energies

Article

Power-from-Shore Optioneering for Integration of Offshore Renewable Energy in Oil and Gas Production

Tiago A. Antunes [1], Rui Castro [2], Paulo J. Santos [3] and Armando J. Pires [4,*]

1 Electrical Engineering Department, Instituto Superior Técnico (IST), Alameda Campus, University of Lisbon, 1049-001 Lisbon, Portugal; tiago.reis.antunes@gmail.com
2 Instituto de Engenharia de Sistemas e Computadores, Investigação e Desenvolvimento em Lisboa (INESC-ID), Co-Owned by Instituto Superior Técnico (IST), University of Lisbon, 1000-029 Lisbon, Portugal; rcastro@tecnico.ulisboa.pt
3 INESC-Coimbra & EST Setúbal, Polytechnic Institute of Setúbal, 2910-761 Setúbal, Portugal; paulo.santos@estsetubal.ips.pt
4 CTS-UNINOVA/LASI & EST Setúbal, Polytechnic Institute of Setúbal, 2910-761 Setúbal, Portugal
* Correspondence: armando.pires@estsetubal.ips.pt

Abstract: Despite the widespread usage of high-voltage alternating current (HVAC) for the connection of offshore wind farms (OWF), its use to power-from-shore (PFS) offshore oil and gas (O&G) production sites is often not feasible. Its limitations for long-distance subsea transmission are usually found at 50–70 km from shore and might be even shorter when compared commercially to a direct-current (DC) alternative or conventional generation. Therefore, this research paper aims to address the standardization of offshore transmission with a particular focus on the high-voltage direct current (HVDC) alternative. While the distance is typically not a limiting factor when using DC, and the voltages used are rather standard, the concept of power envelopes can be quite useful in addressing the high variability of offshore site power requirements and setting a design baseline that would lead to improved lead time. In this article, a full back and front-end genetic optioneering model purposely built from the ground up in Python language is used to #1 define up to three DC power envelopes that would cater to most of the candidate's requirements and #2 provide the lowest cost variance. The results will demonstrate that this can be achieved at a minor overall cost expense.

Keywords: offshore oil and gas production; offshore wind energy; HVAC and HVDC transmission

Citation: Antunes, T.A.; Castro, R.; Santos, P.J.; Pires, A.J. Power-from-Shore Optioneering for Integration of Offshore Renewable Energy in Oil and Gas Production. *Energies* **2024**, *17*, 151. https://doi.org/10.3390/en17010151

Received: 17 November 2023
Revised: 23 December 2023
Accepted: 24 December 2023
Published: 27 December 2023

1. Introduction

The existing offshore transmission landscape has implemented so far (to different degrees) more than 20 different designs across more than 140 sites destined for O&G production and OWF renewable energy production, meaning that less than 10% repetition on average is transported from project to project. The bespoke nature of these interconnections means that most of the engineering efforts, particularly for offshore high-voltage substations (OHVS), could be reduced significantly once standardization measures are in place. The same would also be true for the equipment selection, interface engineering, and overall procurement processes. More than 80% of the OWFs are connected in alternate current (AC), yet despite this consistency in the technology used, the voltages, cable ratings, and overall platform design still vary significantly. O&G, on the other hand, will require DC transmission mostly due to the long distance to shore [1].

One of the challenges faced in this industry is bridging the uncertainty associated with the early stages of development, so a model needs to cope with a certain degree of variance in the reference information and yet still digest standardized solutions that are sustainable throughout the available portfolio.

As captured in earlier research work, standardization processes focused on key design criteria of OHVS are the main driver in the cost-optimization of said infrastructure and enable efficient integration of both onshore and offshore renewable energy production with O&G production.

1.1. Literature Review

The following review was done in three main vectors: transmission and cost models, decision-making and optimization algorithms, and finally, fit-for-purpose software development. While reviewing the models, it is possible to validate their suitability for the subject applicable both in terms of robustness and efficiency. A review of the adequate algorithms was paramount to ensure the standardization goal was substantially achieved.

There is significant work in holistic transmission models that encompass both the onshore and offshore grids. These were also reviewed to evaluate potential advantages that can be considered in this article's research, and it was validated that similar algorithm techniques are also used. The equivalent models for HVAC and HVDC transmission lines are extensively covered in the literature, including calculation processes, boundaries, and assumptions to be regarded depending on the objective [2].

The nature of the compensation systems to be used offshore has also been accepted to be mostly based on static-compensation (STATCOM) systems with some variance in the control methodologies [3–5], while references vary in the location (either 50% on each of the two remote-ends of the cable system, or 100% onshore). Other reviews [6] address the advantages and methods for using the HVDC-VSC (voltage-sourced converter-based HVDC) converters, paired with a multi-objective optimization algorithm, to significantly improve the operation of AC offshore networks.

The methodology for the reactive power incorporation and impact evaluation on the performance of an HVAC export cable system is also validated in [7], and the comparisons between AC and DC are noted in [8]. Alternatively, the advantages of pairing a DFIG-based (doubly-fed induction generator) offshore wind turbine generator (WTG) with VSC-based HVDC to improve the overall performance of the export system are noted [9] while the wide-scale deployment of said technologies for the growing large-scale OWF is once more validated in [10].

While, on average, the offshore cable system typically accounts for just 10% of the overall OWF cost, about 80% of the energy and financial losses in these sites are caused by a failure in this section of the infrastructure [11]. Other reviews [12] highlighted that cable systems can have a 30% failure impact rate, further emphasizing the importance of their proper sizing and maintenance. From a capital expenditure (CAPEX) perspective, the export cable system can exceed both onshore and offshore substations combined [13].

The focus on HVDC is also validated here [14] with multiple multi-GW and 1000-plus kilometer offshore connections in the pipeline for the next 30 years while proposing a concentration on improving 500, 600, and 800 kV solutions. The advantages of HVAC, especially for long-distance sites, including the reduction of offshore space, smaller cables, and the absence of reactive power compensation requirements, are reviewed in [15], and the most suitable export topologies in [16].

This comparison has included both AC and DC topologies, and (for DC grid-access points) it also catered for the possibility of DC and AC array networks. However, it is noted that collection systems should still rely upon HVAC. The added electrical apparatus and infrastructure, as well as protection scheme operation, were the main challenges faced as the DC technology is further pushed into the inter-array network.

The suitability of HVDC for applications such as bulk transmission and offshore interconnections is once more validated in [17], while the solutions and arrangements available are noted in [18]. The critical advantages of HVDC in this transmission range are the reduced cost and higher efficiency (reduced losses) as the distance and power rating increase, particularly past the GW range.

They also do not have the added burden of reactive power compensation systems and can rely on a smaller subsea cable footprint. The decision between HVAC and

HVDC still relies fundamentally on a proper technical-commercial evaluation based on site-specific conditions.

There are also reviews [19] addressing the potential modularization and miniaturization of offshore HVDC systems, which can potentially be incorporated into the design of compact HVDC e-houses for O&G sites. Multiple challenges were found, though, particularly in the control methodologies and inner design of the converters. Another angle is to look at the efficiencies from repetition. The development and project management component in OWFs are typically in the range of 3.5% [13], and economies of scale due to repeated engineering can be incorporated even with a smaller number of projects, in contrast to other efficiencies such as a higher volume of similar equipment being delivered which might require a double-digit repetition.

There is remarkable work as well in the evaluation of multiple techniques for offshore transmission optimization. In [20], a thorough review is made of the multiple techniques for both clustering as well as the planning of offshore substations (OSS) deployment within an OWF, including such as K-Means and Fuzzy C-Means (FCM), Particle Swarm Optimization (PSO), and Genetic Algorithms (GA). Two-Phase Clark and Wright's is also used to optimize the cable selection across the proposed layout.

In [21], a comprehensive comparison of the different optimization techniques is made. The key aspects are the importance as well as the impact of applying clustering methods before the main optimization is made to reduce the scale of the possible solutions for such an extensive cable portfolio and voltage range. The limitation is that clustering methods such as FCM are bound to the coordinates of the candidates and might fail to consider the actual mathematical implications of the overall transmission evaluation problem. Alternatively, the heuristic arc selection algorithm is proposed and validated.

