A Techno-Economic MILP Optimization of Multiple Offshore Wind Concessions

S. Hardy, K. Van Brusselen
CG Holdings Belgium NV – Systems Division
Antwerpsesteenweg 167, B-2800 Mechelen, Belgium
Email: stephen.hardy@cgglobal.com

D. Van Hertem, H. Ergun
KU Leuven - Department of electrical engineering
Kasteelpark Arenberg 10, box 2445 — BE-3001 Heverlee

***Abstract*—The connection of offshore wind requires expensive infrastructure. The development of such infrastructure can be calculated through the use of a techno-economic optimization routine. This paper investigates how two completely different geographic locations, Belgian North Sea and the Indian Cambay wind zones compare. The optimization is formulated as a sequential Mixed Integer linear Program (MILP) considering both AC and DC technology as well as a number of different voltage levels for both technologies. For AC connections, the possibility of mid-point compensation is included. The optimization software utilized is developed in the Julia language at CG Holdings Belgium. In the results section, two optimal topologies are described, one for each analyzed offshore wind power zone. The topologies include the optimal voltage levels, locations of Offshore Substations (OSSs) and transformer and cabling ratings for the transmission grid.**

***Index Terms*—MILP, Optimization, Offshore Wind Power, Transmission Systems, Techno-Economic Analysis.**

I. INTRODUCTION

Currently, the practice within the European offshore wind industry is for countries to designate an offshore wind power zone within their Exclusive Economic Area (EEA). This zone is then further divided into individual concessions which are auctioned off to developers. Developers then optimize concessions independently. As such, research on optimization of the transmission system layout has been heavily focused at the scale of the individual concession, ignoring the possible gains that come from current or future developments in neighboring concessions within the same region [1]. There is a significant opportunity for both cost savings and increased system reliability by optimizing an entire offshore wind zone prior to the development of each individual concession [2]. This work investigates these opportunities in the cases of the Belgian North Sea and zone ”A” as designated by the Facilitating Offshore Wind in India (FOWIND) consortium within the Bay of Cambay in Gujurat India [3]. Investigating both test cases in parallel permits the identification of impacts differing environmental features have on offshore transmission systems. Furthermore, the North Sea case allows for a comparison with an existing real life solution, as the Belgian North Sea is already partly developed.

This paper is structured in the following manner: Section 2 describes the optimization methodology employed. Section 3 describes the optimization domains and in the case of the North Sea the existing solution. In section 4, the wind conditions for each region are presented along with the turbine characteristics. Finally, results are presented in section 5 followed by conclusions extracted from the work.

II. OPTIMIZATION METHODOLOGY

The optimization considers both AC and DC technology as well as a number of different voltage levels for both technologies. In this study HVDC is only considered for point to point connections, meshed HVDC grids are out of the scope of the paper. The objective of the optimization is the minimization of the lifetime cost of the transmission system. For AC connections, the possibility of mid-point compensation has been shown to extend the economic range of HVAC systems and is as such considered in the selection of candidate submarine cables [4].

The methodology employs 4 stages of optimization as shown in Fig. 1. The first 3 stages are used to select an appropriate voltage level for MVAC and HVAC networks, as well as to calculate an initial solution and upper bound for solving the full size problem. The cascading nature of the algorithm allows the best solution from the previous optimization to be introduced as an initial solution and the objective function value as a maximum upper bound in subsequent Mixed Integer Linear Programs (MILPs), which helps to reduce computational time.

In step 1, for a given MVAC and HVAC voltage level, a set of k-1 layouts of feasible Offshore Wind Power Plant (OWPP) clustering strategies are generated, where k is the total number of OWPPs. Then, for each clustering strategy, the optimal transmission cables, transformers and converters, considering costs for material and installation, variable and fixed losses, and Expected Energy Not Served (EENS) are calculated for all candidate lines. More details of the cost calculations can be found in [5]. In step 2, the set of optimal locations of candidate Offshore Substation (OSS) for each clustering strategy is determined using a MILP model. In step 3, an overall system layout consisting of all previous determined OSS locations is generated and the optimal transmission system layout determined via a second MILP model. These 3 steps are repeated for each desired MVAC and HVAC voltage level combination in order to determine the optimal voltage levels. Finally, for the selected voltage levels, the full sized MILP is solved using the best solution so far as an initial point and the corresponding objective function value as an upper bound.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement no. 765585.

