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Economic and environmental benefits from integrated power grid infrastructure designs in the North Sea

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Abstract. The North Sea Offshore Grid (NSOG) is considered an important contributor towards large-scale integration of renewables and electricity market coupling. Different typologies have been studied for such a multinational power grid, ranging from radial point-to-point connections to more integrated meshed typologies. An artificial island enables a high level of integration of both offshore wind power and transnational trade due to economies of scale. This paper present multiple case studies of the Power Link Island (PLI) which is visioned by TenneT in the Doggerbank area. Our results demonstrate that the capabilities of such an island could add significant value to the system as a result of more efficient use of geographically spread, cost-efficient resources. However, depending on the future level of grid integration and generation mix, the added value of a PLI varies between €0.15bn to €20bn. Consequently, this could result in 18% more efficient utilization of renewable resources, primarily offshore wind, and significant reductions of CO2 emissions.

1. Introduction

The North Sea Offshore Grid (NSOG) has been identified as one of the strategic infrastructure projects in EU Regulation No 347/2013 with the twofold purpose of integrating offshore wind resources and integrating markets for increased cross-border trade (EU Commission, 2011; European Commission, 2016). In order to speed up investments and attract private investors, financial support netting €5.35bn is provided by Connecting Europe Facility (CEF), but this is only a small portion of the estimated €140bn worth of necessary electricity infrastructure upgrades the coming decade (ENTSO-E, 2016). Several studies have addressed different grid designs and the added value of a NSOG as a result of cost-efficient utilization of variables renewable energy sources (VRES), reduced greenhouse gas (GHG) emissions, and increased security of supply (Van Hulle et al., 2009; Egerer, Kunz, & Hirschhausen, 2013; Gorenstein Dedecca & Hakvoort, 2016).

Typologies, being a combination of grid topology and technology, are traditionally divided into two groups; radial and integrated (Trötscher & Korpås, 2011; Gorenstein Dedecca & Hakvoort, 2016). A radial typology comprise point-to-point high voltage direct current (HVDC) connections, while an integrated (or meshed) typology enables multiple HVDC connections at one joint – yielding a modular and flexible design. For instance, in order to connect four countries one would need six transmission corridors in order to interlink them all with radial typology, in addition to individual offshore wind power (OWP) connections, while with an integrated typology the number of corridors is reduced from six to four (with approximately half the length, each). Additionally, an integrated typology will also achieve a higher level of utilization at each transmission corridor. The concept of a Power Link Island (PLI) is a large-scale augmentation of the integrated typology with significant potential in economies of scale (van der Meijden, 2016). According to its promoter, TenneT, a PLI can span an area of 6 km^2 and its capital costs are estimated to be €1.5bn for the artificial construction of the island itself; i.e. a pile of stones and sand in the shallow water of the Doggerbank area (TenneT, 2017b).

PLI has the capacity to connect 30 GW OWP capacity and by combining multiple PLIs into a so called offshore wind power hub the capacity can be expanded to 100 GW, which translates into enough energy supply for 70-100 million consumers in Europe (TenneT, 2017a). It could therefore serve an important role towards European 2050 energy and climate targets (EU Commission, 2011) – where approximately 230 GW OWP capacity is needed and 180 GW in the NSOG area (TenneT, 2017a). TenneT has announced that the PLI could be in operation already by 2035 (TenneT, 2017b), connecting Norway (NO), Denmark (DK), Germany (DE), The Netherlands (NL), Belgium (BE), and Great Britain (GB).

This paper presents multiple case studies of the PLI with data from ENTSO-E for year 2030 (ENTSO-E, 2016). Our goal is to demonstrate the added value of a PLI due to the growing interest on this topic. We do this by evaluating its performance under different system designs, i.e. a variety of possible compositions of grid and generation capacity, followed by a sensitivity analysis with respect to an increasing offshore wind capacity.