The cable transmission system accounts for one of the major cost components of OWFs, and reviews with a focus on that scope are also available in [22]. Amongst other conclusions, for the task of cable optimal selection, in particular, methods such as the Minimum Spanning Tree (MST). The use of MST is further evaluated in supporting research from [23,24], yet the available references identified focus again on the layout of the collector and onshore connection system and not on the voltage/cable size selection.

Additional work in [25] shows the impact of Association Rule Mining (ARM) and greedy algorithms to tackle not only the technical aspect but also the CAPEX, as well as the corrective maintenance of the infrastructure, losses, and energy not transmitted. It was found that the impact of ARM as a boundary reduction method was limited. Other references [26] also addressed the use of fuzzy logic focusing on offshore cable routing yet encountered challenges in the validation of the model, such as non-discrete socio-economical aspects, which are difficult to factor into the model, as well as some bias from data obtained from existing projects.

Use cases of GA-based multi-objective optimizations have also been reviewed in applications such as the optimization of the layout [27,28], maintenance [29], and the use of dynamic cables [30] in OWFs, as well as the optimization of the power flow in multi-terminal offshore DC networks [31].

Despite the comprehensive literature on the optimization subjects detailed above, details on the exact approach to the export cable voltage/size selection are mostly undisclosed in all references identified. Those that provide additional detail [32–34] typically consider a single standardized voltage level for both the collector system and export cables and proceed to determine the appropriate cable type and size through comprehensive methodologies, often nested within a wider optimization problem (e.g., including said OWF layout and/or medium-voltage (MV) collector topologies).

Export cable calculation is typically based on an ampacity evaluation, which can be analytical as per industrial standards or based on finite element models [35]. However, these models require knowledge of the installation conditions (such as route, seabed profile, ambient temperature, cable configuration, and local requirements) and the existing onshore grid (point-of-connection (PoC) availability, short-circuit rating (SCR) value).

This variance is significant, especially on a global scale, and hinders the suitability of a standardization model.

There are specific reviews on the connection of OWFs directly to O&G production facilities [36,37]. The first outlines the benefits of VSC-based converters, which, when used in a WTG, can improve the voltage and frequency response while connected to the production sites, including controlling the reactive power supply. It also recognizes the importance of mitigation measures for a potential WTG outage and suitable redundancy. The second review focuses on the joint operation of on-site gas turbines and offshore WTGs, concluding that the latter is a technically stable and economically adequate solution to be used. Consideration must be made to the operation strategy and sizing of both infrastructures.

To a certain degree, there is also a parity between the deployment of PFS for O&G production with offshore green hydrogen (H2) production and OWFs. In those cases, methods such as mixed-integer linear programming (MILP) can be used to reduce the solution sample size prior to the optimization [38] and extract the representative solution candidates, but here, the approach considered pre-selected voltage ratings such as 220 kV for the export cables. MILP was also used in [39], but the offshore electrical system was not fully incorporated in the model, which limited the conclusions from a transmission perspective. Considering the extensive cable portfolio available, MILP can also be tested to reduce the number of suitable configurations for each candidate and reduce overall computation time.

On the last vector, the community has widely accepted both Python and R provide the most efficient solutions to model complex calculation environments, whilst Python, in particular, carries an additional advantage with the available representation and graphical interface frameworks. Multiple models have already been successfully developed and published on this platform [1,40].

1.2. Research Motivations and Contributions

However, the existing research has not yet answered to what extent limiting the range of solutions renders an overall reduction of the potential investment versus a model that simply selects the most efficient scenario case-by-case (site). While, from an individualist perspective, having the most efficient solution per case seems fair, it might defeat the purpose of standardization. Alternatively, placing a clustering model at the center stage in this research work should hypothetically confirm the best balance between a reduced number of combinations and the lowest overall deployment cost. One of the assumptions is that the power-from-shore shall act as the main energy supply to the site (in lieu of gas turbine generation aboard the platform, also referred to later as conventional power generation). It can also be verified if pairing it with offshore renewable energy production can either balance out or even replace the connection to shore.

Another novelty factor is the holistic combination of an exhaustive O&G candidate connection evaluation, calculating the most efficient AC or DC grid access solution by means of a cost-based efficiency selection and clustering genetic algorithm that encompasses connection technology, power rating, and voltage level. The model is a fully tailor-made bespoke Python-language-based application, which includes a detailed graphical interface, allowing for the assessment of project-specific scenarios outside the clustering exercise.

1.3. Research Plan

Our research plan is focused on validating if the optioneering of grid connections is accurately standardized. The high-level plan to address this includes the use of detailed transmission and cost models of offshore systems (both AC and DC) and O&G production site data, together with a robust optioneering model that will calculate the most efficient connection solution for each project site. The innovative layer is to build a clustering model that tests multiple voltage and power envelopes (later referred to as traits to the candidate population) through this optioneering process to identify the overall most effective option for the complete pool of candidates as a whole development (rather than individually). While doing so, the process will also be distilled down to provide a comprehensive sandbox for the testing of bespoke connections.

The main contribution of this paper is an optioneering and clustering model that covers the entire offshore O&G addressable portfolio. The models, which include not only the back-end transmission and cost but also the web-based optioneering and sandbox interfaces introduced in a later publication, are constructed solely based on Python language–this approach allows for easier 3rd-party integration.

1.4. Paper Organization

The outline of this paper is as follows. Section 2 holds the results of our review focused on the transmission and cost models, which set the baseline for the optioneering model. Section 3 details the methods, particularly the back-end portion of the model. The results are detailed in Section 4, and the conclusions are captured in Section 5.

2. Materials

2.1. Databases and Reference Data

The foundation of the model is composed of the following databases:

- AC and DC reference and critical values (Table A1);
- AC and DC reference costs (Table A2);
- AC and DC subsea transmission cable specifications (Table A3);
- Offshore O&G production site characteristics (Table A4).

These are included in the Appendix A. All data has undergone a thorough processing. The transmission reference data (models and cable), as well as the critical parameters, are rather straightforward and based on established literature. In comparison, the characteristics of both the existing PFS and candidate O&G sites were of substandard quality. This meant that an individual analysis of each site was required to mitigate errors or deviations in the data that could compromise the quality of the output from the model.

2.2. Transmission Models

The transmission models used are listed below. The HVAC transmission model in Figure 1 is generally based on [41] and is further utilized based on [1]:

- AC offshore transmission cable system;
- AC offshore transmission cable with SVC-based reactive power compensation;
- DC offshore transmission cable system.

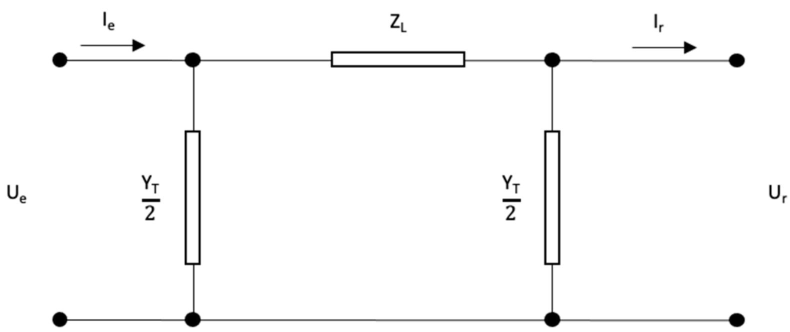


Figure 1. AC Transmission Model.

The compensated AC model includes an adjustment to incorporate the reactive compensation section, as in Figure 2:

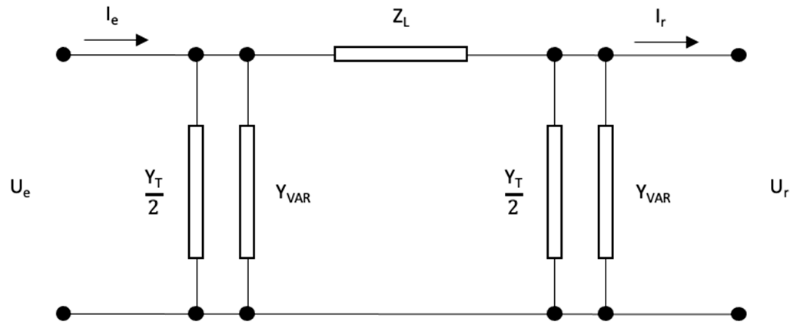


Figure 2. AC Transmission Model + VAR compensation.

