D2.1 EUROPE-WIDE ENERGY SYSTEM SCENARIOS FOR WIND DEPLOYMENT AREAS

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Description	We present methods, data and first scenarios of the upgraded energy system model »Sector-coupled Euro-Calliope«, including novel wind energy technologies airborne wind and floating offshore. This comprises an updated estimation of area potentials for the European countries' EEZ, an evaluation of the available wind resources available to airborne wind and cost estimates. With these implemented to the energy system model, first scenarios are presented that serve as a basis for new optimisation approaches to be developed in the next tasks of WP2.

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1 INTRODUCTION

Wind energy, together with PV, will form the backbone of a future renewable energy system. There is a growing scientific and political consensus that speeding up the deployment and integration of these generation technologies is necessary to reach decarbonization goals. However, at the implementation level, several factors impede the rapid build-up of wind capacity. These can be delayed planning and permitting processes, low popularity and resistance towards new wind projects by local actors, as well as conflicting goals of local governments.

In JustWind4All, we investigate how novel practices and technologies can help find ways to overcome these obstacles. Participatory practices, financial participation or energy communities can facilitate consensus among the local actors and population. Novel technologies can open up new potential for perhaps more acceptable solutions. E.g, repowering existing wind farms and deploying floating offshore wind or airborne wind may offer new and possibly better ways to use existing space and wind resources.

To evaluate how these potential benefits may play out on a system level, energy system modeling can be helpful. State-of-the-art energy system models usually represent wind energy in high spatial and temporal resolution and distinguish between onshore and offshore wind. However, two important novel technologies on the horizon — floating offshore and airborne wind energy (AWE) — have so far not been investigated through energy system model-based scenarios for the entirety of Europe.

Here, we do the following. We implement new wind technologies in the existing energy system model »Sector-coupled Euro-Calliope«. Specifically, we add airborne wind onshore and offshore, and floating offshore platforms for wind energy. To this end, we assess the technical potential for airborne wind energy using meteorological data at high spatial resolution and covering all Europe. We distinguish between several power curves characteristic to the technologies. To investigate floating offshore wind energy, we revise the model's offshore wind-deployment areas to differentiate between areas suitable for fixed-bottom and floating offshore platforms.

The rest of this document is organized as follows: In chapter 2 (Methods and Data), we describe our approach to prepare and add techno-economic potentials for airborne wind energy and floating conventional offshore to the existing energy optimisation model for Europe. In chapter 3, we present area and power potentials as well as hourly capacity factors for multiple weather years. We compare them to the previous model inputs and show initial scenario results obtained by adding the new data and assumptions to the existing energy system model. We conclude and discuss these in chapter 4 (Discussion & Conclusion). The Appendix presents a comprehensive set of plots showing capacity factors for all regions.

2 METHODS AND DATA

2.1 AREA AND POWER POTENTIAL

To assess the potential for deployment for wind energy of a country or region, several criteria need to be considered in a GIS analysis to estimate the available area and the amount of capacity that can be built in that area. For onshore wind energy, common factors that limit the available area are settlements, large infrastructure, forests, nature reserves and areas used for other purposes, e.g. military use.

In this work, we re-use the existing area potential assessments for onshore wind (Tröndle, Pfenninger, and Lilliestam 2019) which are part of our existing model. The model distinguishes between potential areas where only wind turbines can be installed and other areas, where wind competes with open-field PV.

In order to represent novel floating offshore wind technologies, we re-evaluate the area potentials for offshore wind energy within the exclusive economic zones of European countries. To this end, we distinguish between areas with shallow water, suitable for fixed-bottom platforms (tripods or monopiles), and areas with water deeper than 60m. At deeper waters, fixed-bottom platforms reach technical and economic limits, which makes the use of floating platforms favourable.

From the described areas we remove nature reserves defined by Europe's Natura2000 zones. At this stage, we do not consider other criteria like military areas, shipping lanes or others. This means that the results of the analysis overestimate the theoretically available potential.

To estimate the capacity that could theoretically be installed in the eligible areas, we assume an average power density. Attainable power densities for AWE are a topic of ongoing research and, other than those for conventional wind, are not yet backed by empirical data from existing wind farms. When airborne wind energy is to be deployed at scale, it can be assumed to be placed in certain layout in space, just like in conventional wind farms. Keeping the ground stations of AWE systems at a distance of the tether length plus a safety margin gives a conservative estimate of the space required (see Figure 1 for an illustration). A square layout meeting this requirement would give a stacking density of $1 \,/\, L^2$ (L being the tether length). A hexagonal layout, which is the densest packing, would give $\frac{\sqrt{3}}{2} \cdot {}^{1}/_{L^2} \approx {}^{1.15}/_{L^2}$.

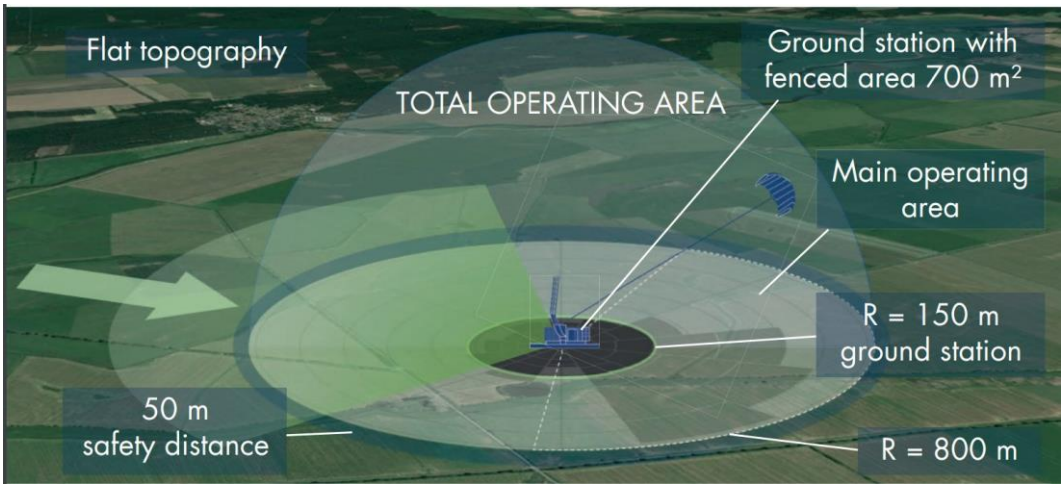

Figure 1: Illustration of the operating area of an airborne wind system. Here, a maximal tether length of 800m is assumed, with a safety distance of 50m (SkySails 2022).

Denser layouts can be achieved when allowing the ground stations to be closer to each other (Figure 2). This can be realized by synchronizing the operation of the kites such that they face in the same direction together with automated safety mechanisms that intervene if a kite unexpectedly leaves their nominal operating area. Estimates for increased packing densities range from $^{1.2}/_{L^2}$ (Licitra 2018) to $^{3}/_{L^2}$ (Kruijff and Ruiterkamp 2018).

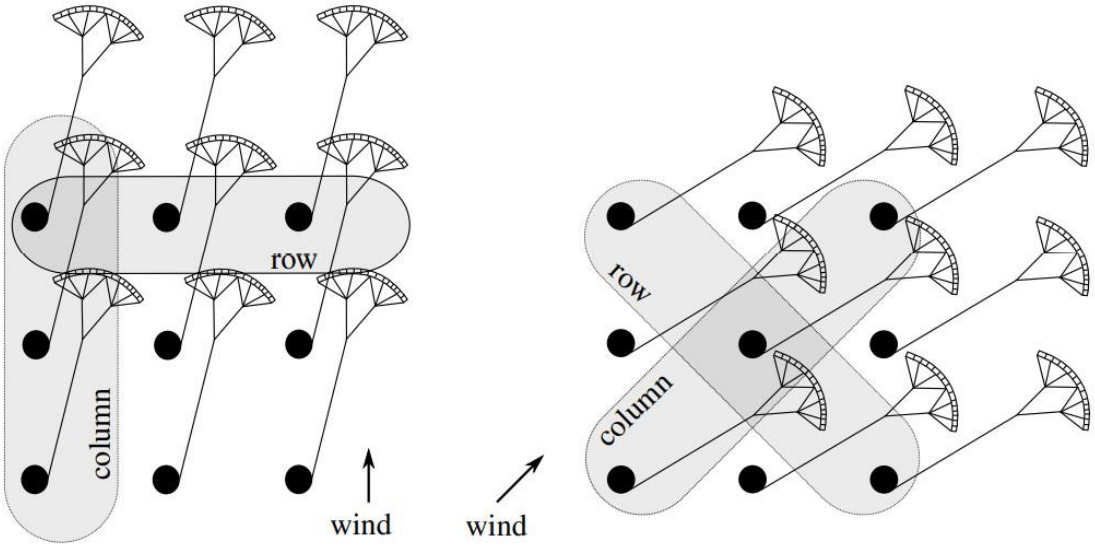

Figure 2: Layout for a higher packing density (Faggiani and Schmehl 2018)

In this work, we assume power densities as shown in Table 1 below. For onshore AWE, we assume a conservative estimate. The power density of 8 MW/km2 for onshore wind corresponds to (Tröndle, Pfenninger, and Lilliestam 2019). Assuming the same capacity density for offshore locations is rather conservative, but not unrealistic, given that not all the technical potential is expected to be exhausted in reality.

