

Responses to the comments by the Referees and resulting changes to the manuscript

The Authors:

We thank the Referees for their constructive comments. The following answers the comments and describes how the paper is revised as a result.

Referee #1:

“This paper looks at three different scenarios for the development of offshore wind in the North Sea region until 2050:

- i) Regular electricity and district heating demand and offshore parks connected to country hubs on a project-by-project basis;
- ii) Regular electricity and district heating demand and hubs in the North Sea for a meshed grid connecting offshore parks to the mainland;
- iii) Adding to the demand industry demand, partial electrification of transport, but no individual heating for buildings.

The paper compares i) and ii) with regards to wind generation and curtailment, then examines these metrics in scenario iii).

The topic is very interesting and the authors have done impactful work in this area in the past, but this paper feels thin and disjointed.

The comparison of i) and ii) repeats results from a previous publication, as the authors admit, adding only the curtailment results, which I don't think is high added value. As they are presented here, the results miss a lot of important information like the total costs, which are presumably in the other paper. The addition of scenario iii) is an important further development of the model, but I'm not sure why it's bundled together with the comparison of i) and ii) in this paper. Also the results are rather minimal and presented in only 1.5 pages. Surely there is more to say here?”

The Authors:

We thank the Reviewer for the comments and critique. The presentation of the scenario iii) is expanded in the revised manuscript to show more disaggregated results for the different sectors and countries. The impact of the different sectors on load growth are presented in Section 3.2.1, annual energy generations towards 2050 in Section 3.2.2 and the split of offshore wind installations in different countries in Section 3.2.3.

Costs of scenarios i) and ii) are presented and compared in the cited papers. Scenario iii) costs are not directly comparable to i) and ii), as additional sectors are included in the analysis; they are thus not compared in this paper. Different scenarios with sector coupling (with the same sectors modelled, but with different assumptions) are compared in ongoing work; this is mentioned as future research in a Discussion section, which is added to the revised version of the manuscript.

The impacts of both the meshed offshore grid and sector coupling on expected offshore wind installations towards 2050 are presented, as both are current popular topics in terms of large-scale energy and power system development in Europe. This paper shows that sector coupling is expected to have a much bigger impact on offshore wind installation growth (which is perhaps not very surprising as sector coupling drives load growth, which drives VRE installations; however, we considered it to be a worthwhile comparison). Joint modelling of both sector coupling and meshed offshore grid is an ongoing work, which is mentioned in the Discussion section in the revised manuscript.

“There is so much more that could be considered:

- What is the role of hydrogen? We're seeing a lot of new projects pairing offshore with electrolyzers, which is relevant for industry demand (steel, heat, ammonia, etc.).
- Why no heat pumps for individual building heating in France / Germany / UK? Only Scandinavia has significant shares of district heating.
- Building renovations?
- Wake effects for offshore? DTU has led the field in this analysis.
- Dependence of offshore build-out on recent cost developments and low acceptance for onshore wind.”

The Authors:

We agree that all these suggestions are very relevant in modelling energy system scenarios. Modelling of hydrogen and synthetic fuel production, also as future fuel in the shipping and aviation sectors, and modelling of electrification of individual building heating are included in current work on expanding the Balmoral model; however, they were not yet ready at the time of writing this paper. They are mentioned as future work in the Discussion section.

Large-scale wake modelling at DTU Wind Energy has been recently applied in the North Sea, looking at very large amounts of GW installed in limited geographical regions; however, the combination of this work to the energy system scenario optimisation is also ongoing work, and was not yet available for this paper. It is mentioned as future work.

Impact of low acceptance of onshore wind on offshore wind build-out has been looked at in previous work, which is cited in the revised manuscript; however, without considering sector coupling. Doing similar analysis on scenarios with sector coupling is ongoing work.

“More specific comments:

- The literature review is minimal and mostly contains self-cites.”

The Authors:

We agree that the literature review is limited. It is expanded significantly in the revised version of the manuscript.

“- Figure 1 has low information content.”

The Authors:

The figure is updated in the revised manuscript to include short description of each block.

“- The year for the reference Gea-Bermudez, Koivisto, & Münster oscillates between 2019 and 2020 or are there 2 publications?”

The Authors:

The year is 2019, and there is 1 publication only from this group of authors. The citations are corrected in the revised paper.

“- What were the values of the CO2 tax?”

The Authors:

Assumed CO2 tax values are: 30, 90 and 120 EUR₂₀₁₅/ton in 2025, 2035, and 2045, respectively. They are the same as in the other related cited papers from the authors (with some interpolations to reach specific scenario years). They are based on the following reference, which is also cited in the revised manuscript: Nordic Energy Research and International Energy Agency, Nordic Energy Technology Perspectives 2016 report (<https://www.nordicenergy.org/project/nordic-energy-technology-perspectives/>)

“- Biofuels: what potentials in particular were considered here?”