During the final optimization stage, it may be found that the solution of optimization stage 3 cannot be substantially improved upon. In this case the global optimum cannot be guaranteed as the full size problem can be too large to solve in a reasonable time even with a good initial guess and upper bound. However, even in this case a lower limit on the theoretical optimal network is established which is useful for planning purposes.

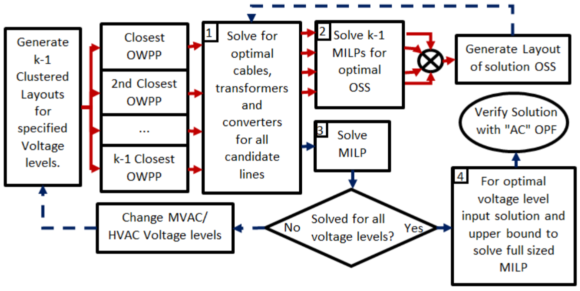

Fig. 1. Sequential MILP Optimization Algorithm.

III. Domain Description

A. Belgian North Sea

The Royal Decree of May 17th 2004 designated an offshore region in the Belgian North Sea of 264 km^2 for sea based renewable energy electricity generation [6]. This area was later reduced slightly to 238 km^2 due to shipping requirements [7]. In 2009, a report commissioned by the Belgian department of climate and energy set an ambitious goal of 2.1 GW of offshore wind production by 2020 [8]. Around the same time, Thorntonbank, a 30MW demonstration OWPPs came online generating Belgium's first offshore wind power [9]. Up until the present the Belgian offshore wind region has seen continuous development towards the 2.1 GW goal. As of the end of 2018, Thorntonbank has had an additional 295 MW of capacity added and 4 more additional OWPPs have been developed. The total installed capacity to date is 1186 MW with a further 1076 MW expected online by the end of 2020 [10].

To provide a benchmark for comparison, an approximate model of the existing Belgian solution has been created and is briefly presented. Fig. 2 shows the approximate state of the 2020 offshore transmission network [11] [12]. OWPPs are labelled as specified in table I. The unnumbered dots represent the locations of the 10 OSSs which are connected to the OWPPs via 33 kV cables. Transmission to shore is accomplished at 220 kV and 150 kV. The same cost model utilized within the optimization is used to calculate total transmission cost. The total cost is calculated as 884.1 M€. Since the transmission system is approximately 15% of the overall system cost [13], the Belgian offshore wind zone would have a total cost of 5.893 B€ or 2.8 M €/MW which matches very well with the average cost of 3.0 M€/MW over the 43 OWPP reported in [14]. Furthermore, a small cost underestimate is to be expected as cable lengths are calculated as the straight line distance.

During the optimization, the 2 GW Belgian offshore wind zone is modelled as 8-250 MW, 30 km^2 OWPPs with geographic centers placed at the GPS coordinates of the existing and planned Belgian offshore concessions. In addition, there are 2 Points of Common Couplings (PCCs) representing the substations at Zeebrugge and Oostende, both are 220 kV nodes. Table I, summarizes the positions of the modelled OWPPs and PCCs and Fig. 3 displays the layout after the transformation into Cartesian coordinates.

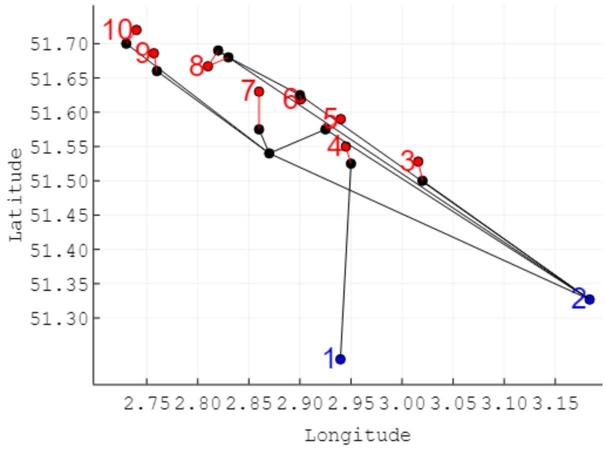

Fig. 2. Existing Belgium Solution

TABLE I
BELGIAN OWPP AND PCC LOCATIONS. []