Table 1: Power density assumptions for the different wind energy technologies..

Technology	Power density (MW/km2)
AWE soft wing onshore	2
AWE fixed wing offshore shallow	8
AWE fixed wing offshore deep	8
Conventional wind onshore	8
Conventional wind offshore shallow	8
Conventional wind offshore deep	8

Future costs of technology are important assumptions that define the economic potential of the novel wind technologies. Table 2 and Table 3 show cost assumptions (Capex, Opex) and lifetime of all wind technologies. The capital costs are overnight costs which are annualized before entering the energy optimization model by multiplying with the following depreciation factor:

$$d = i \cdot \frac{(1+i)^l}{(1+i)^l - 1}$$

For conventional wind, we assume the average of cost estimates by NREL (NREL 2022) and DEA (DEA 2023). Cost assumptions for AWE soft wing are based on BVG Associates on behalf of Airborne wind Europe (2022). For AWE fixed wing, cost assumptions are based on estimates for 2030 (Joshi, R. et al. 2022) which have been extrapolated to 2050 based on a learning rate of 3% per year. For an in-depth explanation of the assumptions, please refer to Vos 2023. We assume the use of fixed wing AWE systems for offshore location and soft wing for onshore. Soft wing systems have the advantage of being less expensive and less fragile than fixed wing systems, which is why there is currently more field study data on the former.

Table 2: Capex and lifetime assumptions for conventional and novel wind technologies.

Technology	Capex in 2030 (EUR/kW)	Capex in 2050 (EUR/kW)	Lifetime (years)
AWE soft wing onshore	1649	609	30
AWE fixed wing offshore shallow	2820	1534	30
AWE fixed wing offshore deep	3120	1697	30
Conventional wind onshore	995	860	25
Conventional wind offshore shallow	2276	1989	30
Conventional wind offshore deep	3344	2945	30

Table 3: Opex assumptions for conventional and novel wind technologies.

Technology	Opex in 2030 (EUR/kW/a)	Opex in 2050 (EUR/kW/a)
AWE soft wing onshore	15.9	6.4
AWE fixed wing offshore shallow	88.0	47.9
AWE fixed wing offshore deep	99.6	54.2
Conventional wind onshore	25.8	22.2
Conventional wind offshore shallow	63.1	52.0
Conventional wind offshore deep	51.1	42.9

We assume the same cost within each of the categories, disregarding any further characteristics of locations like e.g. distance to shore or established undersea cables. Beyond the distinction of fixed-bottom platforms in shallow waters and floating platforms in deep waters we do not consider any cost increase for wind farms that are further away from land.

2.2 WIND RESOURCES

One of the main strengths of energy system models is that they represent spatio-temporal variability of wind energy at high resolution. Accordingly, we need respective data for the new airborne wind technologies.

The temporal structure of available wind resources is commonly described by timeseries of capacity factors (e.g. in hourly resolution). The capacity factor of a wind energy technology is the electricity output at a given time normalized by its nameplate capacity. It mainly depends on the technical characteristics of the wind technology and the current wind speed. This relation is described by the power curve characteristic to the model of the wind turbine.

The spatial structure of wind availability can be captured by using spatially resolved wind data. We base our analysis on ERA5 weather data provided by ECMWF (Hersbach, H. et al. 2017). We use the CDS Python API to request a dataset for the spatial scope of Europe (a cutout) and the years 2013-2018. To represent the wind conditions at the average operating height of airborne wind systems, we use ERA5 model level data (level 127) corresponding to the height 334m above ground.

To prepare the capacity factor timeseries for processing in the energy system model, we compute a weighted average over the respective model regions. The weighing is based on the shape for the potential areas within each region in the case of offshore regions. For onshore regions, the average is based on the shape of the region without taking into account exclusion areas.

The power curves used in this analysis (see Figure 3 for a plot comparing different instances) have been prepared in collaboration with the Airborne Wind Energy Research Group at TU Delft led by Roland Schmehl. They display the typical features of wind power curves, i.e.,

from low to high wind speeds: A minimal wind speed required for any power output, an increase until a maximal power output (at 10-15 m/s) and a plateau until wind speed exceeds the limits of safety, which requires pausing operation.

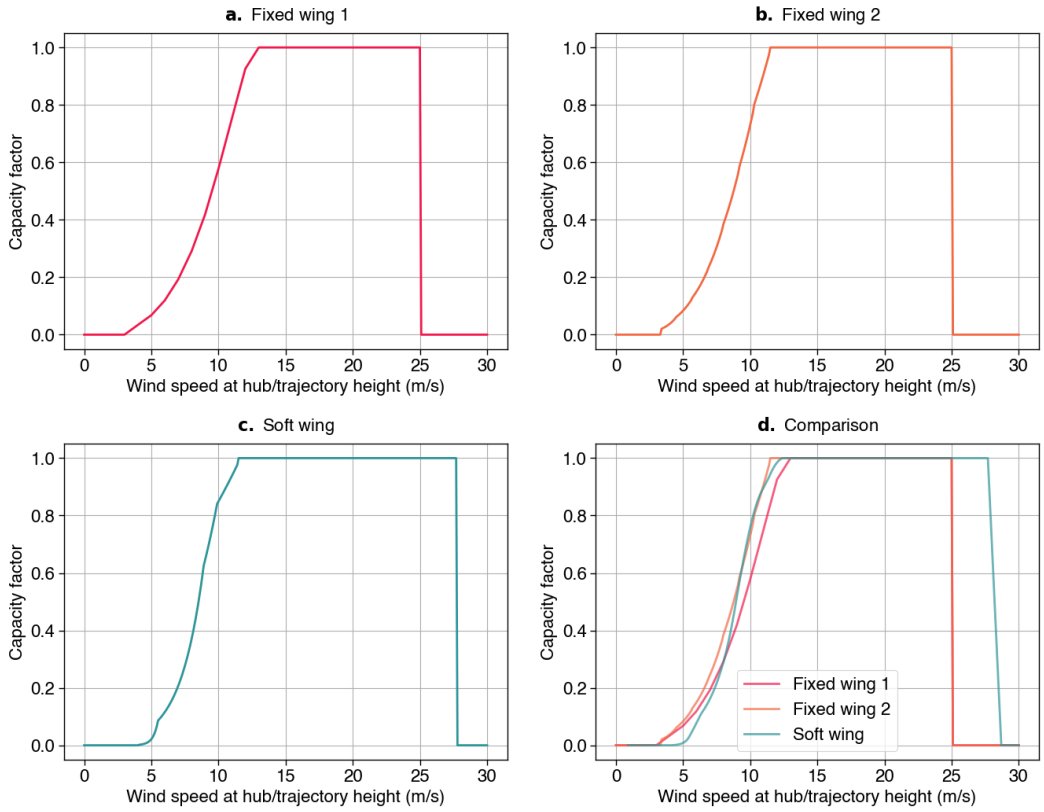

Figure 3: Comparison of power curves for airborne wind energy systems. (a) A 2.5MW fixed wing system optimized for cost, (b) a 2.5MW fixed wing system optimized for performance, (c) a 500kW soft wing system. For this work, (a) has been used to generate offshore capacity factors, (c) for onshore.

The processing of the weather data, preparation of spatial availability, spatial weighted averaging and application of power curves has been implemented by extending the Open-Source tool atlite (Hofmann et al. 2021).

2.3 ENERGY SYSTEM MODEL

This work extends the existing energy system model »Sector-coupled Euro-Calliope«. The model represents the European energy system in high spatial resolution (98 onshore regions, here expanded to 168 onshore and offshore regions), temporal resolution (6h) and sectoral resolution (electricity, heat, synthetic gas and fuels). It is a capacity-expansion model, which means that it finds cost-optimal solutions to both the design and operation of the energy system. See the original publication (Pickering, Lombardi, and Pfenninger 2022) for a detailed description of the model.