The Authors:

The biofuel potentials are the same for the studied countries as in the following reference (the numbers are presented in the revised version of the manuscript):

J. Gea-Bermudez et al.: Optimization of the electricity and heating sectors development in the North Sea region towards 2050, *the 18th Int'l Wind Integration Workshop*, Dublin, October 2019.

(https://backend.orbit.dtu.dk/ws/portalfiles/portal/197181819/Sector_Coupling_Wind_Integration_conference_2019.pdf)

Referee #2:

“This paper looks at three different scenarios of developing the North sea offshore windfarms: 1. Load as of today, offshore wind farms connected to country hubs on a project basis 2. Load as of today, offshore wind farms connected via a meshed grid to the mainland 3. There is a strong sector coupling for the electricity use and windfarm offshore.

The different scenarios are compared and the outcome is very clear:

a) Meshed grid compared to country connections (1 to 2), no big different
b) Sector coupling is very important and make it possible to take away natural gas, coal and oil from the heat production in northern Europe. It also increase the needs of more wind power in the North Sea.

The results are a very important message to how the development of the energy supply can develop.

The paper is well written, and it is very easy to catch the main message and it is clear in the results.

The comparison of i) and ii) repeats results from a previous publication, as the authors point out.

The sector coupling is new and very important. Maybe the sector coupling is enough important to be a paper by itself with more background information.

The literature review is limited and there is other paper also describing the sector coupling and its impact for wind energy development, I recommend to make a new review.”

The Authors:

We appreciate the comments and critique; they allow us to improve the revised version of the manuscript. The presentation of the scenario with sector coupling (3) is expanded in the revised manuscript to show more disaggregated results for the different sectors and countries. The impact of the different sectors on load growth are presented in Section 3.2.1, annual energy generations towards 2050 in Section 3.2.2 and the split of offshore wind installations in different countries in Section 3.2.3. In addition, more background information is given on the assumptions and input data used in the modelling.

We agree that the literature review is limited. It is expanded significantly in the revised version of the manuscript.

North Sea region energy system towards 2050: integrated offshore grid and sector coupling drive offshore wind installations

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Abstract. This paper analyses several energy system scenarios towards 2050 for the North Sea region. With focus on offshore wind power, the impacts of meshed offshore grid and sector coupling are studied. First, a project-based scenario, where each offshore wind power plant is connected individually to onshore, is compared to a meshed grid scenario. Both the amount of offshore wind ~~installed~~installed, and the level of curtailment are assessed. Then, these results are compared to a scenario with sector coupling included. The results show that while the introduction of a meshed grid can increase the amount of offshore wind installed towards 2050, sector coupling is expected to be a more important driver for increasing offshore wind installations. In addition, sector coupling can significantly decrease the level of offshore wind curtailment.

1 Introduction

15 The North Sea offers high offshore wind power potential. In addition, several existing and planned transmission lines are located in the region. Consequently, a meshed offshore grid in the North Sea has been proposed as an option for connecting transmission and offshore wind generation investments in the region ([Konstantelos et al., 2017](#)), ([Gorenstein Dedecca et al., 2017](#)), ([de Decker et al., 2011](#)). [The meshed offshore grid can be optimised assuming a fixed onshore generation development](#) ([Gorenstein Dedecca et al., 2017](#)), ([Gorenstein Dedecca et al., 2018](#)); however, [joint optimisation of the onshore and offshore parts has been suggested to find the overall optimal system](#) ([Gea-Bermudez et al., 2020](#)), ([Gorenstein Dedecca & Hakvoort, 2016](#)). This paper presents results from comparing [ansueh integrated approach, where meshed grid and onshore transmission and generation investments are optimised jointly](#), to a project-based scenario, where each offshore wind power plant (OWPP) is connected individually to onshore.