Number	Name	Longitude	Latitude
1*	Oostende	2.93969	51.23974
2*	Zeebrugge	3.18361	51.32694
3	Norther	3.01583	51.52806
4	Thortonbank	2.94499	51.54999
5	Rentel	2.93997	51.59
6	Northwind	2.90097	51.61897
7	Seastar	2.85997	51.63
8	Nobelwind	2.80997	51.667
9	Northwestern	2.757	51.68597
10	Mermaid	2.74	51.71997

*PCC substation.

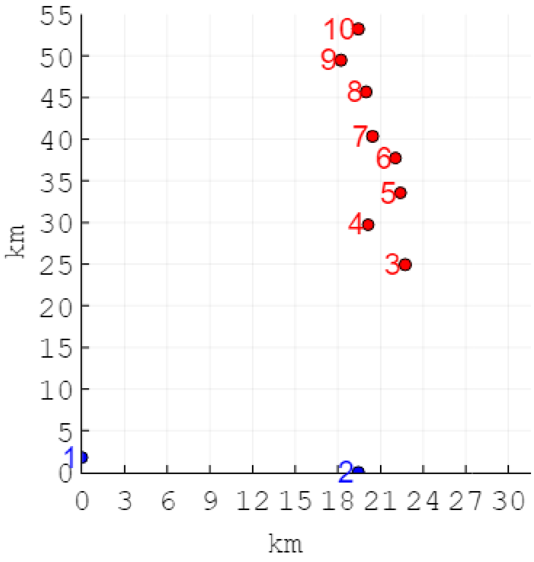

Fig. 3. Belgium OWPPs and PCCs layout

The full domain to be optimized consists of 141 candidate OSSs with candidate MVAC connections between the OWPPs and OSSs, candidate MVAC connections between OWPPs and PCCs, candidate HVAC connections between OSSs and candidate HVAC connections between OSSs and PCCs, all of which are summarized in table II. No candidate HVDC connections between OSSs and PCCs were included as none were deemed the optimal cable selection in stage 1 of the optimization process described in section II.

TABLE II
BELGIAN CANDIDATE LINES.

Type	Start	End	# of Lines
MVAC	OWPP	OSS	1120
MVAC	OWPP	PCC	8
HVAC	OSS	OSS	39173
HVAC	OSS	PCC	665
Total			40966

B. *Bay of Cambay Gujurat*

In order to meet it's commitments to the Paris climate agreement, the government of India has set the ambitious target of having 40% of it's installed generation capacity come from clean sources by 2030 [15]. To date, 73.35 GW of renewable power generation has been installed and a capacity of 175 GW is expected by 2022. Although the majority is to come from onshore wind and solar, a not insignificant contribution of 5 GW by 2022 and 30 GW by 2030 of offshore wind has been targeted [15]. To enable the development of India's offshore resources, the FOWIND consortium has carried out feasibility studies and identified possible development regions off the coasts of Tamil Nadu and Gujarat [3]. In Tamil Nadu a transmission bottleneck exists between the southern wind resources and the northern load centers requiring first the completion of the Green Energy Corridor (GEC). The Gujurat transmission network on the other hand, can currently handle the addition of offshore resources provided proper analysis and grid strengthening is performed [16]. As such, in the Bay of Cambay the National Institute of Wind Energy (NIWE) has expressed interest in the development of 1 GW of offshore wind and India's first demonstration OWPP is under development [15] [17].

The region optimized within this paper is the 1921 km^2, zone "A" as defined by the FOWIND consortium in [3]. It consists of 19 OWPPs, each with a rated power of 500 MW and covering an area of 100 km^2. Two PCCs are defined at the 220 kV substations in Diu and Babarkot. Table III summarizes the positions of the modelled OWPPs and PCCs and Fig. 4 displays the layout transformed into cartesian coordinates.