The model consists of a set of preprocessing routines (see Figure 4) that lead to a structured dataset representing an optimization problem, which can then be solved using the open energy optimization framework Calliope. The results represent the cost-minimal and feasible way to implement an energy system, given the constraints and cost assumptions. There are

many substantially different feasible ways with marginally higher costs, which need further investigation beyond the scope of this work.

Figure 4: : Visualization of the preprocessing steps leading to the »Sector-coupled Euro-Calliope« model (image source: https://github.com/calliope-project/sector-coupled-euro-calliope/blob/main/rulegraph.png)

The processing steps developed for this work are equally implemented as a reproducible data pipeline (using the Snakemake tool), which facilitates altering and refining the analysis at later times or adding them to the larger energy model workflow.

We add the new technologies to the existing model input data of the sector-coupled euro-calliope model by defining so-called *overrides* to the model configuration. The new data prepared via the steps described above is added to the model under the following assumptions:

Onshore, the same area potentials as in the existing model apply (Tröndle, Pfenninger, and Lilliestam 2019). We allow the model to build airborne wind in areas where it competes with open-PV and conventional wind. These are areas with slopes up to 10°, farmland, land cover and use, slope, protected areas, and settlements. Areas which are eligible for conventional wind only (not open-field PV), cannot be used for airborne wind. These include forests and open vegetation and bare land with slopes between 10° and 20°.

Regarding the offshore area potential, offshore competes with conventional wind for the same areas (within deep and shallow water, respectively).

3 RESULTS

3.1 AREA POTENTIAL

For many countries' EEZ, the area of deep water (depth > 60m) is much larger than that of shallow water. This means that the power potential for offshore wind is for most countries significantly increased when using floating offshore platforms that allow to use these areas.

For the purpose of wind resource modelling and capacity deployment, which is the main point of attention for JustWind4All, we increase the number of offshore regions for the Sector-coupled Euro-Calliope model. Starting with the boundaries of 31 European countries EEZ (Exclusive Economic Zones), we segment the offshore area according to the nearest point on the shore of an onshore region, using a Voronoi partition, into 70 offshore regions. Together with the 98 onshore regions, the model therefore has 168 regions in total.

Figure 5 shows a map of the offshore areas, distinguishing shallow waters, deep and nature reserve areas (Natura2000) which are excluded from wind deployment. The share of shallow water (see Table 4) varies across the European countries' EEZ. E.g., the EEZ of the Denmark, Germany and the Netherlands contain little or no deep water. On the other extreme, the EEZ of Norway, Portugal, Spain are by majority deep water.

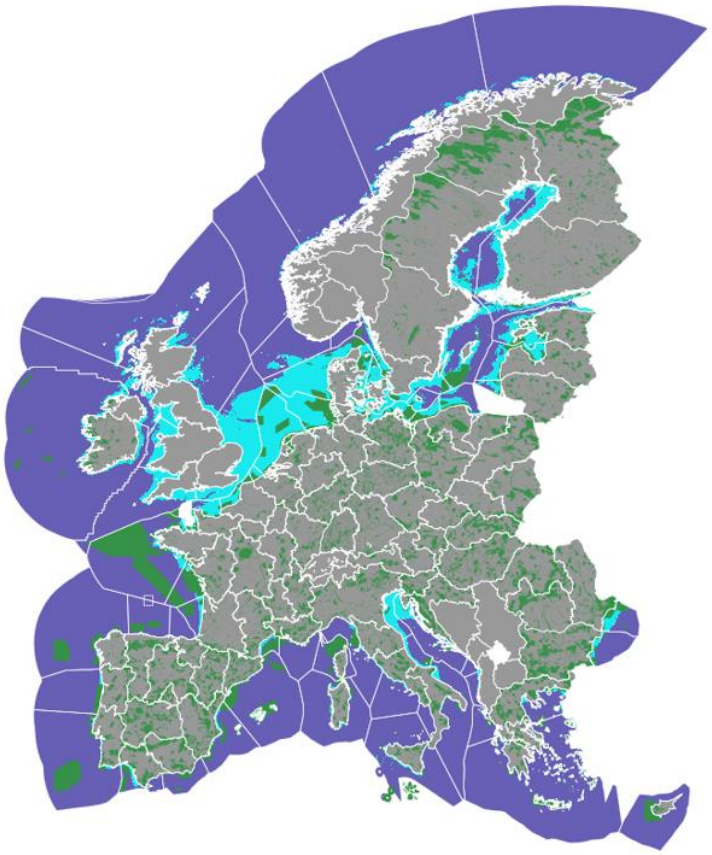

Figure 5: Refined offshore regions for wind energy. Boundaries (white lines) designate the regions that can be used to segment input data during preprocessing for the model Sector-coupled Euro-Calliope. The 98 onshore model regions are adopted from the Ehighways project. The refined offshore regions are based on

the 31 EEZ (Exclusive Economic Zones) of the represented countries, which can be further segmented into 70 regions in total, according to the nearest onshore region (Voronoi partition using representative points on the shore). Shallow waters are drawn in light blue (water depth < 60m). Deep waters (water depth > 60m) are drawn in dark blue. Natura2000 reserve areas which are assumed to be not eligible for wind energy are drawn in green.

Even without applying the full set of spatial constraints, these results show that for some countries, floating offshore platforms are an indispensable technology if offshore wind is to be developed.

Table 4: : Table of offshore area potentials per EE, ordered by total area of the EEZ. Please refer to the appendix for a glossary of the country codes.

Name	Area (km2)	Available area deep (km2)	Available share deep	Available area shallow (km2)	Available share shallow
NOR	933027	894440	0.96	39996	0.04
GBR	731309	566440	0.77	167683	0.23
ESP	561763	489079	0.87	10162	0.02
ITA	536654	479622	0.89	36062	0.07
GRC	482910	445694	0.92	15171	0.03
IRL	427039	401389	0.94	16107	0.04
FRA	345240	187792	0.54	30524	0.09
PRT	315501	278041	0.88	3418	0.01
SWE	155347	74221	0.48	62202	0.4
DNK	105021	13254	0.13	73633	0.7
CYP	98450	88584	0.9	1418	0.01
FIN	81553	28004	0.34	46039	0.56
NLD	64328	0	0	46057	0.72
DEU	56763	56	0	31042	0.55
HRV	55404	37415	0.68	13294	0.24
EST	36451	14066	0.39	15840	0.43
BGR	34745	28667	0.83	3325	0.1
POL	29982	12133	0.4	10658	0.36
ROU	29606	17826	0.6	5830	0.2
LVA	28353	11065	0.39	13129	0.46
ALB	12165	9978	0.82	2209	0.18
GBR/DNK	8011	7847	0.98	159	0.02
LTU	6832	2027	0.3	3368	0.49
MNE	6383	5837	0.91	561	0.09
BEL	3495	0	0	2184	0.62
FRA/ESP	2859	2858	1	2	0
SVN	214	0	0	203	0.95
NOR/SWE	140	137	0.98	3	0.02
HRV/SVN	98	0	0	98	1
FRA/ITA	67	0	0	0	0
BIH	13	0	0	13	0.99

3.2 WIND RESOURCES

The average wind speed for AWE is higher and the winds are more steady for conventional wind, for most of the regions. Figure 6 shows the average wind speeds (mean of all considered weather years 2013-2018) which conventional wind farms experience (100m height assumed) vs. that which airborne wind energy technologies can harvest at higher altitudes (average operating height of 334m assumed). This is true for most places, with the exception of very mountainous regions like the Alps.