Finally, the HVDC bipole transmission model in Figure 3 follows the same references:

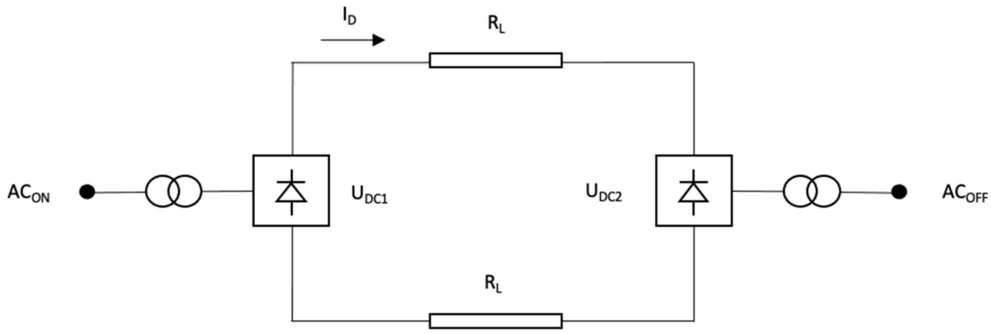


Figure 3. DC Transmission Model.

The assumptions of the AC and DC cable transmission models are as follows:

- Each PFS terminal is composed of a single substation (one onshore and one offshore);
- The cables can be rated at (AC) 33, 66, 110, 132, 150, and 220 kV or (DC) 80 kV;
- Single-phase and three-phase cables (1 or 2 conductors per phase) are proposed;
- Only the offshore section of the export cable is incorporated in the model;
- For HVDC, the model focuses on the selection of the DC interconnection cable;
- In the HVDC setup, the converter stations are alongside the AC substations.

The models assume a nearshore PoC. Since the rating estimated for the O&G sites is limited, it was not necessary to extend the number of conductors/phases further or use higher DC voltage ratings. Such a cable database might require expansion if both PFS/OWF interconnections are studied.

2.3. Cost Models

The cost models incorporate the main components as illustrated in Figures 4 and 5.

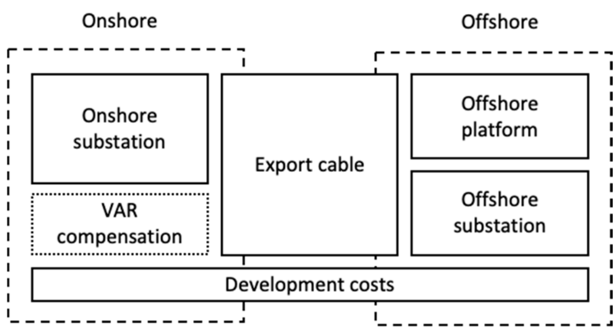


Figure 4. System cost building blocks (HVAC).

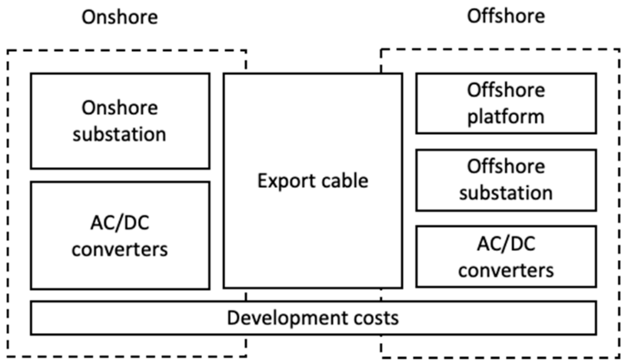


Figure 5. System cost building blocks (HVDC).

These are construed based on the cost coefficients of each of these cost blocks that depend on the power rating, site distance, or the reactive power compensation rating (if applicable). Generally, the cost ($C_{AC\ w/VAR}$ example) is calculated as shown in (1).

$$C_{AC\ w/VAR} = P * C_{MVA} + d * C_{km} + Q * C_{VAR} + C_{Others} \quad (1)$$

The assumptions of the cost model are as follows:

- Costs are calculated based on rates proportional to power rating, distance, or both;
- Each sub-component should be understood as a fully delivered (lump-sum basis);
- The plot areas above are approximate to the typical respective cost breakdown;
- The compensated AC connections include the cost of the SVC-based compensation.

The conventional power generation cost is considered in case neither HVAC nor HVDC solutions are feasible for a candidate. The ratios used are captured in [1].

3. Methods

3.1. Objective Function

The goal is to find a finite set of cost-effective and technically feasible transmission solutions that cover the existing offshore O&G production potential candidates with the lowest deviation possible from the baseline.

The baseline model approach (*BL*), noted in (2), is the comprehensive bespoke association of each site based on the best either AC, DC, or conventional generation, with the voltage and power rating to be tailored to that specific site independently in order to identify the most economical setup. Once that baseline is set, the clustering method will be used to iteratively determine which subset (or pool) of voltages and ratings can best suit a standardized approach. The optimal solution (*OS*) is described in (3).

$$BL = \min\left(C_{AC}, C_{AC\,\underline{w}\,VAR}, C_{DC}, C_{OFFTrb}\right) \quad (2)$$

$$OS = min \sum (C_{AC}, C_{AC\ w/VAR}, C_{DC}) \quad (3)$$

3.2. Optioneering Model

The optioneering model, as described in Figure 6, builds over the transmission and cost models thoroughly reviewed in [1]. By using those, it runs all suitable connection configuration options for each offshore site to calculate the most cost-effective one and finally outputs the clusters that can effectively cater to the wide offshore O&G production portfolio.