The optimization domain consists of 112 candidate OSSs with candidate MVAC connections between the OWPPs and OSSs, candidate HVAC connections between OSSs and candidate HVAC/HVDC connections between OSSs and PCCs. All of which are summarized in table IV. No candidate MVAC connections between OWPPs and PCCs were included as none qualified as the optimal cable choice within stage 1 of the optimization process described in section II.

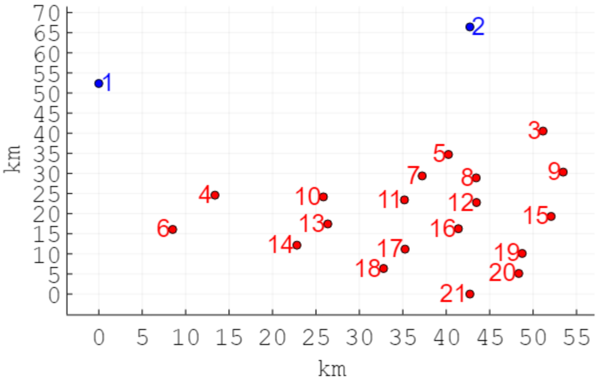

Fig. 4. Gujurat OWPPs and PCCs layout

TABLE III
GUJURAT OWPP AND PCC LOCATIONS.

Number	Longitude	Latitude	Number	Longitude	Latitude
1*	70.991	20.712	12	71.440	20.475
2**	71.399	20.867	13	71.281	20.415
3	71.501	20.639	14	71.249	20.365
4	71.151	20.470	15	71.525	20.449
5	71.401	20.579	16	71.425	20.415
6	71.109	20.391	17	71.371	20.365
7	71.375	20.531	18	71.349	20.319
8	71.435	20.529	19	71.502	20.365
9	71.531	20.549	20	71.501	20.321
10	71.271	20.475	21	71.449	20.271
11	71.359	20.475			

*PCC substation in Diu. **PCC substation in Babarkot.

IV. WIND GENERATION PROFILES

The power generated by an OWPP is dependent on the wind regime and the wind speed-power characteristics of the turbines. The characteristics of the turbines used within this simulation are summarized in table V. As average wind speeds in the Bay of Cambay are low compared to the North Sea, the power curve of a low wind speed, IEC class IIIa, turbine was used [18].

For regionally meaningful results, input wind data must reflect well local conditions. To achieve this, profiles generated via the CorWind software are used. CorWind generates wind time series through a combination of meteorological reanalysis techniques and stochastic simulations. For a detailed description of CorWind please refer to [19]. Unfortunately wind data from the Bay of Cambay is not yet available so a region of similar size and comparable average wind speeds off the southern coast of Spain was used instead to approximate wind conditions in the region.

From the CorWind time series, a generation profile is constructed for each individual OWPP. OWPP wind profiles are then combined as the area of generation increases. As the area grows, the wind profile becomes more diverse, resulting

TABLE IV
BELGIAN CANDIDATE LINES.

Type	Start	End	# of Lines
MVAC	OWPP	OSS	2109
HVAC	OSS	OSS	64889
HVAC	OSS	PCC	1209
HVDC	OSS	PCC	24
Total			68231

in less generating time spent at the extremes of generation, i.e. 0% and 100% production. This is demonstrated in Fig. 5 which compares the Bay of Cambay profiles of OWPP 21 to that of the entire offshore region.

As a consequence of the lower wind speeds in the Bay of Cambay, a lower capacity factor is achieved. Geographic diversity, however, can help to increase the overall capacity factor. This is demonstrated by table VI where the minimum single OWPP capacity factor and the overall regional capacity factor for both Belgium and India are compared. The larger regional variation in India has a substantial effect on overall capacity factor.

TABLE V
MODELLED TURBINES BY REGION. [20] [18]

Region	[MW]	Hub Height [m]	Diameter [m]	Cut in [m/s]	Cut out [m/s]
Belgium	2.0	80.0	90.0	4.0	25.0
Gujurat	3.45	149.0	136.0	3.0	22.5

TABLE VI
CAPACITY FACTOR BY REGION.