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25 Another development that can have significant impact on variable renewable energy (VRE) generation is sector coupling ([Brown et al., 2018](#)), ([Münster et al., 2020](#)), ([WindEurope, 2018](#)). With expected increase in electricity consumption, there is more load that can be met by VRE generation. In addition, sector coupling can provide additional flexibility to the power system, e.g., via electrification of heating demand in both individual heating ([Brown et al., 2018](#)) and industry ([Gea-Bermudez, Koivisto, et al., 2019](#))~~sector~~. [The value of cross-border and cross-sector coupling were compared in](#) ([Thellufsen & Lund,](#)

30 2017), with cross-sector coupling showing stronger benefits. However, the complementarity of the two was not analysed. In addition, the geographical resolution was low. In (Brown et al., 2018), a combined optimisation of sector coupling and transmission reinforcement was carried out, considering individual-user heating sector, road transport and power-to-gas. The results show that sector coupling and transmission expansion reduce costs, with a combination of the two found optimal. Energy supply for all of Europe for one year was optimised on hourly resolution, with one node per country and without

35 including industry. The benefits of coupling the electricity and transport sectors were shown in (Helgeson & Peter, 2020). (Hedegaard et al., 2012) showed that electric vehicles (EVs) can help in integrating more wind energy to the power system. Different types of storages were compared in (Victoria et al., 2019), with the result that large-scale thermal storage can help in balancing the system at a seasonal level, while EVs contribute to balancing in the short-term.

40 In this paper, the North Sea region energy system is analysed on regional level for the Nordic countries (matching the Nord Pool market bidding zones). Regional modelling is applied also for Germany to model important intra-country grid congestions. Transmission expansion is modelled jointly with sector coupling to study their combined impact. When considering sector coupling, the electricity and heating sectors are optimized jointly towards 2050, with electrification of industry and district heating expansion also modelled. In addition, increasing EV penetration is considered. Electrification of

45 industry heat demand is modelled considering three temperature levels. Electrification increases electricity consumption; however, sector coupling has also potential to provide flexibility to the system, which is modelled. Following the modelling in (Gea-Bermudez et al., 2020), intertemporal rather than myopic optimisation is carried out to capture the long-term perspective in investment decisions.

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With focus on the effects on offshore wind power, this paper analyses and compares the impacts of a meshed North Sea offshore grid and sector coupling. Both the expected installation of offshore wind towards 2050 and the level of curtailment due to grid congestion are analysed and compared. The analyses are carried out using a combination of CorRES (Correlations in Renewable Energy Sources) and Balmorel tools. CorRES provides the wind and solar generation time series used in 55 analysing the impacts of VRE generation on the energy system. The expected technology development of VRE generation towards 2050 is modelled and offshore wind installations are analysed considering nearshore and far offshore AC and DC investments, as shown in (Koivisto, Gea-Bermudez, et al., 2019). -Balmorel takes the CorRES simulations as an input and analyses the expected evolution of the North Sea region energy system towards 2050. With simulated operation of the energy system, considering both the electricity and heating sectors, Balmorel is used to model the behaviour of the system on hourly 60 level. Electricity and heating sectors are optimized jointly towards 2050, with electrification of industry, district heating expansion and electric vehicle penetration also considered. Electrification increases electricity consumption; however, sector coupling has also potential to provide flexibility to the system, which is modelled in Balmorel.

The project-based and the meshed offshore grid scenarios have been published before (Koivisto, Gea-Bermudez, et al., 2019).

65 However, they are supplemented with recent results on the level of VRE curtailment (Gea-Bermudez, Das, et al., 2019) the presented scenario with sector coupling is new work. In addition to presenting the scenario with sector coupling modelled, this paper contributes by comparing the expected impacts of introducing a meshed offshore grid in the North Sea to the impacts of sector coupling both on the amount of offshore wind power installed and the level of curtailment expected.

70 The paper is structured as follows. Section 2 describes the methodology used in analysing the North Sea region energy system development towards 2050. Section 3 presents the results for the studied scenarios and compares them. [Section 4 provides discussion on the results and assumptions](#). Section [54](#) provides a conclusion of the presented results.

2 Methodology

All scenarios are analysed using a combination of CorRES and Balmorel, following the approach shown in (Gea-Bermudez et al., 2020), with CorRES providing the VRE time series and Balmorel carrying out the energy system modelling, as shown in [Figure 1](#)[Figure 4](#). The following subsections present [both of these](#)[both](#) tools. [Figure 2 shows the North Sea region countries in focus in this paper](#).



80 **Figure 1. The scenario modelling flow chart.**

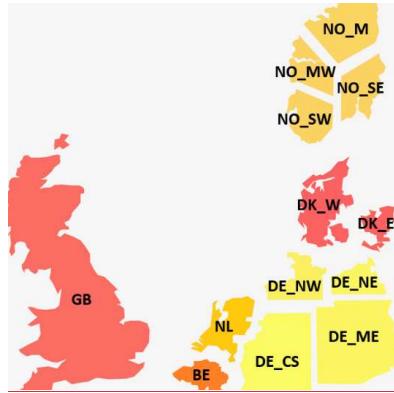


Figure 2. The North Sea region countries in focus (the regional split refers to the project-based and meshed grid scenarios); figure is taken from [\(Koivisto, Gea-Bermudez, et al., 2019\)](#). The north region of NO (NO_N) is not shown in the graph but included in the aggregated results.