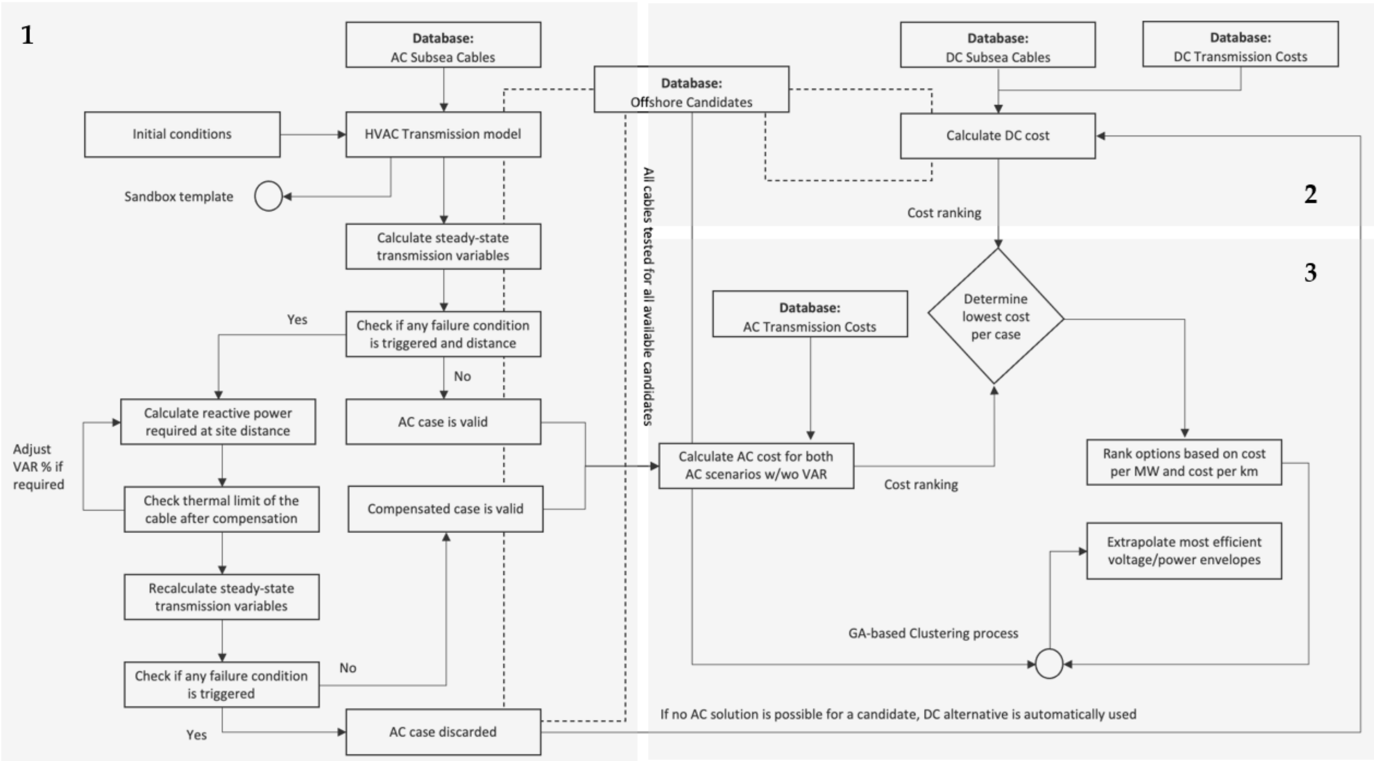


Figure 6. Overview of the optioneering model [1].

The model introduced in Figure 6 is composed of three main parts (1–3).

1. AC evaluation;
2. DC evaluation;
3. Optioneering algorithm.

The AC and DC transmission and cost evaluation are based on the models from Figures 1–5, respectively. For a selected candidate, the algorithm will check the most cost-effective yet suitable voltage/cable combination. The AC evaluation is done based on both a non-VAR-compensated system and a VAR-compensated system by adjusting the respective system admittance. The decision on the best solution is made based on the results of the respective equations, this being AC transmission ((4), (5)), DC transmission ((6), (7)), and finally the individual cost (8) [1].

$$\begin{bmatrix} U_r \\ I_r \end{bmatrix} = \begin{bmatrix} cosh\sqrt{Z_L Y_T} & \frac{Z_L sinh\sqrt{Z_L Y_T}}{\sqrt{Z_L Y_T}} \\ \frac{Y_T sinh\sqrt{Z_L Y_T}}{\sqrt{Z_L Y_T}} & cosh\sqrt{Z_L Y_T} \end{bmatrix} \begin{bmatrix} U_e \\ I_e \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} U_r \\ I_r \end{bmatrix} = \begin{bmatrix} A & -B \\ -C & D \end{bmatrix} \begin{bmatrix} U_e \\ I_e \end{bmatrix} \tag{5}$$

$$I_{DC} = \frac{U_{DC2} - U_{DC1}}{R_L} \tag{6}$$

$$P_{DC}^{1} = P_{DC2} + R_L {I_{DC2}}^2 \tag{7}$$

$$c_n = \left(P \sum c_{MVA} + d \sum c_{km} + P\, d \sum c_{MVA-km}\right) * \left(1 + \sum c_{\%}\right) \tag{8}$$

What is referred further as the optioneering algorithm finally is the component that locates the most cost-effective solution for the candidate taking the proposed AC and DC solutions from the previous two parts (1 and 2) of the optioneering model.

This is made by calculating, comparing, and ranking the cost of each of the grid access solutions proposed, done iteratively for each voltage and cable solution. The final cost ranking is done based on the least expensive and technically sound option.

3.3. Clustering

While the goal is to find the minimum cost of connection per candidate, having still a widespread selection of rating/voltage configurations would defeat the purpose of standardization. The alternative, as explained, is to set a restrictive pool of voltages, and the envelopes are then calculated so that (1) most of the candidates can be connected and (2) the overall infrastructure spending is the lowest.

Clustering was a two-fold process. Former clustering techniques [40] were used to determine the most effective number of clusters (standardized designs) to be used. Based on a K-means clustering framework extensively covered in [42], the following quantification methods were tested:

- Elbow;
- Gaps;
- Silhouette.

The efficiency of each method is shown in the results section. The baseline for the clustering exercises was an exhaustive calculation that would evaluate all possible voltage/cable size connection options applicable to each of the candidates, as previously reviewed in [1].

Having determined the quantity, the ideal positioning is then calculated based on a cost minimization function. This means that the potential O&G candidates are (1) evaluated to identify the most cost-effective setup, and (2) the model extrapolates the clusters (unique configurations, voltage, and conductor size) that render the lowest overall cost.

3.4. General Genetic Algorithm

Considering that invariably, each site will have specific grid connection settings such as cable size and reactive power compensation, it was determined that a suitable way to do a standardization exercise was to perform an initial screening of the most technical- and cost-effective voltages to be used offshore and then run a second model over this which would pre-select a narrower set of voltages (and inexplicitly AC or DC technology) based on the total cost of deployment.

From a holistic perspective, what this means is that the most cost-efficient for the individual candidates does not necessarily translate into the most cost-efficient standardization process—this is particularly important once we narrow down the number of possible connection voltages in the sense that smaller voltage options might drive up the cost of some individuals yet this shall be balanced-out on the model due to the cost efficiencies of an increased repetition.

The genetic model is, therefore, the logical [1,40] and last step of the optioneering process and draws from the clustering model, thus encompassing the sample candidate database again with the pool of suitable AC and DC connections identified in the latter. Said model is predicated on the following assumptions:

- The population is sized to include all site candidates in the sample;
- Candidates are modeled as power rating/shore distance tuples;
- The traits (grid connection solution) to assign to each individual are restricted to the pool from the optioneering model, and only one grid connection will be assigned to each individual, and all candidates must be connected;
- The grid configuration pool of options must include a minimum of one DC solution as a fallback to ensure the above point and the size of the pool will be determined based on the K-Means evaluation methods.

The candidates are then assigned to the respective clusters. The number of cycles has been adjusted empirically by evaluating the deviations over the course of several runs.

Several parametric exercises were made with the sample data to assess empirically the most efficient genetic rates, as shown in Table 1 of the GA baseline settings:

Table 1. Genetic algorithm configurations.

Population Size (Offshore Sites)	Individual Traits (Voltage Levels)	Clusters	Number of Cycles	Fitness Rate	Crossover Rate	Mutation Rate
102	6	3 + 1	50	20%	-	-

Multiplst focusing only on the AC option, the advantages of having a standardized modetes. It was possible to adjust the fitness rate empirically to fine-tune convergence speed and deviation to a suitable level. On the other hand, the cross-over and mutation were not possible to implement as crossing or mutating voltage/cable solutions either independently or from other candidates could mean that the solution chosen was not technically feasible for that candidate and thus compromised the results-assigning a given individual to another power-voltage envelope could result in the assignment of an unsuitable technical solution and failure of the model progress (e.g., envelope rated at a lower value than the candidate active power requirement). Also, using those two traits would mean that other voltages (other than those on the population round) were brought. Therefore, to ensure the proper quality of the results, the following measures were then taken:

- The percentages for fitness are adjusted to reflect an integer number of candidates.
- The ranking of the population is done both based on the cost/km or the cost/MW (alternatives shown in Results); this introduced small variations in speed/accuracy.
- A threshold was set at 100 km, whereas any upward connection of such length would be deemed connected in DC. This resulted in improved model speed with no compromise on overall infrastructure cost as this distance set-point was validated in the baseline calculations.

Several empirical runs were done while adjusting the GA rates (number of cycles and fitness rate), and these were found to render the best outcome. In general, the baseline deviation had no significant variation, and the convergence was not improved for a higher cycle number.

The results are shown in Section 4.2.

3.5. DC-Specific General Genetic Algorithm

For this review, the GA settings were adjusted to consider all sites to be connected in DC. This indirectly limited the connection voltage to 80 kV since this can cater to the full distance range (there is no technical limitation outside voltage drop) and is also sufficient to meet the entire power range requirement of the candidate sample. Therefore, in this case, the output was not a set of recommended voltages but a set of recommended power rating envelopes.