2. Methodology

A mathematical optimization model for transmission and generation expansion planning is used in order to assess the impact of an artificial island in a NSOG with respect to different system designs - ranging from planned to optimal. This allows for a wide specter of case studies that are demonstrated with respect to a varying degree of OWP capacity levels.

The following assumptions are made for the PLI study:

- OWP capacity is not connected to the grid in any case. Hence, we measure the system's ability to incorporate this capacity as cost-efficient as possible given a certain degree of freedom in the model (outlined by the following cases). This means that grid investments has to be made in order to include this OWP capacity.
- Zero investment cost for PLI. This yields an implicit break even value when the option to utilize a PLI is active, in terms of system cost savings.
- Unlimited capacity restrictions for the PLI island. That is, the optimization model might invest in multiple and fractional number of islands.
- Domestic grid restrictions in the range of 5-15 GW. This represent a bottleneck for the offshore grid expansion.

2.1. An expansion planning model for grid- and generation investments

We use a generation and transmission expansion planning (GTEP) model that is adapted for the NSOG case study. Six countries are covered in total; Norway (NO), Denmark (DK), Germany (DE), The Netherlands (NL), Belgium (BE), and Great Britain (GB), as depicted in Figure 1. The model is open-source and a documentation can be found in, e.g., (Kristiansen, Munoz, Oren, & Korpås, 2017) or (Kristiansen, Korpås, & Svendsen, 2018). Hence, only a brief introduction is given here as the model is already well documented and transparent.

The model assumes perfect competition, inelastic demand, and a welfare-maximizing system planner. Technically, it originates from a bi-level structure where generators respond to transmission investments. However, due to the aforementioned assumptions, we can recast this bi-level equilibrium model as an optimization program that co-optimize both investment- and operational costs (Samuelson, 1952). The objective is therefore to minimize total system

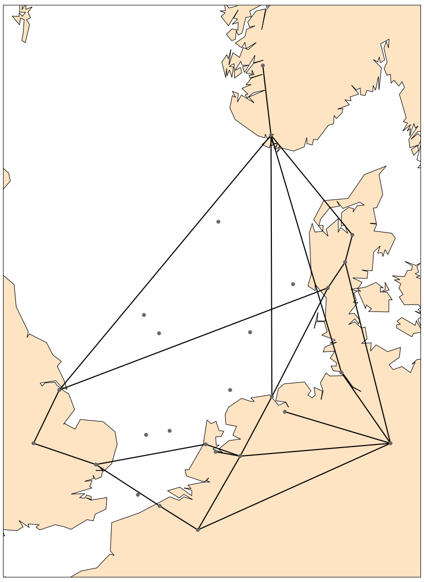

Figure 1: The North Sea Offshore Grid as it is modelled for this study. The base case excludes offshore wind connections, which are to be optimally determined by the model in the following case studies using input data from Table 1.

costs over an economic lifetime spanning 30 years. Everything is discounted back to net present value using 5% discount rate.

In order to cope with computational challenges for the resulting mixed-integer linear program (MILP), a k-means clustering algorithm (Härtel, Kristiansen, & Korpås, 2017) is used to reduce full-year time series (8760 hours) to a fraction (400 hours). Despite the dimension reduction of input data, operational system dynamics are still well represented for the interplay between, e.g., wind, solar, hydro, and load. To this end, the model captures the underlying value of the system's ability to balance and distribute power variability with varying power flow patterns.

Kirchhoff's voltage law (KVL) is ignored since a majority of the system infrastructure consists of high voltage direct current (HVDC) corridors that are fully controllable. This results in a transport model with no loop-flows. However, linear losses are incorporated to reflect both the transmission distance and use of necessary voltage transformers and power electronics.

2.2. Input data

Data from ENTSO-E (ENTSO-E, 2016) is applied in order to replicate a future system (year 2030) with relatively high shares of variable renewables energy sources (VRES). The data is summarized in Table 1.

The variability of wind, solar, hydropower, and load is incorporated using full-year, hourly profiles from both historical data and numerical weather data, where the latter source is particularly relevant for offshore coordinates with limited historical data (Kristiansen, Korpas, Farahmand, Graabak, & Hartel, 2016).