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2.1 CorRES

CorRES [\(Koivisto, Das, et al., 2019\)](#) is used for simulating the VRE generation time series used in Balmorel. CorRES allows modelling of pan-European scale wind and solar PV generation time series [\(Nuño et al., 2018\)](#), with both the spatial (between the modelled countries and regions) and temporal dependencies in VRE generation modelled. In addition to analysing current VRE installation, CorRES can be used in analysing the expected impacts of technology development on both the capacity factors (CFs) and the spatiotemporal dependencies in the VRE time series [\(Koivisto, Maule, et al., 2019\)](#). For the analysed scenarios, wind power is expected to experience both increased hub heights and lower specific power towards 2050. The expected technology developments are linked to the costs of VRE installations, as shown in [\(Gea-Bermudez et al., 2020\)](#), to model the combination of both costs decreasing and technology advancing. For offshore wind, the distance from shore impacts CF and the cost of grid connection, with both nearshore and far offshore AC and DC installation connections modelled, as presented in [\(Koivisto, Gea-Bermudez, et al., 2019\)](#). For onshore wind and solar PV, each region is split in at least two resource grade areas with different potentials and CFs [\(Gea-Bermudez, Koivisto, et al., 2019\)](#). This is done to model that VRE resource quality is not constant within a region.

2.2 Balmorel

100 For energy system optimisation, the Balmorel model (www.balmorel.com) is [\(Wiese et al., 2018\)](#) is used. Balmorel is an open source (github.com/balmorelcommunity/Balmorel), deterministic and takes a bottom-up approach. The objective function in

Balmorel is to minimize total system costs (Wiese et al., 2018). Balmorel has been traditionally used to perform joint optimisation of the electricity and district heating sectors, although it is –being constantly developed to include additional sectors, e.g., industry (included in this paper), individual heating (not included) and transport (partially included with EVs) scenarios based on (Gea-Bermudez, Koivisto, et al., 2019)). Joint modelling of the electricity and heating sectors allows assessment of benefits from integrating the markets of the different sectors. The setup of the model is similar to (Gea-Bermudez, Koivisto, et al., 2019), although with some important differences. The main difference is that the modelling of industry in Balmorel is based in this paper on three temperature levels (low (<100°C), medium, and high (>500°C)) to reflect that not all technologies can satisfy all types of heat demand. Heat pumps are assumed to be capable of satisfying low temperature demand, CHP low and medium temperature demand, and boilers and electrification low, medium, and high temperature demand.

Compared to (Gea-Bermudez, Koivisto, et al., 2019), Additionally, the only tax and tariff used in this paper compared to on (Gea-Bermudez, Koivisto, & Münster, 2020) is the CO₂ tax, which pushes VRE penetration on the expense of fossil generation. Assumed CO₂ tax values are: 30, 90 and 120 €₂₀₁₅/ton in 2025, 2035, and 2045, respectively; they are based on (NORDEN and IEA, 2016). Since the costs of biofuels are very sensitive to their demand, biofuels are modelled with step-wise price functions as in (Gea-Bermudez, Koivisto, et al., 2019). The aggregated biofuel potentials and its corresponding prices are shown in Table 1 for the countries in focus. More details about the assumptions and technologies included in the model can be found in (Gea-Bermudez, Koivisto, et al., 2019).

In this paper, Balmorel is used to perform for the sector coupling scenario: 1) a capacity development optimization; and 2) day-ahead market simulations. In (Gea-Bermudez, Koivisto, et al., 2019) only the first optimization was performed. Investments in generation, storage, power transmission and district heating expansion, as well as decommissioning of generation capacity, are allowed. Due to computational complexity, 8 spread-over-the-year weeks with 1-every-3 hours are used as representative time steps in the optimization. VRE time series are scaled using the approach described in (Gea-Bermudez et al., 2020), so the statistical representation of the full year is kept. Unit commitment integer variables are relaxed in this optimization. EV charging is assumed to be non-flexible. The capacity development is then used as input in the day-ahead market simulations.

The day-ahead market simulation for the sector coupling scenario has two steps: 1) full year simulations to obtain storage levels at the beginning of each day, planned maintenance and, daily resource allocation; and 2) day-by-day market simulation. Resource allocation is relevant for limited fuels, such as municipal solid waste or biomass. In the full year simulations, all days and 1 every 3 hours are used, EV charging is assumed to be non-flexible, and the relaxation of unit commitment integer variables is applied due to computational limitations. The method is based, and further explained in (Gea-Bermudez, Das, et al., 2019). In the day-by-day simulation, EV smart charging is allowed. The hourly dispatch values from the day-by-day

market simulations are used to compute annual generation, demand, emissions, prices, intercountry transmission flows and wind power curtailment, among others.