The power ratings of the sample vary between 10 and 115 MW/un; hence, a total of 12 envelopes in 10 MW steps were used for the traits. For the clusters, the same premise of three clusters was used, all to be based in DC, as mentioned. Table 2 provides the new GA baseline settings:

Table 2. Genetic algorithm configurations (DC-only).

Population Size (Offshore Sites)	Individual Traits (Power Slots)	Clusters	Number of Cycles	Fitness Rate	Crossover Rate	Mutation Rate
102	12	3	150	20%	-	-

Therefore, the GA model explained further was done in two separate runs: first overall selection (AC and DC), and a second GA run focused on the clustering of the DC setups. The DC clustering preparation sits on the same sampling models from Section 3.5, and the results are presented in Section 4.1.

3.6. GA Models

The model basically evaluates the restricted set of voltages or power envelopes for all candidates and classifies them based on the per-MW or per-km cost ratios. These options are picked at random based on the HVAC and HVDC subsea cables catalog and are (1) validated technically and (2) their cost is quantified, as explained already in the main optioneering model. The selection as per the defined percentage later is carried forward for the upcoming population, yet cross-over and mutation cannot be done, as explained in Section 4.4.

The flowchart in Figure 7 explains the simplified GA process. A subset of (3) AC voltages and (1) DC voltage is randomly selected from the pool. Those are assigned as per the model to generate a population of individuals (O&G candidates) with their respective traits (connection setup). The model is run iteratively based on the selection criteria and by using random voltage sets that are applied to the individuals. Once the stopping criteria are reached, the population and their respective connection setups are extracted. The voltages used will be those classified as the most suitable for the overall pool.

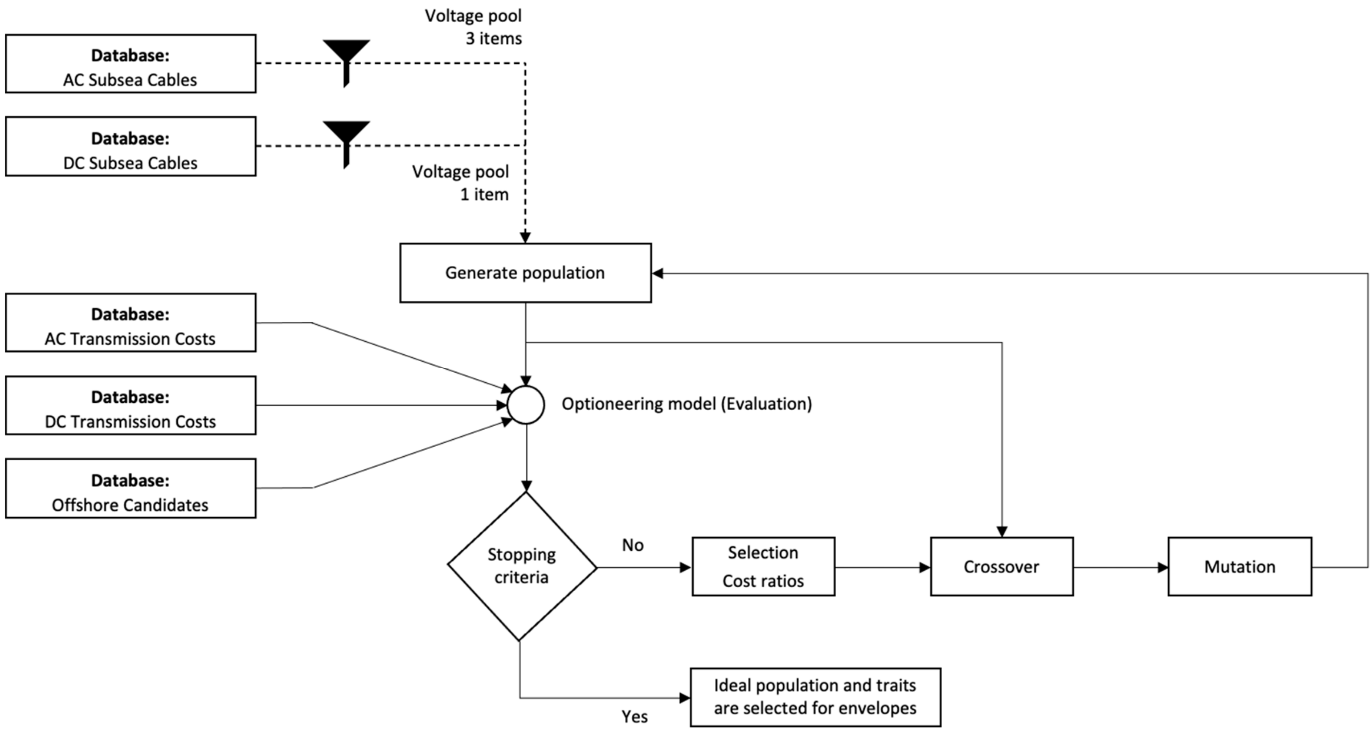


Figure 7. Clustering genetic model (HVAC and HVDC scenarios).

While Figure 7 includes the general GA model, Figure 8 shows a simplified version of said model to address only HVDC scenarios across the pool of candidates. This clustering is made based on a fixed voltage (in this case, 80 kV_{DC}), and the slots are of active power, meaning that the randomization is of the cables used (rather than voltages as in AC).

On the ranking front, two separate methods are covered based on the average cost/km or cost/MW of the infrastructure. While the first is biased toward the variation in the distance to the site, the other is based on the rating of the site. The cost ratios are detailed for each of the components of the system (substations, cable system, compensation if AC, etc.), and the ranking method impact is included in the results shown in Section 4.3.

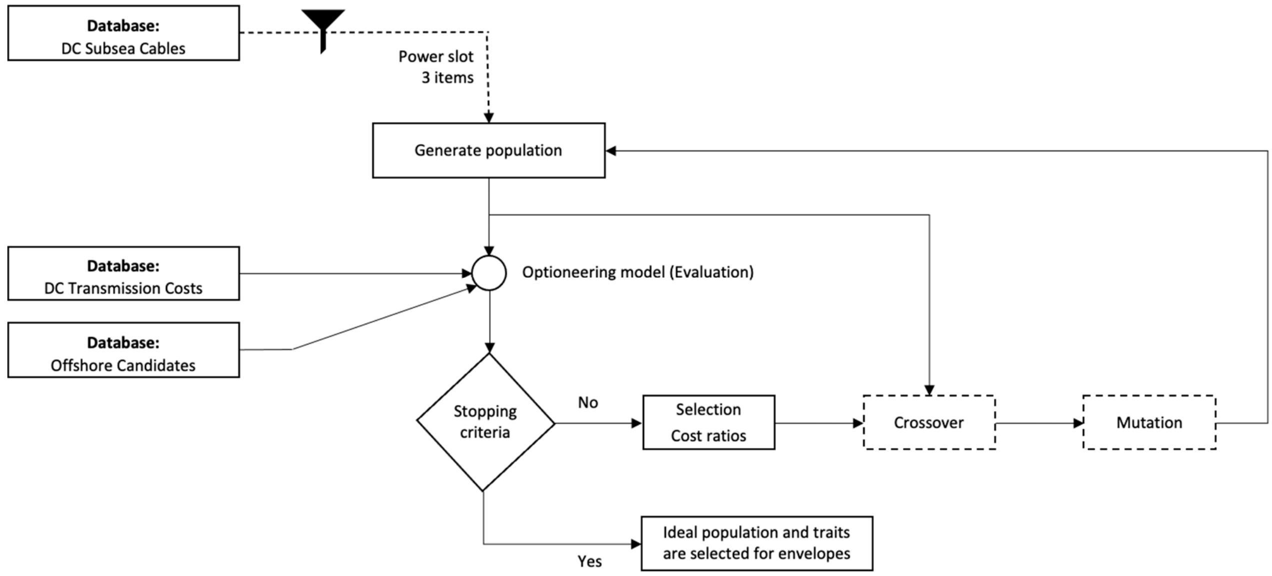


Figure 8. Clustering genetic model (HVDC-only).