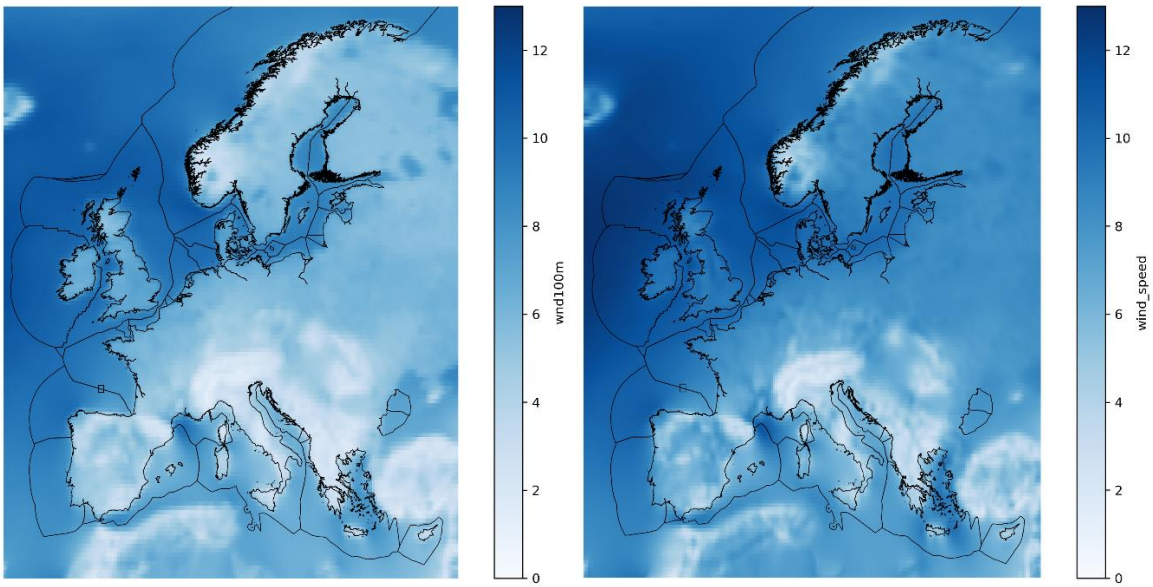

Figure 6: Map of average wind speeds at 100m heigh, relevant for conventional wind (left), and wind speeds at 334m height, relevant for AWE (right).

Correspondingly, yearly capacity factors are generally higher for AWE than for conventional wind. Figure 7 and Figure 8 show annual capacity factors of conventional wind and AWE, for all modelled countries and weather years (2010-2018 and 2013-2018, respectively). For both technologies, the variance across weather years is relatively small compared to the variance across regions. Where conventional wind can reach capacity factors up to 0.5 for the most productive regions, capacity factors for AWE exceed 0.6 for some regions. Also, the distribution of average capacity factors of AWE is leaned towards higher capacity factors than that of conventional wind (see Figure 9).

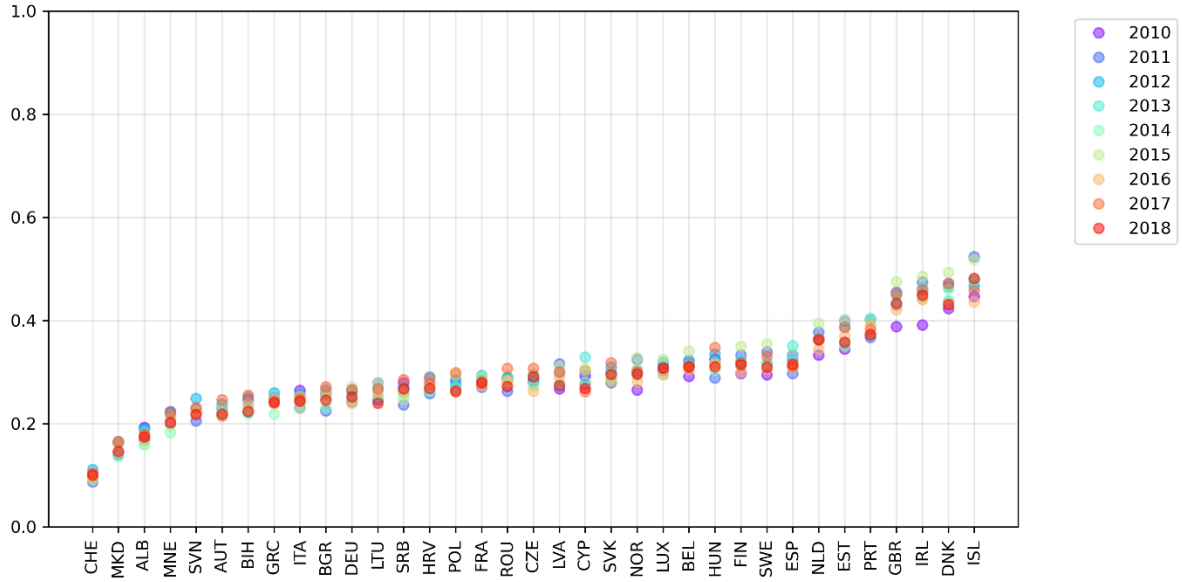

Figure 7: Annual capacity factors for conventional onshore wind for onshore regions, in ascending order

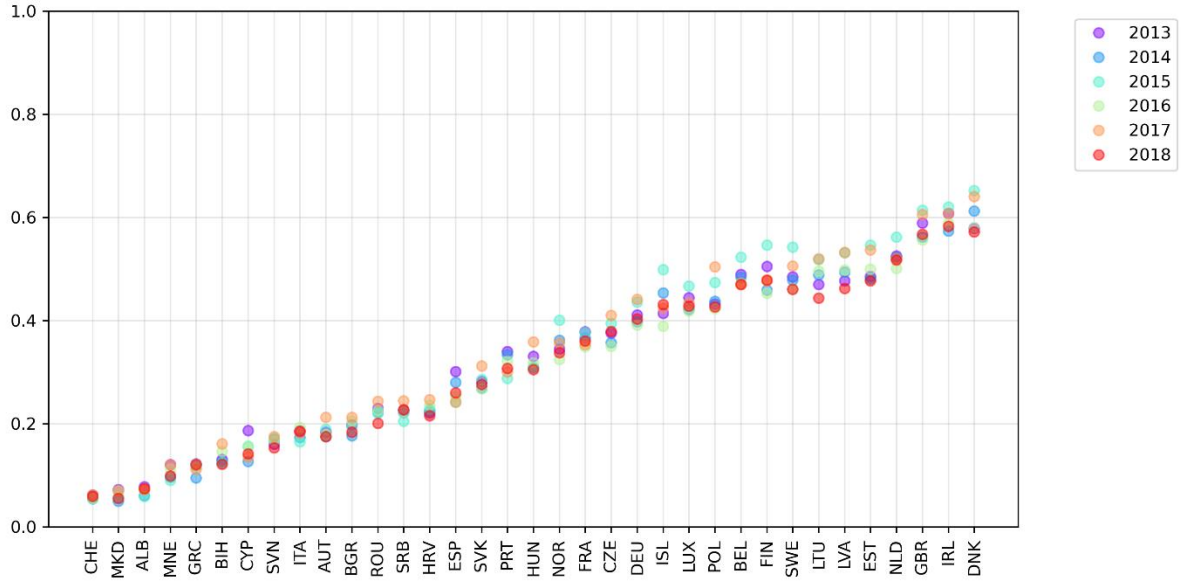

Figure 8: Annual capacity factors for airborne onshore wind for onshore regions, in ascending order.

Within a year, hourly capacity factors of AWE are more steady than those of conventional wind. Load duratation plots of the temporal distribution of hourly capacity factors can be found in Appendix 5.2.

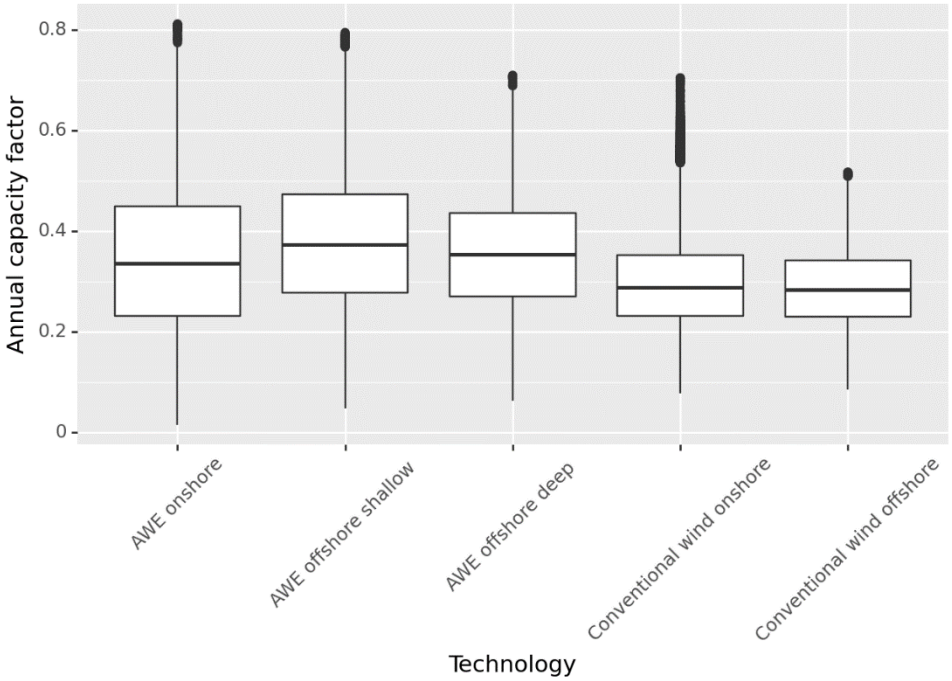

Figure 9: Distribution of annual capacity factors for different wind technologies. The median annual capcity factor accross regions and weather years is higher for AWE technologies, compared to conventional wind.