140 **Table 1. Aggregated biofuel potentials and corresponding prices for the countries in focus (the UK, NL, DK, BE, DE and NO); each fuel is modelled with a stepwise price function with three levels. Data gathered as shown in (Gea-Bermudez, Koivisto, et al., 2019).**

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Fuel	Biogas			Straw			Wood chips			Wood pellets		
Price (€ ₂₀₁₂ /GJ)	9.5	16.5	142.3	3.5	6.0	51.9	4.1	7.1	61.0	5.8	10.1	87.1
Potential (PJ)	7	202	530	39	1086	2857	253	6965	18313	39	1077	2831

3 Results

145 This section presents and compares the resulting scenarios. The first subsection compares the meshed offshore grid scenario to the project-based one. First, the renewable energy shares and offshore wind installations are compared. Then, the expected levels of VRE curtailment are assessed. In subsection 3.2, the scenario with sector coupling is presented, considering the renewable energy share, annual energy generation mix, and amount of offshore wind installations and the expected level of curtailment. The sector coupling scenario does not include a meshed offshore grid.

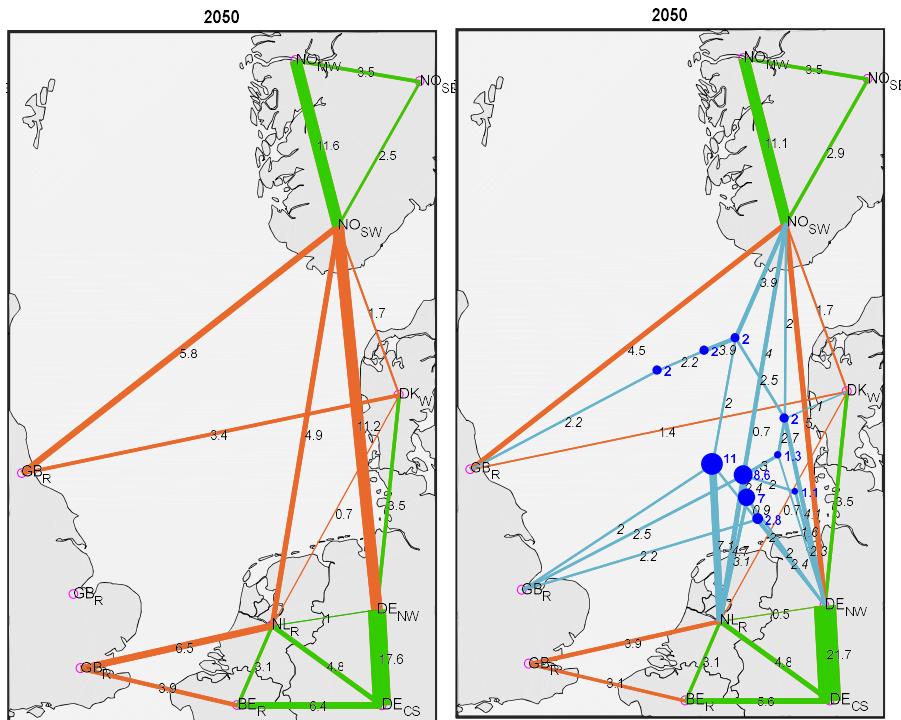
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The project-based and offshore grid scenarios were performed optimizing investments in GB, DK, NO, DE, BE, and NL (Figure 2), whereas the capacity development for surrounding countries was exogenously given (Koivisto, Gea-Bermudez, et al., 2019). In the sector coupling scenario, the capacity development was optimized in all included countries. Additionally, compared to the project-based and meshed offshore grid set up, in the sector coupling scenario UK was analysed instead of GB, a different regional set up for DE was defined to better capture transmission congestion, and Estonia, Lithuania and Latvia were excluded from the runs to reduce computational complexity. However, the scenarios can still be compared on aggregate level, as is done in the following subsections. The results are shown for the countries in focus (Figure 2), so the results between all analysed scenarios can be compared.

160 3.1 Impacts of a meshed offshore grid

This section compares the project-based and the meshed offshore grid scenario. The scenarios have been presented before (Koivisto, Gea-Bermudez, et al., 2019); however, the second subsection adds additional information regarding VRE curtailment. The main difference between the scenarios can be seen in Figure 3: in the project-based scenario, only country-to-country transmission lines are allowed (OWPPs are connected to shore project-by-project); in the meshed offshore grid

165 scenario, meshed connections in the North Sea are allowed in Balmorel investment optimisation (in addition, OWPPs can be connected to the hubs that are part of the meshed offshore grid infrastructure). More information on how the meshed offshore grid is modelled in the Balmorel investment optimisation can be found in [\(Gea-Bermudez et al., 2020\)](#).