2.3. Case study setup

The case studies are designed with the intention to cover a wide range of future, possible system designs represented from Case (a) to (d) asserted below. That is, different levels of grid and generation mix. Our basis is the planned infrastructure for year 2030 without any OWP connections, as depicted in Figure 1 (Case (a)). In addition to this, we allow the model

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Table 1: Supply, demand and fuel price data from ENTSO-E Vision 4 (ENTSO-E, 2016). Onshore and offshore wind capacities are divided according to data from WindEurope (Nghiem & Pineda, 2017). CO_2 price is 76€/tonCO_2.

Supply/	Fuel price	Installed capacity [MW]					
Demand	[€/MWh_e]	BE	DE	DK	GB	NL	NO
Bio	50	2500	9340	1720	8420	5080	0
Gas	65	10040	45059	3746	40726	14438	855
Hard coal	21	0	14940	410	0	0	0
Hydro	10-30	2226	14505	9	5470	38	48700
Lignite	10	0	9026	0	0	0	0
Nuclear	5	0	0	0	9022	486	0
Oil	140	0	871	735	75	0	0
Solar PV	0	4925	58990	1405	11915	9700	0
Onshore wind	0	3518	76967	6695	27901	5495	1771
Offshore wind	0	4000	20000	6130	30000	4500	724
Total supply	-	27209	249698	20850	133529	39739	52050
Peak demand	-	13486	81369	6623	59578	18751	24468

to find other optimal, future system designs by progressively expanding the model's freedom to invest in additional grid and/or generation capacity (Case b to d). For instance, the fact that we are using a GTEP model allows us to anticipate the response in generator investments as a result of different grid designs.

The main objective with the case studies is to quantify the added value of a PLI, utilizing its geographical location and economies of scale on top of each of the aforementioned system designs. This means that we first optimize for a given system design (case (a) to (d)), followed by subsequent optimizations with the option to connect to a PLI. The PLI is provided for free, i.e. the offshore construction itself, while the grid connections comes at an expense. Hence, the final metrics could be viewed as break-even values for the construction of the island.

The added value of a PLI is measured with respect to the following cases:

(a) Planned cross-border capacity (Figure 1). In this scenario, the already planned infrastructure is implemented and OWP can be included at a cost.

(b) Optimal cross-border capacity. Contrary to (a), we allow the model to expand cross-border capacity to an optimal level.

(c) Planned cross-border capacity + optimal generation mix. Expanding the possibilities in (a) to include an optimal generation mix.

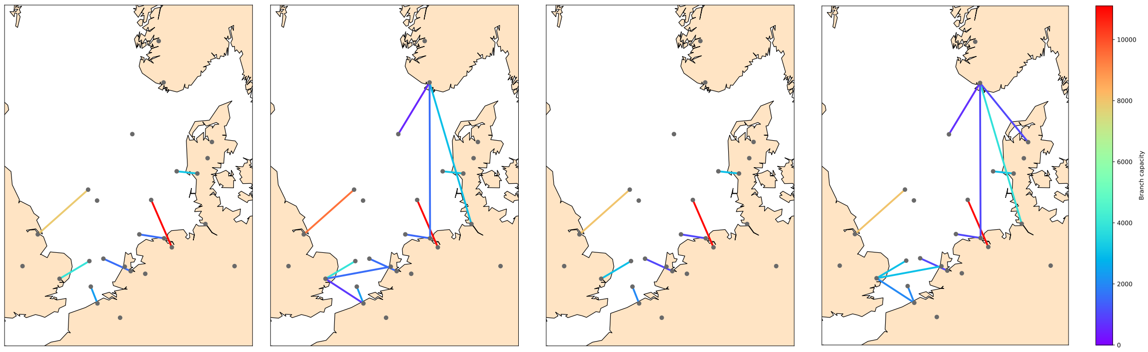
(d) Optimal cross-border capacity + optimal generation mix. Expanding the possibilities in (b) to include an optimal generation mix.