3.3 FIRST ENERGY SYSTEM SCENARIOS

Here, using the energy system model and novel technology definitions described above, we show first cost-optimized scenarios without (Figure 10) and with the additional wind technologies airborne wind and floating offshore wind (Figure 11). These results are preliminary, diagnostic model runs and not to be taken as plausible scenarios for 2050. They demonstrate that as we change the available technology options for the energy system model, it makes considerably different choices.

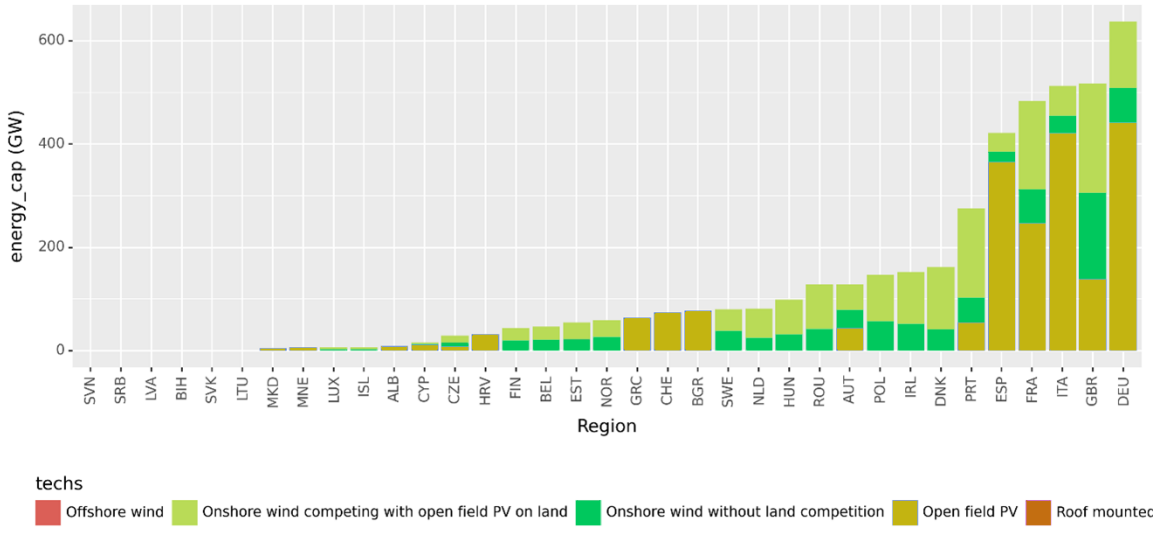

Figure 10: Cost-minimal renewable capacities in the base model.

In the base model run, all regions rely on onshore renewable generation exclusively. Rooftop PV capacities are not built at all. For many regions, renewable generation capacity is pronounced towards either PV or wind. Further iterations of the model setup are still required in order to calibrate the constraints, for example, if we want rooftop PV capacity to be included (which likely, will play a critical role in the European transition).

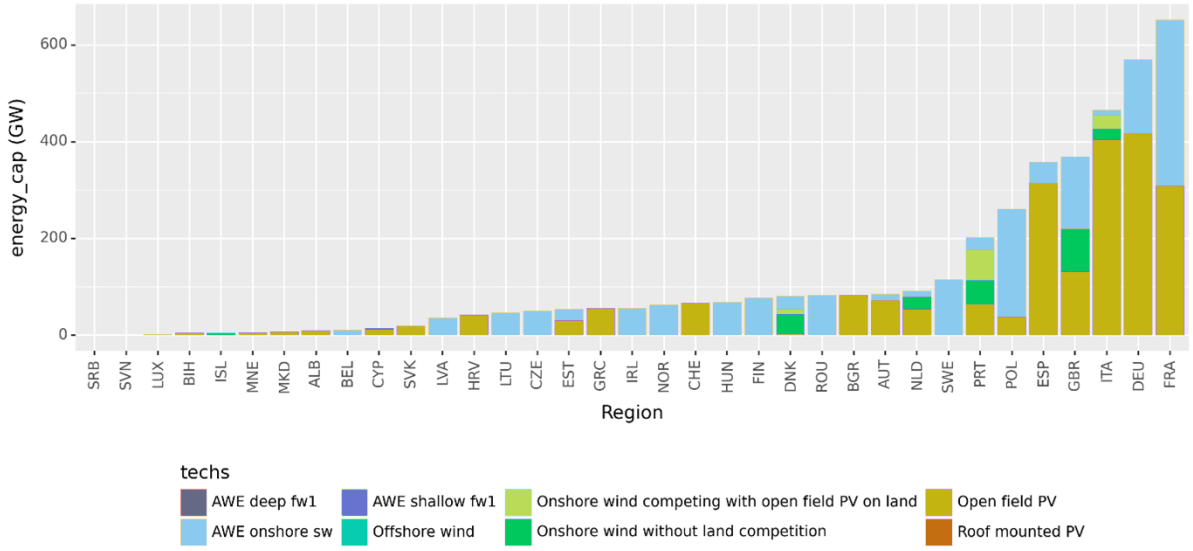

Figure 11: Cost-minimal renewable capacities in the extended model (base model plus novel wind technologies).

In contrast, the first scenario with expanded technology choice shows extensive capacities of onshore AWE in most regions. This indicates that within the model assumptions and the techno-economic characteristics of AWE, integrating it allows the model to decrease total system cost. As in the base scenario, offshore wind does not appear in the results; which also indicates further calibration is needed for future model runs.

4 DISCUSSION & CONCLUSION

We have presented an upgrade to the existing European sector-coupled energy system model, increasing its spatial and technical resolution with respect to novel wind energy technologies (airborne wind and floating offshore platforms). To account for the additional potential of floating offshore wind, we evaluated the area potential within the European countries' EEZ. We have presented wind speed data, power curves and resulting hourly capacity factors for airborne wind and discussed the potential benefits these can have for the energy system. Finally, we have presented first diagnostic model runs that showcase the implementation of the new wind technologies in the model. First cost-optimised scenarios show that under the presented assumptions, onshore airborne wind does have an advantage within a larger-scale renewable energy system.

These results have several limitations. When estimating offshore potentials, we did not consider all criteria limiting the offshore area potential (e.g shipping routes, military areas), which would decrease the eligible area. We neglect the fact that investment and operation

& maintenance costs for offshore wind energy depends on the precise location and should in particular increase with distance from shore. The presented energy system model scenarios are preliminary examples and should not be mistaken for realistic cases. There are several aspects to this. We determine a cost optimal solution for a single year without taking into account a deployment pathway. A future renewable energy system is the product of the status quo and a transformation taking many years, which is not considered in a single-year optimisation model. This disregards the higher technological and market maturity of conventional wind compared to airborne wind energy systems. In the presented model runs, rooftop PV and offshore wind is not represented at all. The underestimation of rooftop PV can be attributed to the fact that the weighing of capacity factors for different roof orientations leads to disadvantageous capacity factor profiles. The primary reason for offshore wind not appearing in the results is that in these first runs, we allow the model to use the full technical potential, which are magnitude larger than the socio-technical potential that can actually be realised given all use of land and water area which are not explicitly modeled. These issues will be addressed in the next stages of our work in JustWind4All, along with the work on methods to produce a more diverse set of scenarios, in Task 2.2.

The energy system model runs are first diagnostic examples to showcase how the new technologies can be implemented into the model. They allow a first investigate of how the advantages of the novel wind technologies may play out in the wider context of a sector-coupled energy system. With the data processing pipeline set up, we can start from here to refine some of the assumptions in order to arrive at more realistic scenarios.