170 Figure 3. The resulting transmission and hub-connected offshore wind GW by 2050 in the project-based (left) and offshore grid scenario (right). Green shows on-land lines, orange offshore country-to-country lines, light blue meshed offshore lines and dark blue hub-connected offshore wind power installations. The figures are taken from [\(Koivisto, Gea-Bermudez, et al., 2019\)](#).

3.1.1 Renewable energy shares and offshore wind installations

175 Aggregate results (for countries shown in [Figure 2](#)) for the project-based and meshed offshore grid scenarios are shown in Table 2. [It can be seen that in](#) both scenarios the renewable generation share increases close to 90 % towards 2050 (in addition to VRE, renewable share includes hydro and biofuels). Total electricity generation remains on 2020 level, as electricity

consumption is not changing significantly in these scenarios. Offshore wind installations increase close to 100 GW towards 2050 in the North Sea region, with meshed offshore grid scenario showing 10 GW more offshore wind installations. The 180 meshed offshore grid scenario is also expected to be cheaper than the project-based scenario (Koivisto, Gea-Bermudez, et al., 2019).

Table 2. Aggregate North Sea region results for the project-based and meshed offshore grid scenarios; data from (Koivisto, Gea-Bermudez, et al., 2019).

Scenario	Year	Total electricity generation [TWh]	Renewable generation share in electricity sector (%)	Offshore wind installations [GW]
Starting point	Approx. 2020	1199	46	22
Project-based	2030	1188	75	64
Meshed		1193	76	69
Project-based	2050	1192	88	92
Meshed		1207	89	102

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3.1.2 VRE curtailment

Table 3 shows VRE curtailment results for the project-based and meshed offshore grid scenarios; data are from (Gea-Bermudez, Das, et al., 2019). Especially in 2050, significant curtailment is expected for wind power. The high share of offshore 190 wind curtailment compared to onshore wind may be a result from Balmoral optimisation; offshore wind is expected to have a higher operational (per MWh) cost than onshore, and thus the curtailment of offshore rather than onshore wind is found optimal in the Balmoral run.

For the analysed region, solar PV curtailment is negligible. It needs to be noted that that the reported curtailment considers only high-level transmission level grid congestion (between the regions shown in Figure 2), as lower level transmission is not 195 modelled. Thus, there can be additional congestion challenges, especially for generation connected to lower voltage levels, such as solar rooftop solar PV.

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Table 3. VRE curtailments for the project-based and meshed offshore grid scenarios. Shares with respect to available production.

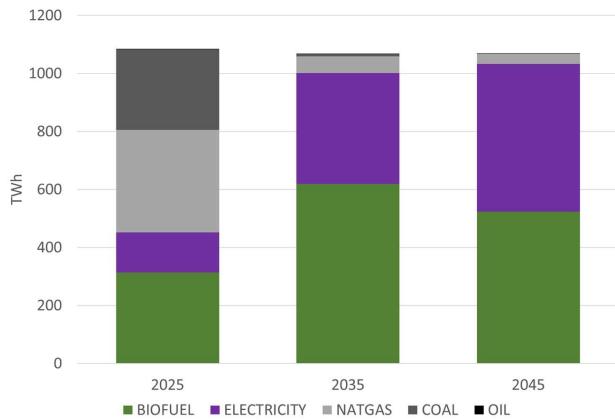
Scenario	Year	Onshore wind (%)	Offshore wind (%)	Total wind (%)
Project-based	2030	0.2	2.2	1.2
Meshed		0.2	2.4	1.3
Project-based	2050	0.2	10.3	6.0
Meshed		0.3	10.4	6.5

3.2 Impacts of sector coupling

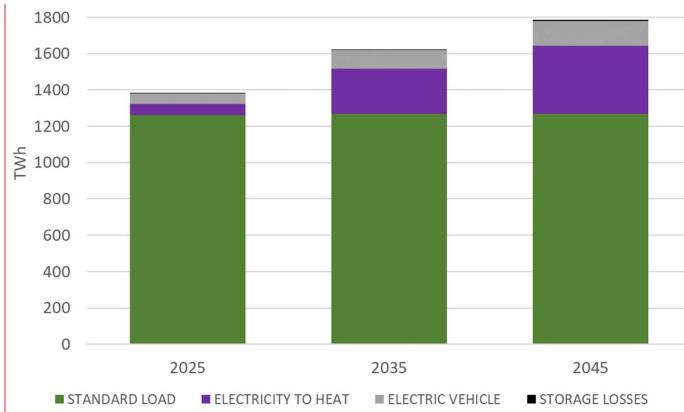
This section presents the scenario where the modelling of sector coupling has been included in the Balmoral investment 205 optimization.