2.4. Sensitivity analysis

In order to carry out a sensitivity analysis with varying shares of OWP one would need to try keeping capacity- and energy levels consistent throughout the analysis. That is, different levels of OWP from 0-200% should yield about the same system properties in terms of available capacity and energy throughout a year.

A representative substitute for the residual OWP capacity (i.e. a unit that bridges the gap from X% OWP to 200%) is, in our case, a fictive "thermal VRES" unit for each country. The idea is that it should represent the marginal unit in each country with its respective properties in terms of CO2 emission rate and fuel costs, but with a yearly utilization factor equivalent to

OWP. The thermal VRES unit will therefore approximate the same level of capacity and yearly energy inflow as OWP. However, the main difference is the flexibility – meaning that yearly, disposable energy can be used at any time for thermal VRES, whereas OWP has to follow wind speed feed-in at its respective geographical coordinate. More information about this approach can be found in (Kristiansen et al., 2018).



(a) (b) (c) (d)

Figure 2: Different scenarios for OWP integration (a)-(d) depending on underlying system design. The colored lines indicate the level of capacity investments determined by the GTEP model spanning from 0 GW (purple) to 14 GW (red).

3. Results

Results are obtained for the base cases in the previous section which, in turn, is narrowed down to an impact analysis of a PLI – both in economic and environmental terms. Finally, a sensitivity analysis is presented in order to evaluate the value of a PLI under varying shares of OWP.

3.1. Different system designs with varying degree of grid and generation mix

Figure 2 depicts which transmission corridors that are expanded for each of the case studies, hence the same notation (a)-(d). For instance, Case (a) comprise only planned interconnectors without any other options than integrating its OWP capacity. This can be seen from the colormap indicating the level of capacity expansion in Figure 2. Note that for the planned infrastructure, the model does not find it beneficial to incorporate OWP in NO as the costs for grid connection exceeds the operational cost savings. This means that all OWP production in NO is curtailed. This observation is also true for Case (c), i.e. planned infrastructure with generation capacity expansion.

Contrary to the planned infrastructure cases, Figure 2 clearly illustrates that it is more beneficial to include OWP when allowing for optimal cross-border transmission capacity. This is because the increased trade capacity from NO to the continent and GB results in more trade options at a relatively higher price, justifying the grid investment costs for OWP to NO.

One occurring observation for all four cases is that the ones with generation expansion does not deviate too much from the ones without, in terms of infrastructure investment portfolio. This can be seen by comparing (a) with (c), and (b) with (d) in Figure 2. This could imply that the interconnectors are less sensitive to moderate changes in the generation mix. However, it might have a more evident impact on economic- or environmental metrics due to the bulky and capital intensive nature of international transmission corridors.

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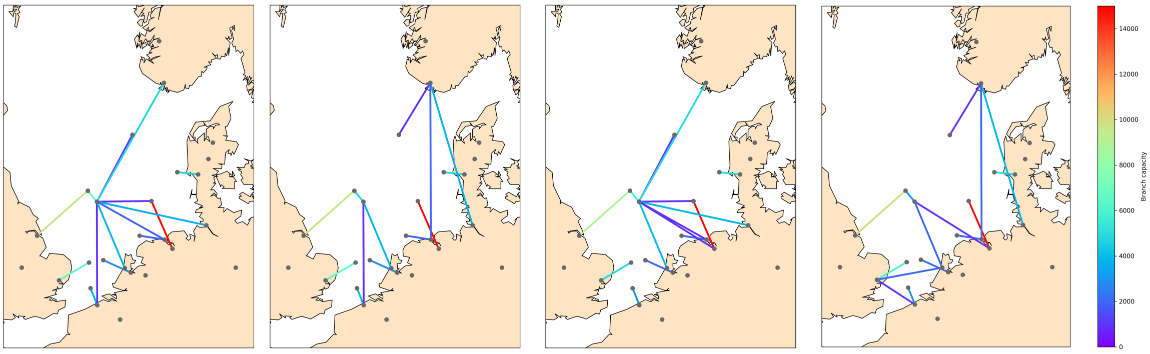

(a) (b) (c) (d)

Figure 3: Case (a)-(d) including the option to utilize a free PLI. The colored lines indicate the level of capacity investments determined by the GTEP model spanning from 0 GW (purple) to 14 GW (red).