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1. APPENDIX 1

5.1 EEZ ABBREVIATIONS

Code	Long name
ALB	Albanian Exclusive Economic Zone
BEL	Belgian Exclusive Economic Zone
BGR	Bulgarian Exclusive Economic Zone
BIH	Bosnian and Herzegovinian Exclusive Economic Zone
CYP	Cypriote Exclusive Economic Zone
DEU	German Exclusive Economic Zone
DNK	Danish Exclusive Economic Zone
ESP	Spanish Exclusive Economic Zone
EST	Estonian Exclusive Economic Zone
FIN	Finnish Exclusive Economic Zone
FRA	French Exclusive Economic Zone
FRA/ESP	Joint regime area Spain / France
FRA/ITA	Joint regime area Italy / France
GBR	United Kingdom Exclusive Economic Zone
GBR/DNK	Joint regime area United Kingdom / Denmark (Faeroe Islands)
GRC	Greek Exclusive Economic Zone
HRV	Croatian Exclusive Economic Zone
HRV/SVN	Joint regime area Croatia / Slovenia
IRL	Irish Exclusive Economic Zone
ITA	Italian Exclusive Economic Zone
LTU	Lithuanian Exclusive Economic Zone
LVA	Latvian Exclusive Economic Zone
MNE	Montenegrin Exclusive economic Zone
NLD	Dutch Exclusive Economic Zone
NOR	Norwegian Exclusive Economic Zone
NOR/SWE	Joint regime area Sweden / Norway
POL	Polish Exclusive Economic Zone
PRT	Portuguese Exclusive Economic Zone
ROU	Romanian Exclusive economic Zone
SVN	Slovenian Exclusive Economic Zone
SWE	Swedish Exclusive Economic Zone