Region	Minimum CF	Regional CF
Belgium	0.377	0.384
Gujurat	0.282	0.354

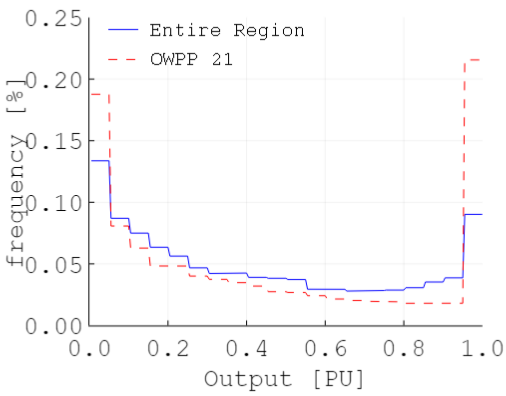

Fig. 5. Comparison of wind profiles of OWPP 21 and and the entire Bay of Cambay offshore wind region.

V. RESULTS

A. Belgian North Sea

TABLE VII
COSTS OF 6 BELGIAN TOPOLOGIES.

MV [kV]	HV [kV]	Cost [M€]	# of OSS
33	132	870.6	5
66	132	818.9	3
33	220	690.8	5
66	220	648.7	3
33	400	744.9	4
66	400	693.3	3

For the Belgian offshore region, 6 optimal topologies were found. The costs and number of required OSSs is summarized in table VII. A 66 kV MV network combined with 220 kV transmission is the most economic option, while a 132 kV, 33 kV system the most expensive. The optimal transmission topology is shown in Fig. 6. Table VIII shows the optimal cables and table IX the transformers and OSS locations. The total cost of the network is 648.7 M€ with a gap of 4.43% remaining between the integer solution (the global optimum) and continuous lower bound. The per MW cost for the Belgian transmission system is 0.324 M€/MW. The optimal network requires only 3 OSSs and 2 connections to shore. Comparing this to the current system design in the North Sea described previously, savings of 235.4 M€ or 26.6% are possible.

Independent of the transmission voltage, a 66 kV MV network was always found to reduce the cost. 66 kV not only reduces line losses but permits better clustering, therefore reducing the number of OSSs. The lowest cost topology utilizing 33 kV is at 220 kV and requires 5 OSSs. With this topology a maximum of only 2 OWPPs were connected to a single OSS. The minimum number of required OSSs at 33 kV is 4 if coupled with a 400 kV HV network.

As Belgium considers the development of their second offshore wind region it has already been proposed that a new approach be used. One which gives a larger role to Elia the Belgian TSO. Elia has proposed the modular offshore grid 2 (MOD2) project which would see 1 or more offshore platforms built in order to centralize 220 kV transmission to shore [21]. To take full advantage of the MOD2 project a 66 kV MVAC network would be a wise investment.

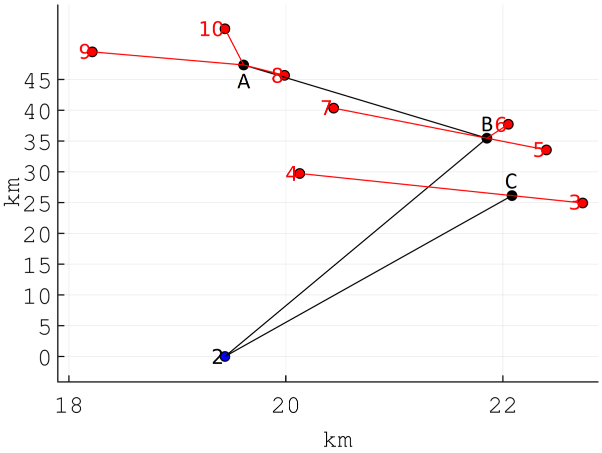

Fig. 6. Optimal transmission system topology of the Belgian North Sea. MV voltage level: 66 kV, HV voltage level: 220 kV

TABLE VIII
OPTIMAL CABLE SIZES FOR THE BELGIAN OFFSHORE.