3.2. The impact of a PLI on grid designs

The four base cases represented in Figure 2 are in Figure 3 considered with the option to utilize a PLI in the Doggerbank area. Hence, the added value of such an option can be quantified. The PLI functions as a transnational transportation hub in addition to including offshore wind resources. Note that the OWP capacity in NO is included for all cases, contrary to the base cases where we excluded the option to use a PLI (see Figure 1).

For the planned infrastructure and generation mix, Case (a), about 31 GW of new transmission capacity is built to the PLI – including both offshore wind and transnational trade capacity. This is approximately equivalent to €28bn worth of investments, in terms of additional investments exceeding the base case. However, the operational cost savings are almost 60% higher netting €48bn. This means that the added value is around €20bn for Case (a).

The other three cases leads to smaller amounts of cost savings and the most influential factor is grid expansion. Case (b) assumes that, by year 2030, cross-border transmission corridors reach an optimal capacity level determined by the model (exceeding case (a) with 11.4 GW in total transmission capacity). With this, the optimal grid reach a way more efficient system operation than Case (a) which, consequently, means that the value potential for a PLI concept decay. The added value of a PLI in Case (b) is as low as €0.15bn since the model sees other competitive expansion alternatives.

By trying to anticipate changes in the generation mix, i.e. Case (c) and (d), Figure 3 shows that the two latter cases result in almost the same grid typologies as when ignoring changes in the generation mix (Case (a) and (b)). The value of a PLI does, however, deviate considerably. As expected, the added value in Case (c) is lower than for Case (a) as it is reduced to €15bn. But, for Case (d), the added value is higher than for Case(b) reaching almost €1bn.

Among changes in grid and generation, grid is definitely the most influential one in terms of its impact on the profitability of a PLI. Hence, the value of a PLI would most likely depend on the future development of the NSOG to a larger extent than changes in the generation mix.

3.3. The added value of a PLI under variable shares of OWP

A sensitivity analysis is performed in order to get more in-depth insights on the added value of a PLI – both in terms of cost savings and reductions in CO2 emissions. An important driver for these values, given the outline for our case studies, is the share OWP capacity. As a result, a wide range of OWP capacity levels are evaluated spanning from 0 GW to double the amount of our input data, i.e. up to 2x65 GW. The horizontal axis in Figure 4 and Figure 5 does therefore

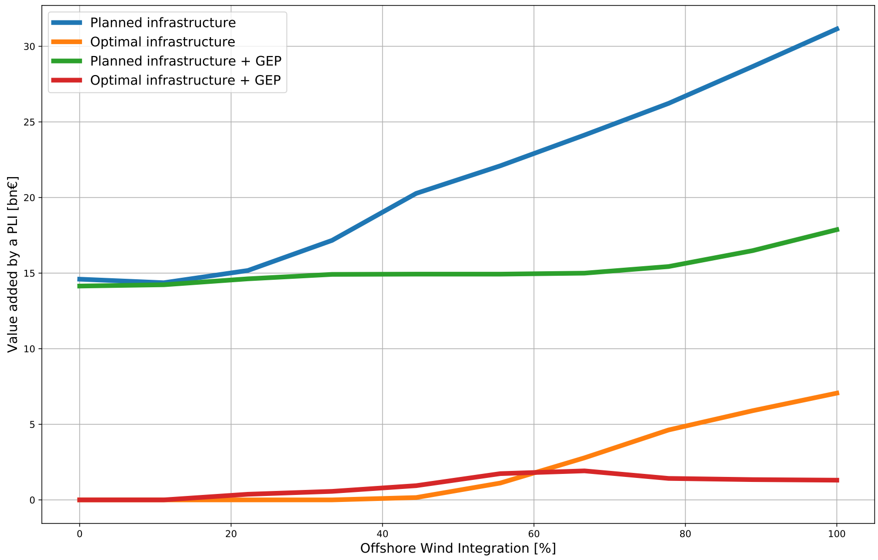

Figure 4: The added value of a PLI under an increasing share of OWP ranging from 0 GW to twice the capacity as the original input data from ENTSO-E Vision 4 (i.e. 130 GW). The added value is quantified on top of different system designs defined by Case (a) to (d).