4. Results

4.1. Cluster Baseline

The initial data dispersity based on the rating/shore distance of the candidate sample and the model results are shown in Figures 9 and 10, respectively, separated by AC and DC connections. While the latter (DC option) represented 88% of the sample and was consistently at 80 kV_{DC} (meaning that no other DC voltages were required/proposed), multiple voltages/sizes were proposed for the AC alternatives.

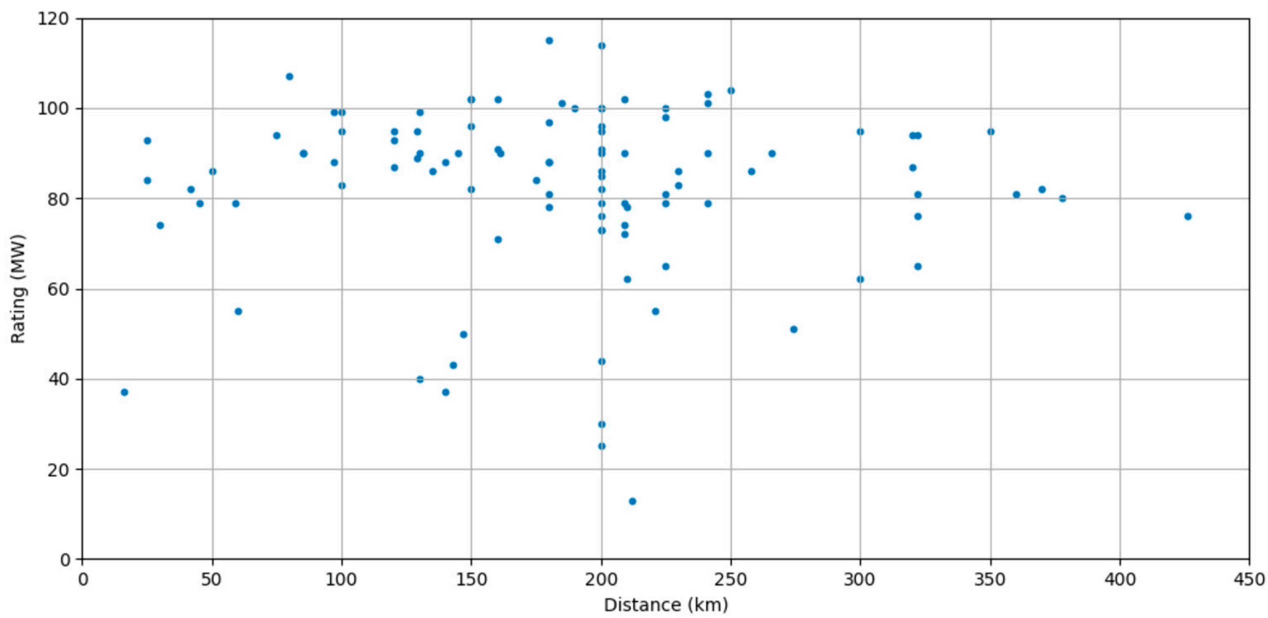


Figure 9. Overall distribution of site candidates by Rating/Voltage.

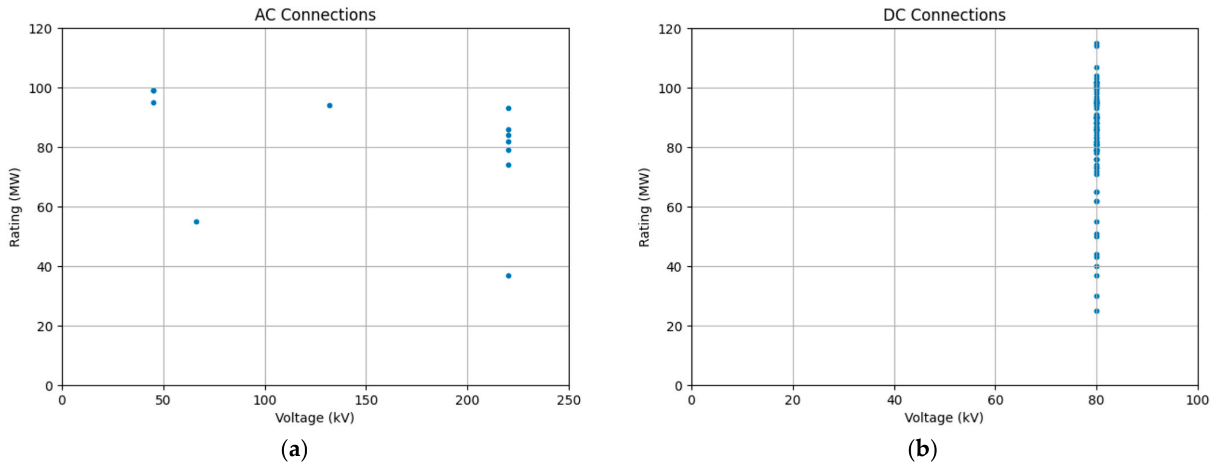


Figure 10. Overall distribution of candidates by Rating/Voltage for AC (**a**) and DC (**b**).

A sample and the average (fifty iterations) test results for clustering analysis are shown in Figures 11 and 12, respectively.

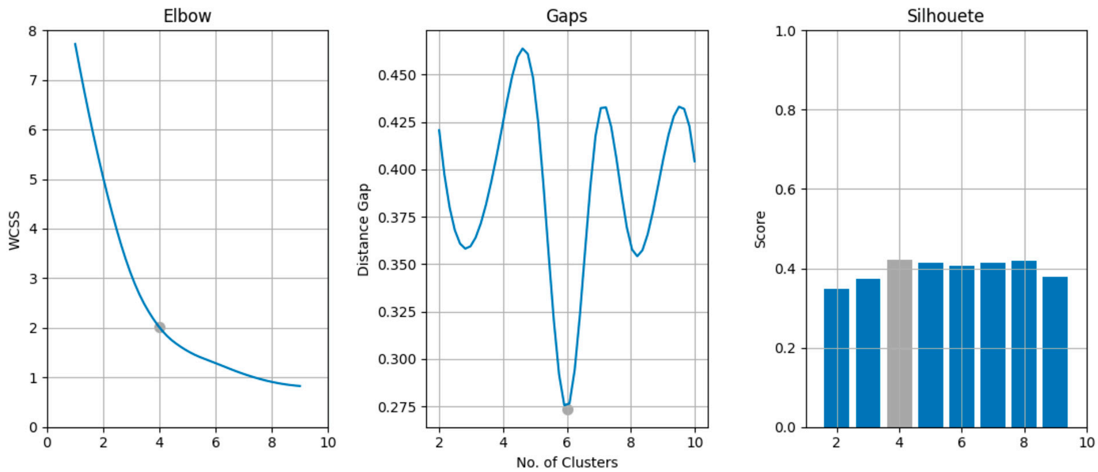


Figure 11. Cluster quantification evaluation results (One iteration).

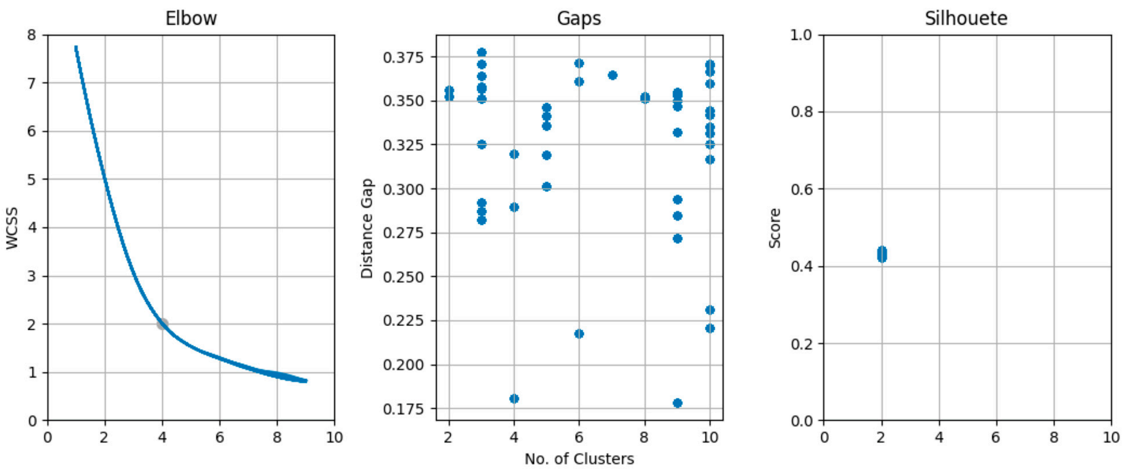


Figure 12. Cluster quantification evaluation results (Average of 50 iterations).