5.2 CAPACITY FACTORS

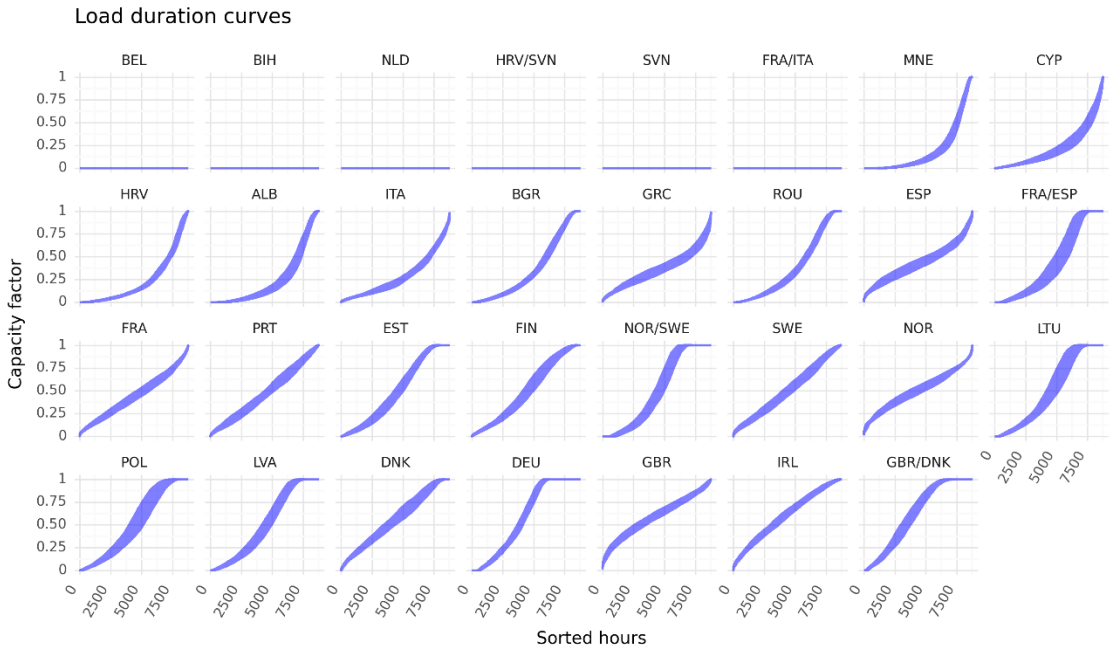

Figure 12: Load duration curves for wind offshore deep awe

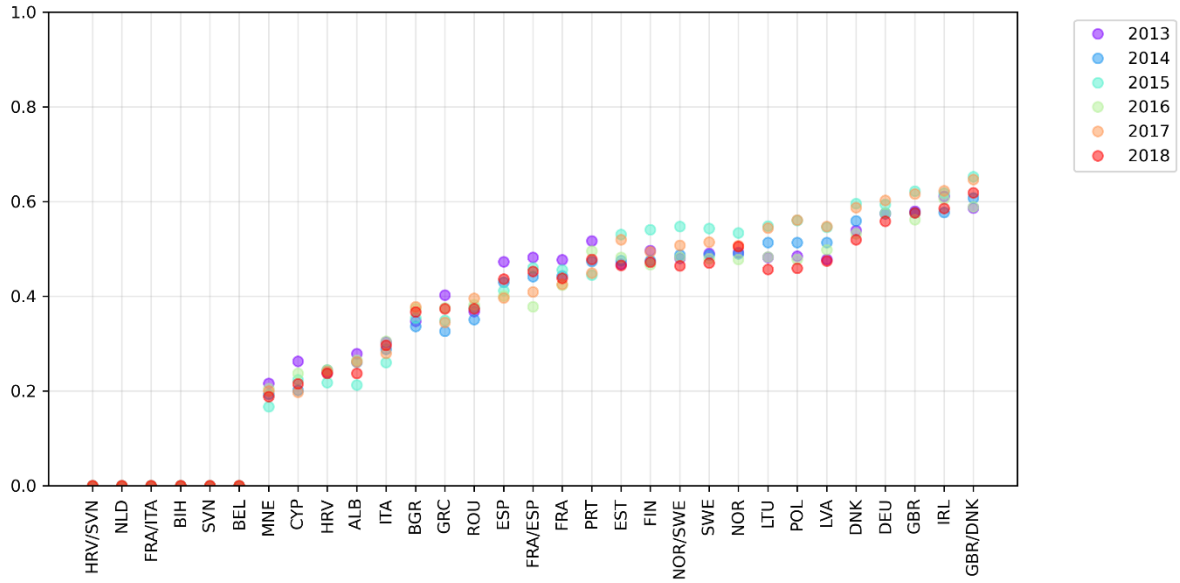

Figure 13: Annual capacity factors for wind offshore deep awe

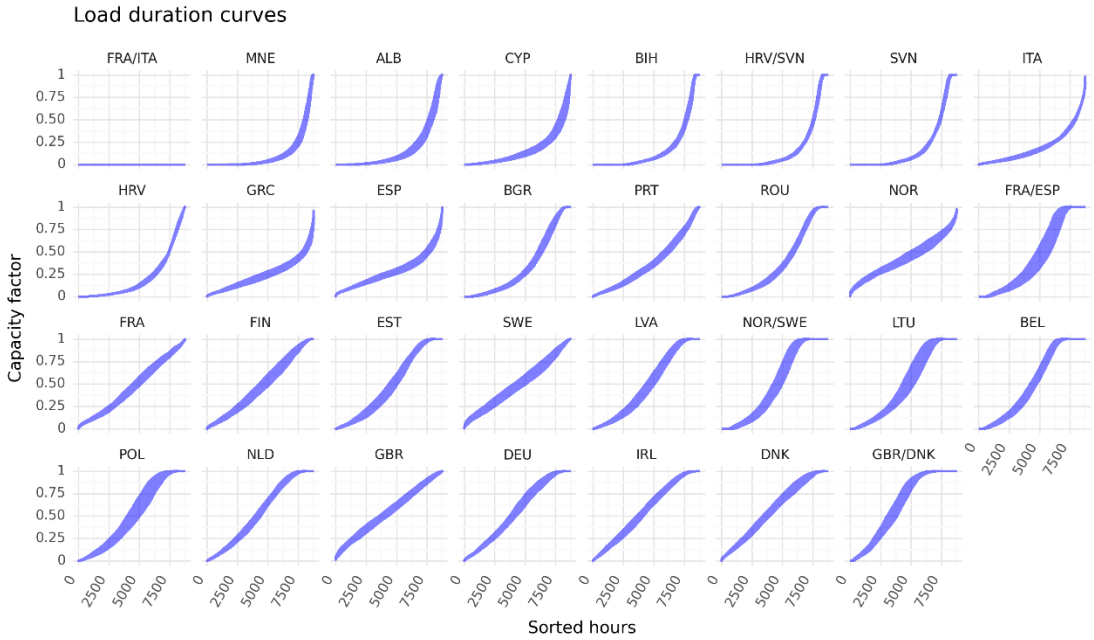

Figure 14: Load duration curves for wind offshore shallow awe

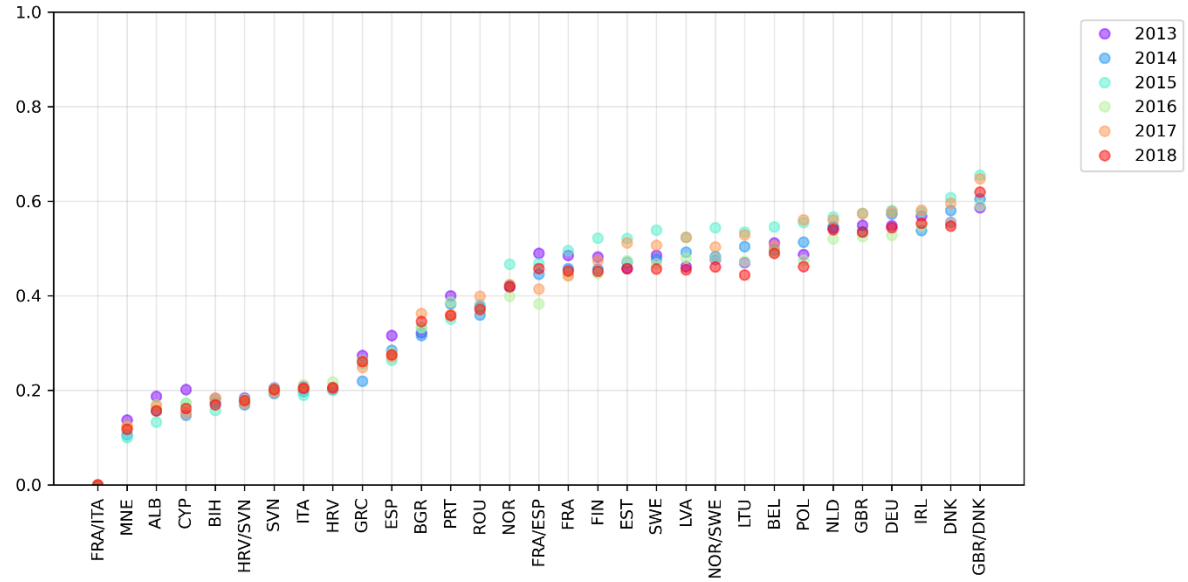

Figure 15: Annual capacity factors for wind offshore shallow awe

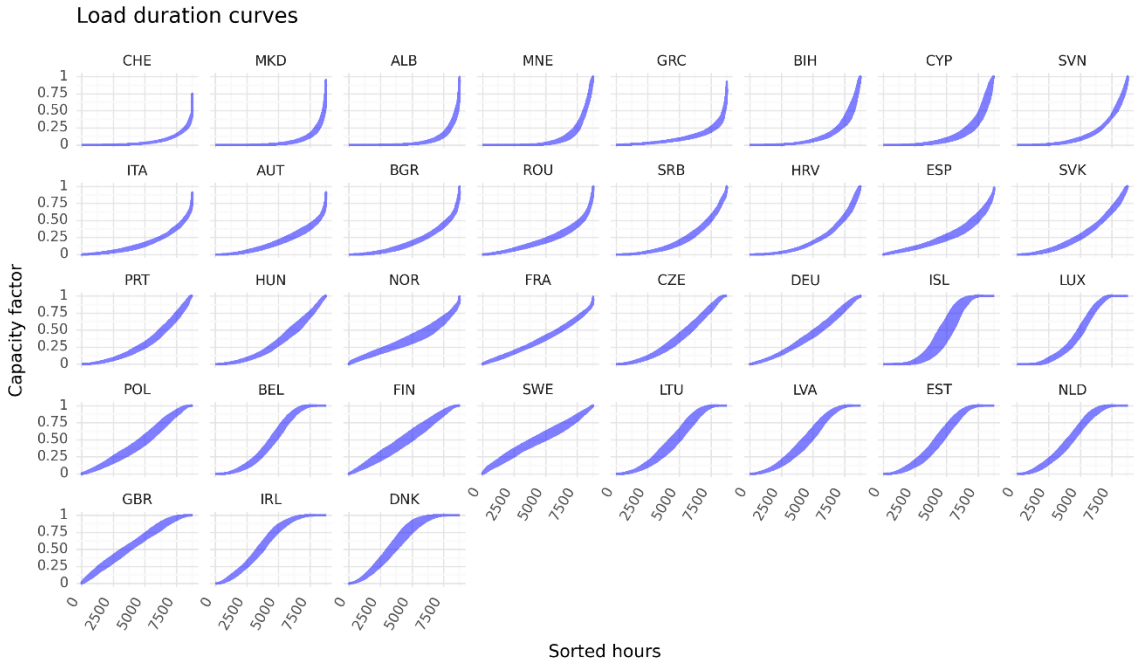

Figure 16: Load duration curves for wind onshore awe

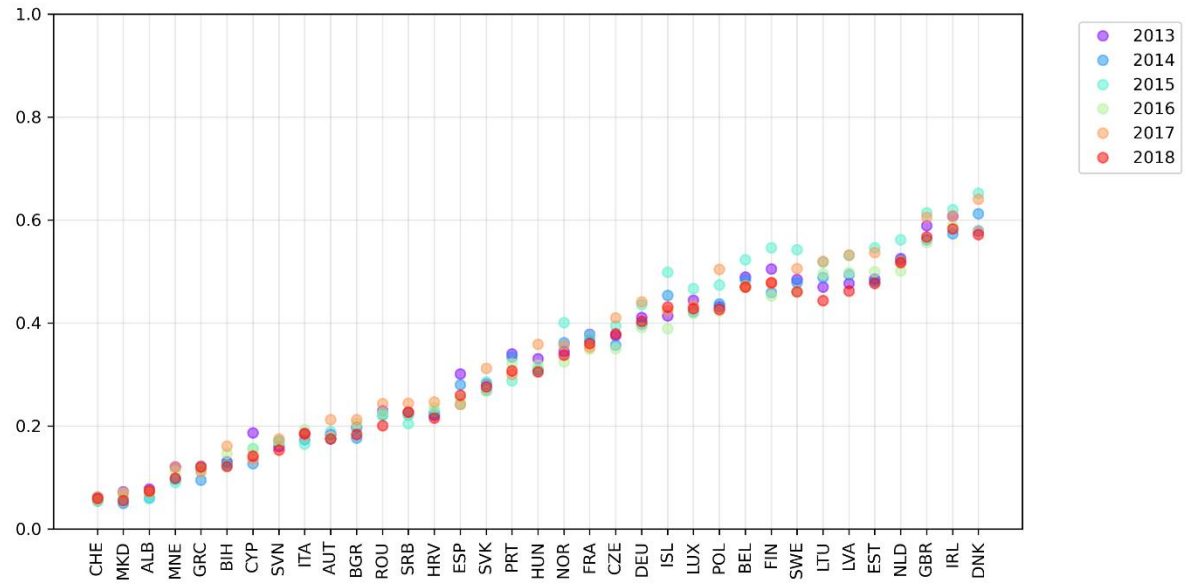

Figure 17: Annual capacity factors for wind onshore awe

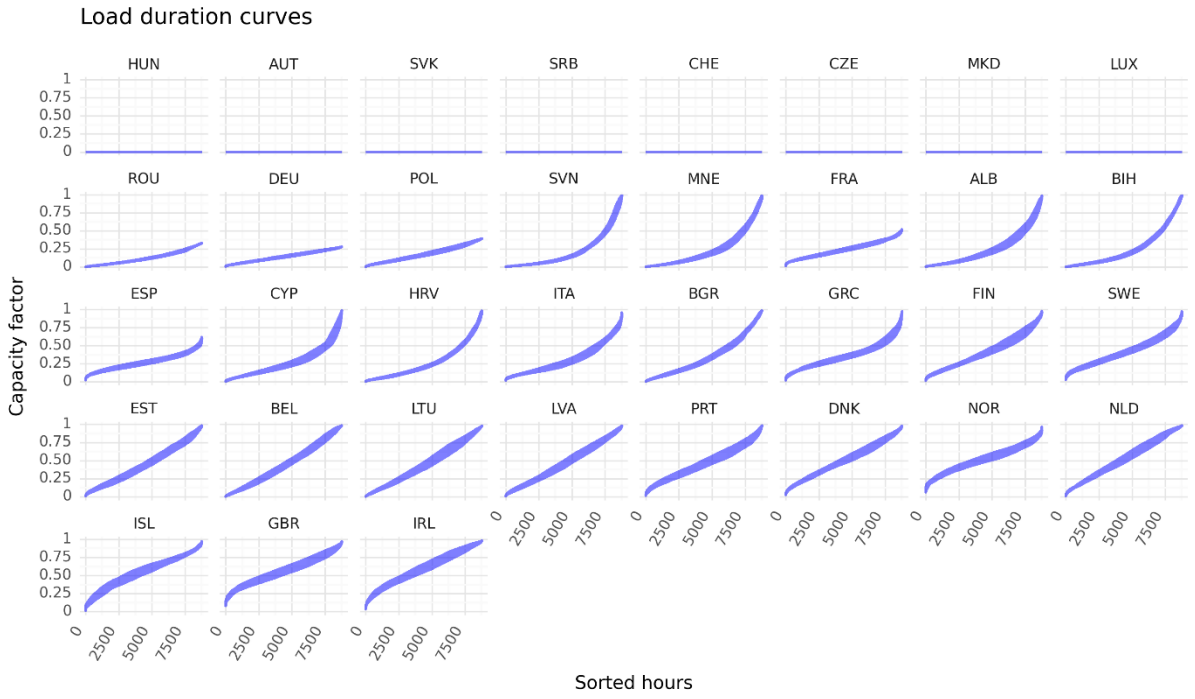

Figure 18: Load duration curves for conventional wind offshore.