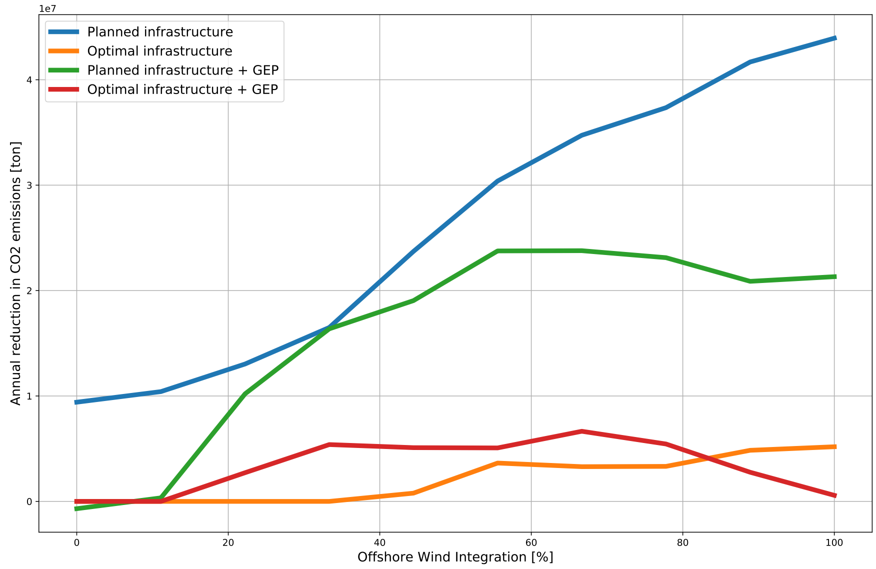

Figure 5: The CO2 emission impact of a PLI under an increasing share of OWP ranging from 0 GW to twice the capacity as the original input data from ENTSO-E Vision 4 (i.e. 130 GW). The CO2 reductions are quantified in relative terms to different system designs defined by Case (a) to (d).

vary with respect to the aforementioned range of capacities, where 100% is equivalent to 130 GW OWP. Peak demand is, in comparison, around 204 GW.

First, note that 50% OWP share should yield approximately the same results as obtained in the previous analysis since it represents the same amount of OWP as in the original data input. However, due to the use of a fictive thermal VRES unit, the results might deviate slightly. For instance, Figure 4 implies that the added value of a PLI is around €21bn (which is supposed to be closer to €20bn). However, the goal with the sensitivity analysis is rather to visualize the relative impact of a PLI under different system designs (Case (a)-(d)) and different OWP capacity levels.

As expected, the value of a PLI in Case (a) comprise a steeper increase with respect to an increasing share of OWP compared with the other cases. This observation is even more conspicuous for CO2 emission reductions, as seen from Figure 5. This could imply the important role a PLI plays as a transnational transmission hub, ensuring high utilization of renewable resources by providing a high degree of spatial flexibility.

The two cases with generation expansion, i.e. Case (b) and Case (d), seems to be rather independent of the OWP capacity levels in cost terms which can be seen from the relatively flat green and red line in Figure 4, respectively. However, a PLI shows increasing value in terms of CO2 reductions in Case (b) when varying the share of OWP. Again, this demonstrates the robustness of a PLI's ability to harvest VRES potential.