Start	End	[km]	[kV]	[MVA]	Number	[mm]
10	A	6	66	265	3	800
9	A	3	66	265	3	800
8	A	2	66	265	3	800
7	B	5	66	265	3	800
6	B	2	66	265	3	800
5	B	2	66	265	3	800
4	C	4	66	265	3	800
3	C	1	66	265	3	800
A	B	12	220	759	3	400
B	2	36	220	1525	5	630
C	2	26	220	504	2	400

TABLE IX
OPTIMAL OSS LOCATIONS AND TRANSFORMERS FOR THE BELGIAN OFFSHORE.

OSS	transformers	Latitude	Longitude
A	3-350MVA	51.67747	2.79139
B	3-350MVA	51.60119	2.9176
C	3-240MVA	51.53354	2.99813

B. *Bay of Cambay*

The optimal solution in the Bay of Cambay was also found to have a 66 kV MVAC network and a 220 kV transmission network. The total cost of the system is 3.25 B€ with a gap of 6.62% remaining between the integer solution (global optimum) and the continuous lower bound. The per MW cost of the Indian transmission system at 0.342 M€/MW, is more expensive than that of the North Sea despite the conglomeration of a much larger area of generation. This is not a surprising result, however, as capacity factors are much lower.

Fig. 7 along with tables X through XIII describe the network. All MVAC connections consist of 6 parallel 3-core copper cables, each with a 800 mm^2 cross section. Through observation, it is apparent the best solution obtained is in fact not the global optimal of the transmission system. This can be easily proved by observing the OWPP 6 to OSS A to PCC 1 connection. By shifting the position of OSS A onto the straight line distance between OWPP 6 and PCC 1, a shorter cable length and therefore a cheaper overall solution is obtained. An OSS in this position does exist within the search space. A further reduction in cost with minimal computational effort could therefore be obtained by adding a further optimization stage which maintains the connection topology but minimizes cable length. This investigation is saved for future work.

There is very limited grouping between OWPPs compared to the Belgian case. Only OWPPs 5 and 7 are grouped with MVAC connections while no more than 3 OWPPs are grouped to a single OSS with HVAC connections. The minimal grouping is likely due to the large capacity of 500 MW of each OWPP. More extensive grouping was found to be economical at 400 kV, however, gains made were more than offset by the higher cable and compensation costs. A dual voltage 220 kV/400 kV offshore transmission system could possibly lead to lower cost but was out of the scope of the current optimization. HVDC connections were not found to be economical as the distance from shore is too little.

A positive effect of the limited grouping is the uniformity of equipment. Only 1 - MVAC cable size and 3 - HVAC cable sizes are used throughout. As for transformers, 3 - 180 MVA transformers are ideal on all OSSs except for OSS I which is best serviced by 4 - 270 MVA transformers. The uniformity of transformer size requirements can be easily leveraged to increase reliability as a single spare transformer can service all 180 MVA units. A further in-depth analysis may show that replacing the 3 - 270 MVA with 180 MVA transformers directly or via an additional OSS is justified in order to take full advantage of the benefits gained through lower cost reliability.

An interesting observation is that the optimal layout is naturally split via the closest PCC. This suggests that a grouping technique could be used to simplify the problem by further subdividing the offshore region based on the closest PCC. Further investigation into this possibility is saved for future work.

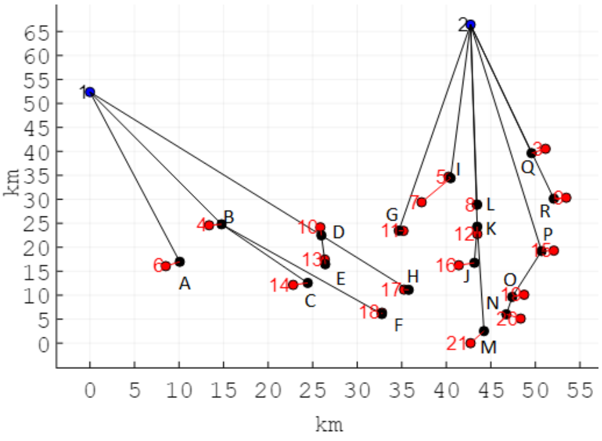

Fig. 7. Optimal transmission system topology of the Bay of Cambay. MV voltage level: 66 kV, HV voltage level: 220 kV

TABLE X
66KV CABLE LENGTHS FOR THE GUJURAT OFFSHORE.