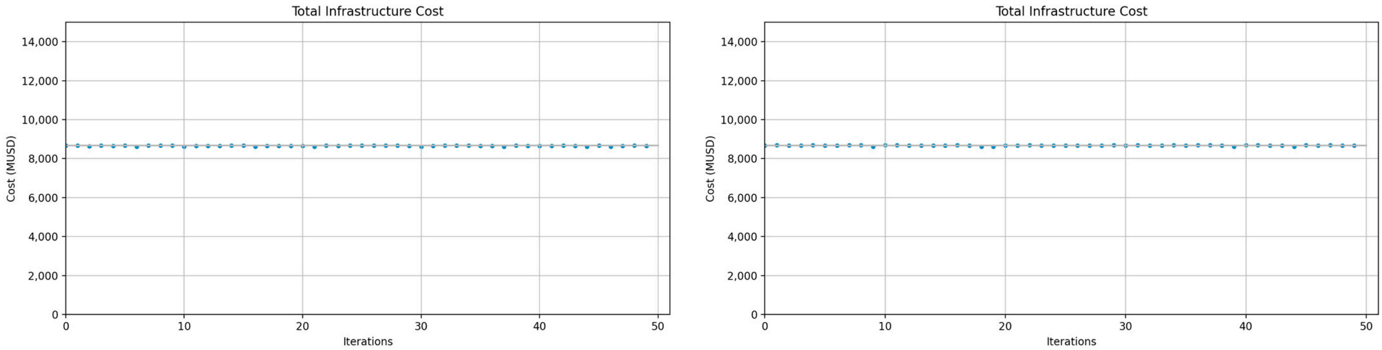
While the silhouette analysis clearly recommends the use of two clusters, both the elbow and the gap analysis suggest four clusters instead for this data set; hence, it was decided to move ahead with the proposal of four clusters. Based on these premises, the exercises shown in Table 3 were performed:

Table 3. Summary of tests performed.

Exercise Set	Sub-Exercises	Summarized Description
#1	#1.1	Baseline model; Calculate all options
#1	#1.2	GA-based; Optimized for cost/MW
#1	#1.3	GA-based; Optimized for cost/km
#2	#2.1	Baseline model; Calculate all in AC only
#2	#2.2	GA-based for AC only; Optimized for cost/MW
#2	#2.3	GA-based for AC only; Optimized for cost/km
#3	#3.1	Baseline model; Calculate all in DC only
#3	#3.2	GA-based for DC only; Optimized for cost/MW
#3	#3.3	GA-based for DC only; Optimized for cost/km

4.2. HVAC Clustering

The results in Figure 13a (distance-based, cost/km ratio) are aligned with previous research in [1] and show an extremely small variance in the total infrastructure cost by means of the deterministic approach versus the GA. An optimization run based on the cost/MW ratio was also performed and included in Figure 13b, rendering similar results, summarized in Table 4.



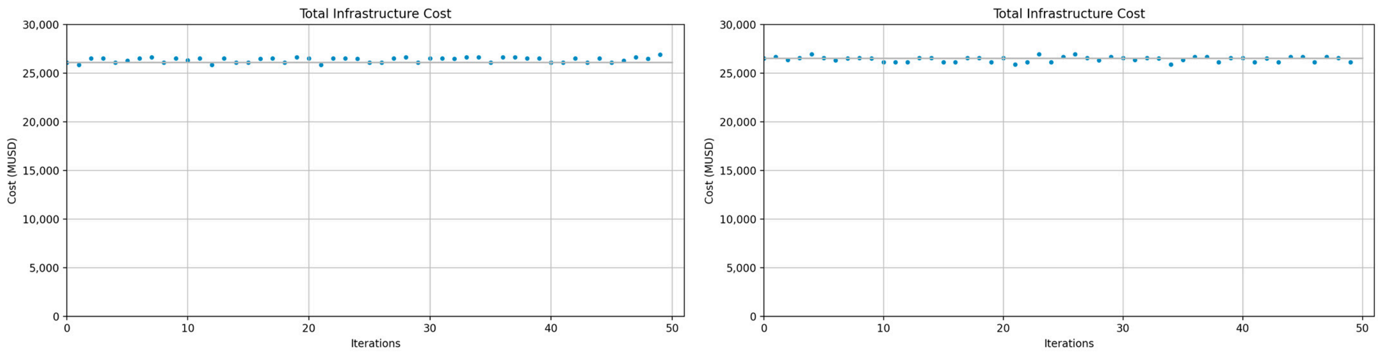
(**a**) (**b**)

Figure 13. Test results for MW-ratio (**a**) and km-ratio (**b**) (All connections).

Table 4. GA model summary for the proposed exercises (All connections).

Exercise	Candidates	Number of Cycles	Initial Total CAPEX [MUSD]	Final Total CAPEX [MUSD]	Running Time (s)	Voltage Pool
#1.1	104	1	8686	-	15	AC: 66 and 110 kV; DC: 80 kV
#1.2		50	8686	8614	571	AC: 66, 110 and 132 kV, DC: 80 kV
#1.3		50	8688	8677	569	AC: 66 and 132 kV, DC: 80 kV

Figure 14 (and Table 5) present an analysis based on AC cases only.



(**a**) (**b**)

Figure 14. Test results for MW-ratio (**a**) and Km-ratio (**b**) (AC connections).

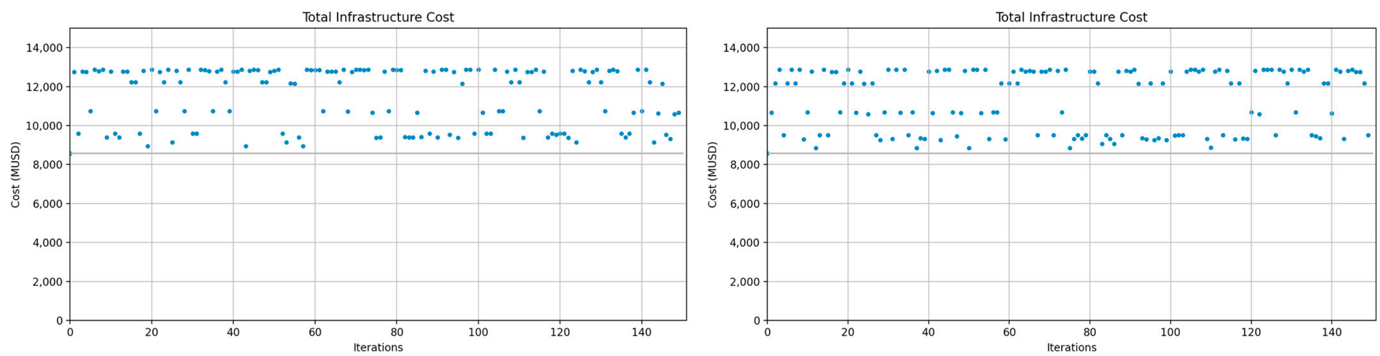
Table 5. GA model summary for the proposed exercises (AC cases only).

Exercise	Candidates	Number of Cycles	Initial Total CAPEX [MUSD]	Final Total CAPEX [MUSD]	Running Time (s)	Voltage Pool
#2.1		1	26,655	-	15	AC: 66, 150 and 220 kV
#2.2	15	50	26,326	25,887	547	AC: 110, 132 and 275 kV
#2.3		50	26,544	26,315	549	AC: 110, 132 and 220 kV

Whilst focusing only on the AC option, the advantages of having a standardized model are very limited. If the computation time is also factored in, it is more advantageous to run a deterministic evaluation of all case scenarios. It is worth emphasizing that the distance filter implemented in Section 4.3 has drastically reduced the running time.