3.4. Discussion of results
The added value of a PLI is, as expected, lower in a future with a strong grid infrastructure and optimal generation mix, e.g. like in Case (d) where the break even cost amounts to €0.15bn (the red line in Figure 4). This will not justify the estimated investment costs for the artificial construction of the island itself (€1.5bn). However, there are two things that should be noted; i) Case (d) comprise of 11.4 GW more cross-border capacity than Case (a) which is slightly unrealistic, and ii), the latter is the main driver for the potential benefits of a PLI. To this end, it would be safe to assume a lower boundary around €0.15bn given the methodology behind this case study. Contrary, an upper bound could be approximated with Case (a) where the added value amounts to €20-21bn accounting for a planned infrastructure and a rather ambitious (fixed) generation mix (ENTSO-E Vision 4).

An interesting observation, that strengthens one of the key purposes with a PLI, is that although costs might be less sensitive to changes in OWP capacity, CO2 emissions varies significantly more in relative terms. Particularly between 0% to 50% OWP in Figure 5 which is likely the most realistic range of future OWP capacity levels in the North Sea, i.e. between 0 - 65 GW. In comparison, the current level is 11.2 GW OWP capacity in the North Sea (Pineda, 2018). This demonstrates the flexibility a PLI provides to the system in terms of efficiently harvesting offshore wind resources, and depending on the outlooks for additional OWP capacity in the region it might have a considerable positive impact on CO2 emissions ranging from 12-26 million ton annual reductions (given 11.2-65 GW OWP).

However, there are several challenges with both quantifying the added value and deploying such a large project. The first is obviously related to data, uncertainty, and model assumptions as demonstrated briefly in this article. Maybe more important is that a project like this borders multiple countries which naturally leads to conflicting objectives and incentives among stakeholders regarding allocation of resources, power flows, and consequently investment costs and benefits. Economic principles of fairness and stability might solve such allocation problems (Kristiansen et al., 2017), but as these mechanisms often relies on side payments[1] it might be difficult to implement in practice. Especially uneven distribution of costs and benefits reached several billion euros.

4. Conclusion
This paper evaluates different degrees of grid integration for a North Sea Offshore Grid (NSOG), with a particular focus on the economic impact of an artificial island compared to traditional

[1] Side payments are used as a mechanism to reallocate value. For instance, if Country A benefits more than Country B from a bi-literal project, the former may pay the latter as a compensation (side payment).

solutions such as radial grid typologies. Results are obtained using a transmission and generation expansion planning model incorporating data that reflects a future power system in year 2030 with relatively high shares of renewable supply capacity. With this, we are able to evaluate how different degrees of grid integration manage to utilize variable energy sources, such as offshore wind power (OWP), in addition to transnational trade.

Sensitivity analyses are presented in order to assess the added value of an artificial island under varying capacity levels of offshore wind power ranging from 0-200% of the original input data (ENTSO-E Vision 4). A fictive thermal unit is used for the analyses in order to approximate consistent energy- and capacity levels in the system for all shares of OWP. Impact on system cost savings and CO2 emission reductions are quantified.

The presented work provides more insights on topics concerning the construction of an artificial island in the NSOG and its potential range of added value to the system. The value range is determined by different degrees of grid and generation mix capacity, i.e. for a planned and optimal offshore infrastructure, and for an estimated and optimal generation mix. To this end, one is able to assess the landscape of opportunities for a PLI, both in terms of cost savings and environmental impact.

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The authors would like to extend their gratitude to the developers behind Pyomo (Hart et al., 2017), as well as Gurobi Optimization.

Nomenclature

CEF	:	Connecting Europe Facility
ENTSO-E	:	European Network of Transmission System Operators
GHG	:	Greenhouse gas
GTEP	:	Generation- & transmission expansion planning
HVDC	:	High voltage direct current
KVL	:	Kirchhoff's voltage law
MILP	:	Mixed-integer linear program
NSOG	:	North Sea Offshore Grid
OWP	:	Offshore wind power
OWPH	:	Offshore wind power hub
PLI	:	Power Link Island
VRES	:	Variable renewable energy sources

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