Start	End	[km]	Start	End	[km]
6	A	2	16	J	2
4	B	1	12	K	2
14	C	2	8	L	1
10	D	2	21	M	3
13	E	1	20	N	2
18	F	1	19	O	1
11	G	1	15	P	1
17	H	1	3	Q	2
5	I	1	9	R	1
7	I	6			

TABLE XI
OPTIMAL OSS TO OSS CABLE SIZES FOR THE GUJURAT OFFSHORE.

Start	End	[km]	[kV]	[MVA]	Number	[mm]
O	P	10	220	1076	3	800
E	D	6	220	506	2	400
O	N	4	220	506	2	400
K	J	8	220	506	2	400
H	D	15	220	506	2	400
F	B	26	220	504	2	400
M	K	22	220	505	2	400
C	B	16	220	505	2	400

TABLE XII
OPTIMAL OSS TO PCC CABLE SIZES FOR THE GUJURAT OFFSHORE.

Start	End	[km]	[kV]	[MVA]	Number	[mm]
A	1	37	220	502	2	400
B	1	31	220	1528	5	630
D	1	40	220	1522	5	630
G	2	44	220	500	2	400
I	2	32	220	1006	3	1000
K	2	42	220	1520	5	630
L	2	38	220	502	2	400
P	2	48	220	1514	5	630
Q	2	28	220	504	2	400
R	2	37	220	502	2	400

TABLE XIII
OPTIMAL OSS LOCATIONS AND FOR THE GUJURAT OFFSHORE.

OSS	Longitude	Latitude	OSS	Longitude	Latitude
A	71.1243	20.3992	J	71.4414	20.4207
B	71.1632	20.4728	K	71.4388	20.48875
C	71.2654	20.3698	L	71.435	20.53
D	71.2724	20.46	M	71.4625	20.29375
E	71.2812	20.4063	N	71.4839	20.3269
F	71.35	20.3175	O	71.4875	20.36
G	71.355	20.475	P	71.5118	20.4481
H	71.375	20.365	Q	71.4856	20.6308
I	71.4024	20.5775	R	71.5167	20.5472

VI. CONCLUSION

Within this paper an optimization of 2 offshore wind regions has been performed using a software developed in house at CG Holdings Belgium using the Julia language [22]. One of the regions in the Belgian North Sea was compared to the existing as built solution to quantify possible savings from utilizing the proposed optimization method. A significant cost savings of 26.6% over the existing installation in the Belgian offshore region was found. The second offshore region modelled is in the Bay of Cambay, Gujurat. In both cases, it was found that the optimal offshore transmission voltage levels are a 66 kV MVAC network and a 220 kV HVAC network. 66 kV MVAC connections allow for easier grouping of OSSs as well as a reduction in cable losses.

In the case of the Bay of Cambay the best solution obtained is in fact not the global optimal of the transmission system, since a reduction in cost was shown to be possible by shifting the location of a single OSS. This suggests that a further reduction in cost with minimal computational effort could be obtained by adding a further optimization stage which maintains the connection topology but minimizes cable length.

Less grouping than expected was found in the Bay of Cambay case. This is likely due to the large unit size of each OWPP. Despite this, 66 kV was still found to be the best choice. A mixed voltage 220 kV/400 kV transmission system may provide further cost reductions and should be further investigated. Despite the very large capacity of the Bay of Cambay region HVDC transmission was not found to be economic as the transmission distance is too short.

A natural separation appeared between OWPPs based on which PCC they are closest to. This suggests large problems with multiple PCCs could be subdivided into smaller problems without loss of optimality. Further investigation into this is required.

REFERENCES

[1] S. Lumbreras and A. Ramos. Offshore wind farm electrical design: a review. *Wind Energy*, 16(3):459–473, April 2013.