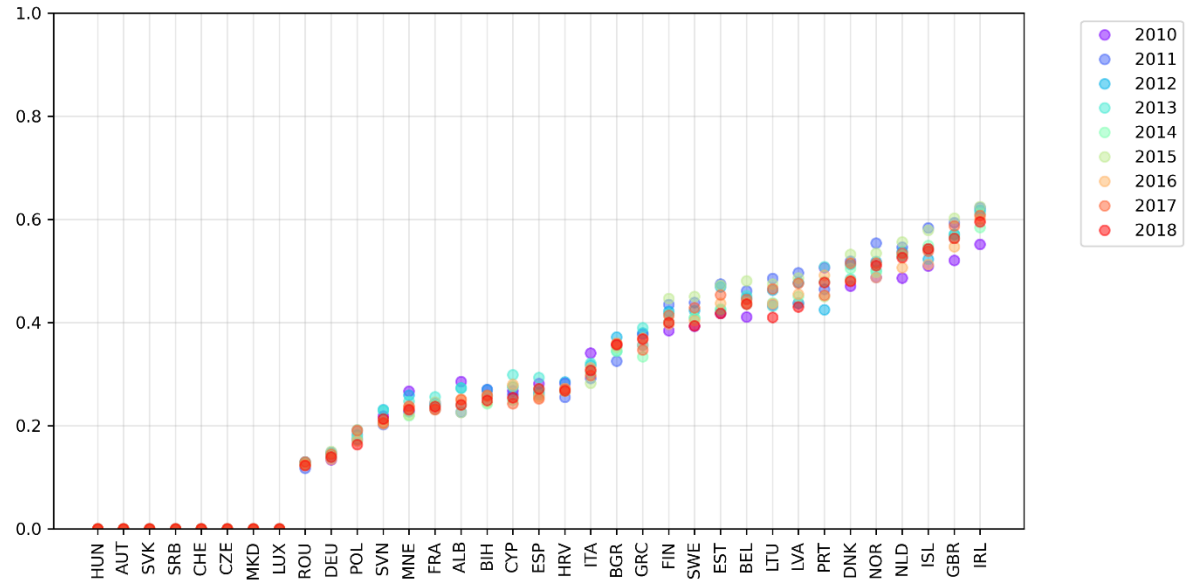

Figure 19: Annual capacity factors for conventional wind offshore.

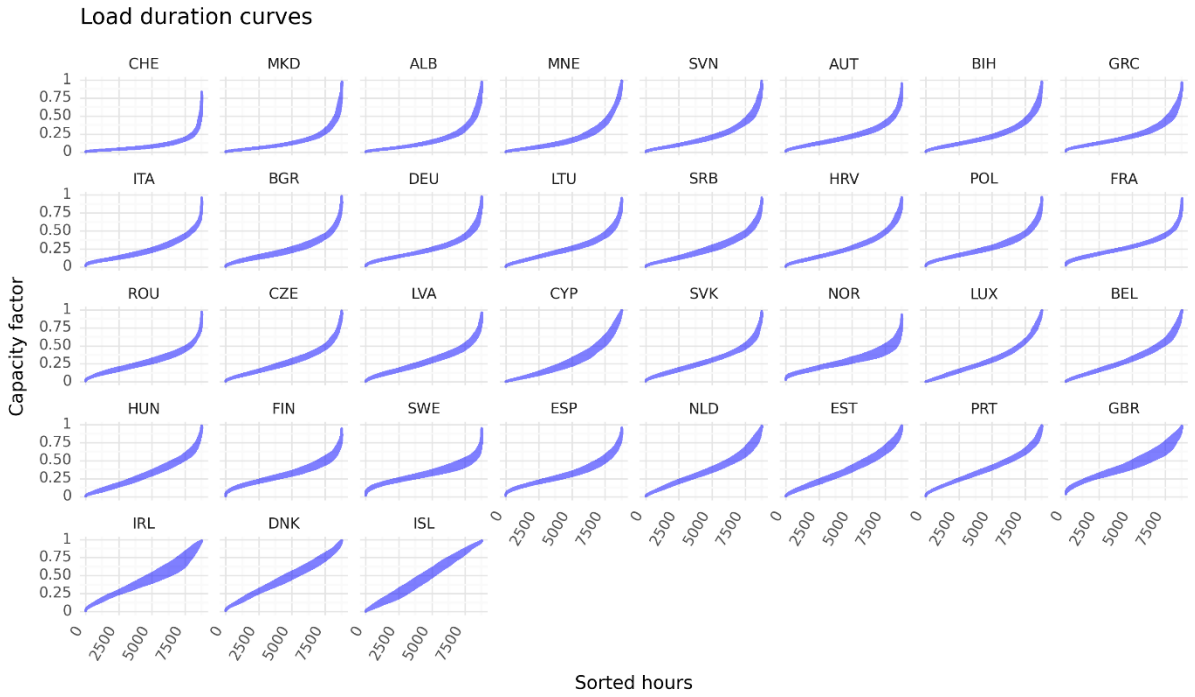

Figure 20: Load duration curves for conventional wind onshore.

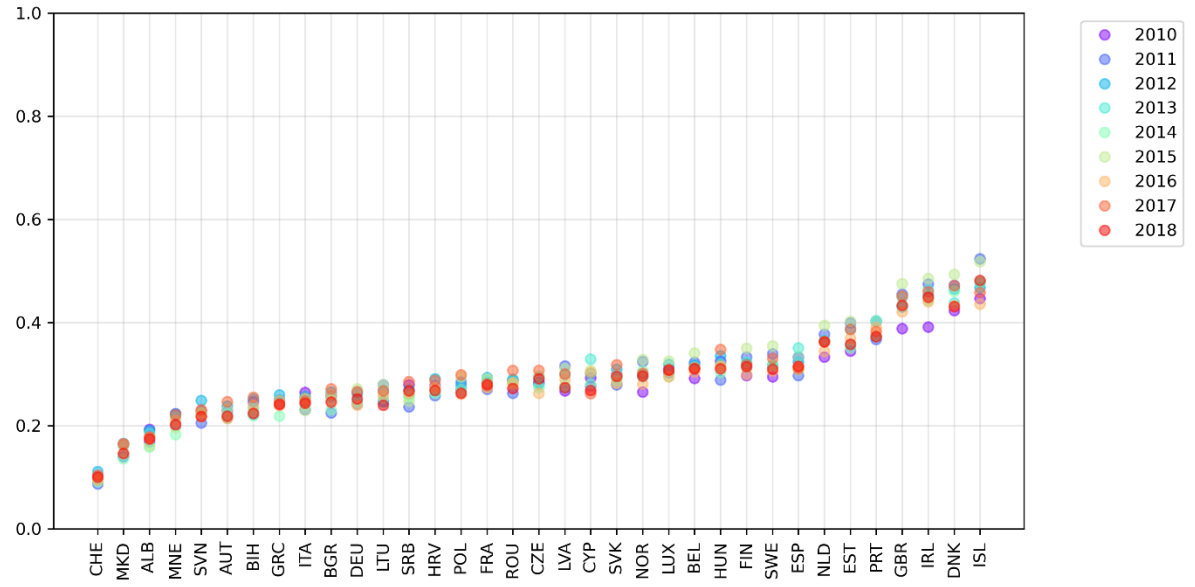

Figure 21: Annual capacity factors for conventional wind onshore

2. APPENDIX 2: EC SUMMARY REQUIREMENTS

Changes with respect to the DoA	
Dissemination and uptake	Results will be disseminated in a project-internal webinar.
Short Summary of results (<250 words)	We present methods, data and first scenarios of the upgraded energy system model »Sector-coupled Euro-Calliope«, including novel wind energy technologies airborne wind and floating offshore. This comprises an updated estimation of area potentials for the European countries' EEZ, an evaluation of the available wind resources available to airborne wind and cost estimates. With these implemented to the energy system model, first scenarios are presented that serve as a basis for new optimisation approaches to be developed in the next tasks of WP2.
Evidence of accomplishment	