3.2.1 Changes in heat production and electricity load

Figure 4 shows how the heating sector is expected to change towards 2050 as an aggregate for the North Sea region countries in focus. Due to electrification, but also as biofuel use is expanded, coal and gas are almost entirely removed from the heating system. Figure 5 shows that electricity load increases as electrification of heating increases and EV fleet expands. It needs to be noted that not all sectors are considered in the presented analysis. Electrification leads to significant increase in required electricity generation, as shown in the next subsection. The possibility to utilise biofuels in the heating sector can be debated; its role is planned to be analysed in future work this is discussed more in Section 4.



[215] **Figure 4.** Aggregated heat production per fuel for the countries in focus (countries shown in [Figure 2](#)). The industrial sector and individual users connected to district heating are included.



[Figure 5.](#)

[220] **Figure 5.** Aggregated electricity demand per type for the countries in focus. (countries shown in [Figure 2](#)). Standard load means classic existing electricity load, with small additional load assumed to come from data centres.

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225 **3.2.21 Renewable energy shares and offshore wind installations**Annual energy generations towards 2050

As can be seen in Table 4, there is a significant increase of electricity generation from the 2020 level shown in [Table 2](#)[Table 4](#) towards 2045. This can be expected based on the increasing electrification of the heating sector [and the expanding EV fleet](#)[\(Figure 4\)](#), and it leads to a significant increase in offshore wind installations. Compared to the impact of meshed offshore grid, as shown in [Table 2](#)[Table 4](#), the effect of sector coupling is expected to be tens of GW of more of offshore wind power.

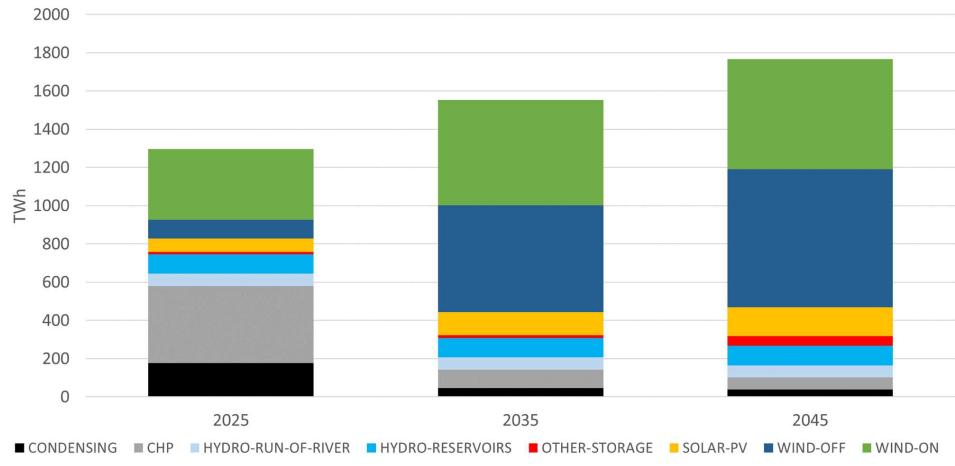
230 In addition to increasing the overall level of generation (both GW and TWh), sector coupling increases the renewable generation share from around 90 % in the scenarios presented in [Table 2](#)[Table 4](#) to close to 100 % in Table 4.

235 [Figure 6](#)[Figure 6](#) shows how the aggregate annual energy generations from different generation sources develop towards 2050. The system is expected to be highly wind-dominated by 2045, but with some solar generation. The share of offshore wind grows from 2035 to 2045 to cover most of the increased electricity demand, with solar generation also increasing slightly. Some natural gas generation remains until 2045, with hydro and biofuel also providing some dispatchable generation to the system. Storage (other than hydro reservoirs) use increases, especially from 2035 to 2045. This increase is mainly electricity battery storage. By 2025, a significant part of CHP generation takes place in the industry sector. However, after 2025 CHP generation decreases significantly, driven by the increasing electrification of the heat sector.

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Table 4. Aggregate North Sea region results for the countries in focus in the scenario with sector coupling.