[2] Hakan Ergun, D. Van Hertem, and R. Belmans. Transmission system topology optimization for large-scale offshore wind integration. *Sustainable Energy, IEEE Transactions on*, 3(4):908–917, 2012.

[3] Baldock et al. Pre-feasibility study for offshore wind farm development in gujarat. Technical report, FOWIND, 2015.

[4] D. Elliott, K. R. W. Bell, S. J. Finney, R. Adapa, C. Brozio, J. Yu, and K. Hussain. A comparison of ac and hvdc options for the connection of offshore wind generation in great britain. *IEEE Transactions on Power Delivery*, 31(2):798–809, April 2016.

[5] Stephen Hardy, Kristof Van Brusselen, Stijn Hendrix, Hakan Ergun, and Dirk Van Hertem. Economic analysis and comparison of options for hvac, hvdc and ofac offshore wind power connections. *IEEE PES Powertech*, 2019.

[6] Moniteur Belge. 17 mai 2004. - arrêté royal modifiant l'arrêté royal du 20 décembre 2000 relatif aux conditions et à la procédure d'octroi des concessions domaniales pour la construction et l'exploitation d'installations de production d'électricité à partir de l'eau, des courants ou des vents, dans les espaces marins sur lesquels la belgique peut exercer sa juridiction conformément au droit international de la mer. Technical report, 2004.

[7] Steven Degraer, Robin Brabant, Bob Rumes, and Laurence Vigin. *Environmental impacts of offshore wind farms in the Belgian part of the North Sea: A continued move towards integration and quantification.* 12 2017.

[8] Dufresne et al. Quel mix énergétique idéal pour la belgique aux hirizons 2020 et 2030? rapport final. Technical report, Groupe GEMIX, 2009.

[9] C-Power project phase 1 overview. http://www.c-power.be/index.php/project-phase-1/overview. Accessed: 2019-07-02.

[10] Belgian Offshore Platform projects. http://www.belgianoffshoreplatform.be/en/projects/. Accessed: 2019-07-02.

[11] Global Offshore Renewable Map 4c offshore. https://www.4coffshore.com/offshorewind/. Accessed: 2019-07-17.

[12] Modular Offshore Grid elia. https://www.elia.be/en/projects/grid-projects/Modular20Offshore20Grid. Accessed: 2019-07-17.

[13] Offshore wind project cost outlook. Technical report, Clean Energy Pipeline, 2014.

[14] PE Morthorst and L Kitzing. *Economics of building and operating offshore wind farms.* 2016.

[15] Press Information Bureau Government of India Ministry of New and Renewable Energy year end review 2018 – mnre. http://www.pib.nic.in/Pressreleaseshare.aspx?PRID=1555373. Accessed: 2019-07-02.

[16] Parker et al. Grid integration study for ooffshore wind farm development in gujurat and tamil nadu. Technical report, FOWIND, 2017.

[17] Giles et al. Feasibility study for offshore wind farm development in gujarat. Technical report, FOWIND, 2018.

[18] Vestas V136-3.45 datasheet. https://en.wind-turbine-models.com/turbines/1282-vestas-v136-3.45powercurve. Accessed: 2019-07-03.

[19] Matti Koivisto, Kaushik Das, Feng Guo, Poul SÃ¸rensen, Edgar NuÃo, Nicolaos Cutululis, and Petr Maule. Using time series simulation tools for assessing the effects of variable renewable energy generation on power and energy systems. *Wiley Interdisciplinary Reviews: Energy and Environment*, 8(3):e329, 2019.

[20] Vestas 90 datasheet. https://en.wind-turbine-models.com/turbines/16-vestas-v90powercurve. Accessed: 2019-07-03.

[21] Project 120 - MOG II: connection of up to 2 GW additional offshore wind Belgium, howpublished = https://tyndp.entsoe.eu/tyndp2018/projects/projects/120, note = Accessed: 2019-07-17.

[22] Jeff Bezanson, Alan Edelman, Stefan Karpinski, and Viral B Shah. Julia: A fresh approach to numerical computing. *SIAM review*, 59(1):65–98, 2017.