure 15: Composition of reserve capacities in the different scenarios, MW

4.7 CO_2 emission

The CO_2 emission of Hungary decreases over time, cf. Figure 16. More wind capacity in the region tends to reduce Hungary's CO_2 emissions by around 1000 kt in 2030 and 500 kt in 2040 and 2050 comparing the low and high scenarios.

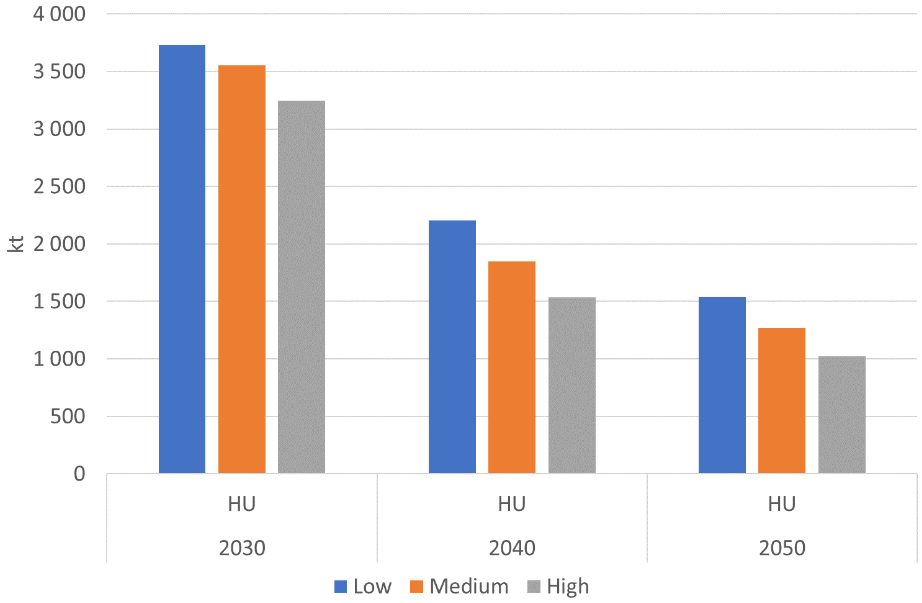


Figure 16: CO_2 emissions in the different scenarios, kt

5 CONCLUDING REMARKS

The overall potential for onshore wind in Hungary 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 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.

Taking a closer look at the role of wind power in Hungary at present (0.3 GW) and in current energy planning (i.e., no uptake planned until 2030 according to the 2019 National Energy and Climate Plan of Hungary (Republic of Hungary, 2019)), 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. 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, Hungary offers promising wind sites at comparatively cheap 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 Hungary and it will be beneficial for Hungary's combat against climate change, causing a further decline of carbon emissions in future years.

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