Year	Total electricity generation [TWh]	Renewable generation share in electricity sector (%)	Offshore wind installations [GW]
2025	1284	58	25
2035	1537	94	126
2045	1717	96	158



245 **Figure 66.** Aggregated annual electricity generation per type for the countries in focus. (countries shown in Figure 2). |

Commented [MJK4]: New figure

3.2.34 Offshore wind installations in the different countries

Offshore wind installation development towards 2050 is shown in Table 5. By 2045, almost half of the installed offshore wind generation in the North Sea region countries is expected to be in the UK, driven by large potentials with high CFs. Germany shows the second highest offshore wind capacity development, with Netherlands and Denmark also reaching higher than 10 GW by 2045.

Table 5. Offshore wind installations per country for the scenario with sector coupling (GW).

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Country	2025	2035	2045
Belgium	1.2	9.1	8.4
Denmark	2.9	5.0	11.0
Germany	9.6	43.5	46.7
Netherlands	1.0	12.2	14.9
Norway		3.5	4.6
The UK	10.6	52.3	72.7

Total	25.2	125.6	158.4
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3.2.42 VRE curtailment

260 VRE curtailment in the scenario with sector coupling is shown in Table 6. The expected level of curtailment is significantly lower than the numbers reported in [Table 3](#)[Table 2](#). This indicates increased flexibility of the energy system, as it can absorb more VRE generation ([Table 4](#)[Table 3](#)) while simultaneously reducing the curtailment. The specific reasons for this increased flexibility will be studied in future work; however, the strong coupling between the electricity and heating sector (Figure 4) is expected to be a significant contributor. Curtailment of solar PV is negligible.

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Table 6. VRE curtailments for the scenario with sector coupling. Shares with respect to available production.

Scenario	Onshore wind (%)	Offshore wind (%)	Total wind (%)
2025	0.0	0.0	0.0
2035	0.1	0.6	0.4
2045	0.0	1.1	0.6

4 Discussion

270 The modelled sectors include electricity, district heating, industry and EVs. Individual heating sector modelling and data collection for the analysed countries was not fully completed at the time of writing this paper but will be considered in future research. Ongoing research includes also modelling of the other parts of the transportation sector, such as shipping and aviation, where power-to-gas is expected to play a significantly role.

275 The CO₂ tax levels in 2035 and 2045 may be considered high, although the 2025 level is not far from current market prices of around 25 €/ton in Europe. Future research will consider a CO₂ price sensitivity study. In this paper, biofuels play a significant role in the heating sector. However, when considering, e.g., the transportation sector more broadly, it may be that biofuels are required to cover other demands than the ones modelled in this paper. In addition, considering, e.g., power-to-gas for ships, may change the overall structure of the energy system so that stronger electrification of the heating sector becomes more attractive. These aspects will be considered in future research, where the transportation and heating sectors are covered more comprehensively. CO₂ price and other cost sensitivities and sensitivities on assumptions, e.g., on biofuel potentials, can be

280 used to compare costs of different scenarios.

285 The impact of assumptions on onshore wind potentials has a significant impact on the offshore wind buildout, with limiting onshore wind driving offshore wind installation (Koivisto & Gea-Bermudez, 2018). Future work will consider how the onshore wind potential assumptions impact offshore wind installations when sector coupling is modelled. Future work will also include modelling both sector coupling and the meshed offshore grid jointly.

290 In Table 5, the offshore wind installations in Belgium and Netherlands by 2025 are below the most recent agreed plans in these countries. The starting point for the offshore wind installations will be reassessed in future analyses. When considering offshore wind installations on the level of tens of GW, the impact of large-scale wake losses, where OWPPs cause wake losses to neighbouring OWPPs (in addition to the internal wake losses inside an OWPP), may become very significant. Future research will consider how to apply such large-scale wake modelling in the context of large-scale energy system analysis.

5 Conclusion

This paper has showed that integrating offshore transmission lines and generation investments in the North Sea region can be beneficial and lead to around 10 GW higher offshore wind installation compared to a project-based scenario towards 2050.

295 Sector coupling is expected to boost offshore wind installations by tens of GW, as electricity consumption increases. In addition, the energy system can benefit from increased flexibility from sector coupling. Indicative results on this were found, as the level of VRE curtailment decreased significantly when sector coupling was considered in the modelling.

Code and data availability

The Balmorel model is available at: github.com/balmorelcommunity/Balmorel.

300 Author contributions

Matti Koivisto wrote most of the paper, did the CorRES runs and gave inputs to the Balmorel modelling. Juan Gea-Bermúdez ran the Balmorel optimizations, wrote the Balmorel section of the paper and gave comments. Polyneikis Kanellas helped with the Balmorel runs and gave comments. Kaushik Das gave inputs to the CorRES and Balmorel runs, especially on the day-by-day runs and curtailment analyses, and provided comments on the paper. Poul Sørensen provided comments.

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