4.3. HVDC Clustering

The analysis of DC-connected-only scenarios is presented. Based on the results of the comprehensive approach and to improve the efficiency of the model (and as already validated in the baseline exercise), the voltages were limited to 80 kV_{DC}—the outcome is presented in Figure 15 (and Table 6).



(**a**) (**b**)

Figure 15. Test results for MW-ratio (**a**) and Km-ratio (**b**) (DC connections).

Table 6. GA model summary for the proposed exercises (DC cases only).

Exercise	Candidates	Number of Cycles	Initial Total CAPEX [MUSD]	Final Total CAPEX [MUSD]	Running Time (s)	Voltage Pool
#3.1	104	1	9123	-	12	80 kV/50–120 MW
#3.2		150	8579	9369	67	80 kV/50, 120 MW
#3.3		150	8579	9315	64	80 kV/50, 120 MW

It is worth noting that the overall CAPEX for the DC-only setup is very similar (about 5% off) from a combination of AC and DC. This is sustained in the fact that AC cases are only about 10%, but the cost of DC interconnections is very high for the medium distance range (80–130 km). For a full DC landscape, economies of scale are achieved not only for the DC substations but also for the cable systems, which was not fully possible, while AC options were standardized as well.

4.4. HVAC vs. HVDC Approach

The accuracy of the model was validated by comparing the baseline total infrastructure cost with the result of the GA runs. Table 7 shows that the model, while restricting the number of the AC and the DC up to three variants, in either case, the overall infrastructure cost within a deviation of less than 3%.

Table 7. GA results comparative summary.

Exercise Set	Sub-Exercises	Initial CAPEX [MUSD]	Final CAPEX [MUSD]	Deviation to the Baseline (%)
#1	#1.1	8686	-	-
#1	#1.2	-	8614	−0.8
#1	#1.3	-	8677	−0.0
#2	#2.1	26,655	-	-
#2	#2.2	-	25,887	−2.9
#2	#2.3	-	26,315	−1.3
#3	#3.1	9123	-	-
#3	#3.2	-	9369	+2.7
#3	#3.3	-	9315	+2.1

In the DC-only approach, the default onboard generation was selected on average to less than 2–3% of the sites despite being present in about 50% of the GA runs. Comparing these results to the baseline confirms that standardization can be achieved at a minor overall infrastructure cost expense (−2.9% to +2.7% of the baseline). This range is aligned with the engineering/design expenditure contribution to the cost distribution in this type of project, as seen in the literature review. The economies of scale ratio assumed for the standardized envelopes was about 1% (20% of 3.5% [13]).

Based on the results shown, in the case of a full DC approach, it was decided to propose three steps of the same value (50 MW), meaning 50, 100, and 150 MW at 80 kVDC—and the results for said GA run are shown in Figure 16. From a design standpoint, this means that major components, such as the HVDC converters and the main AC/DC power transformers, can be modularized for 50 MW and scaled 1–2 times to fully cater to the complete candidate pool.

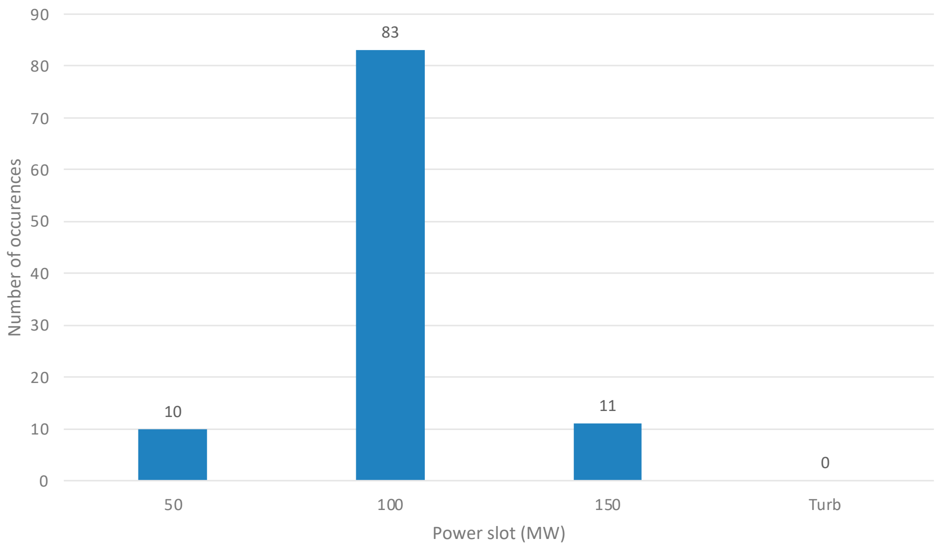


Figure 16. Final accuracy evaluation of 50, 100, and 150 MW @ 80 kVDC power envelopes.

The power envelopes outlined in [1] could now also be adjusted, as shown in Figure 17.

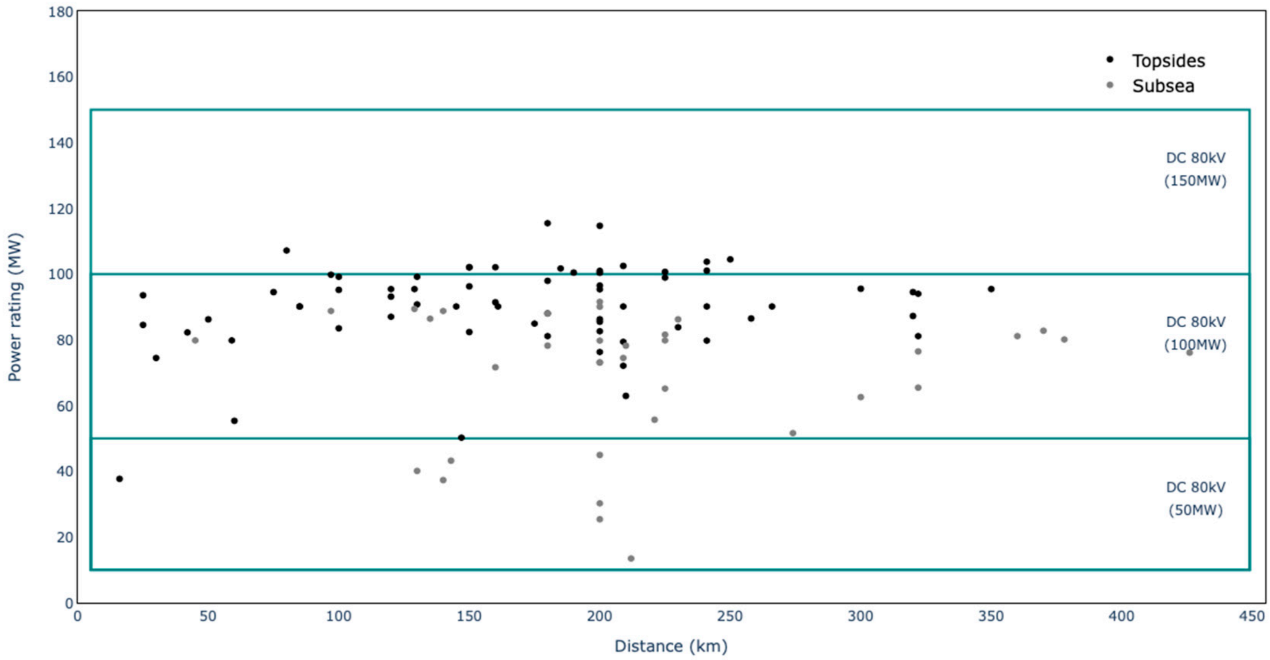


Figure 17. HVDC power envelopes.

4.5. Optioneering Sandbox

The next section provides an overview of the results directly on the application. Figure 18. includes a general view of the HVAC transmission pre-evaluation done. Here, the HVAC voltage/power envelopes were tested to get an empirical operational distance range for each selection of cable available. The cut-out distances were calculated based on AC failing criteria from Table A2.

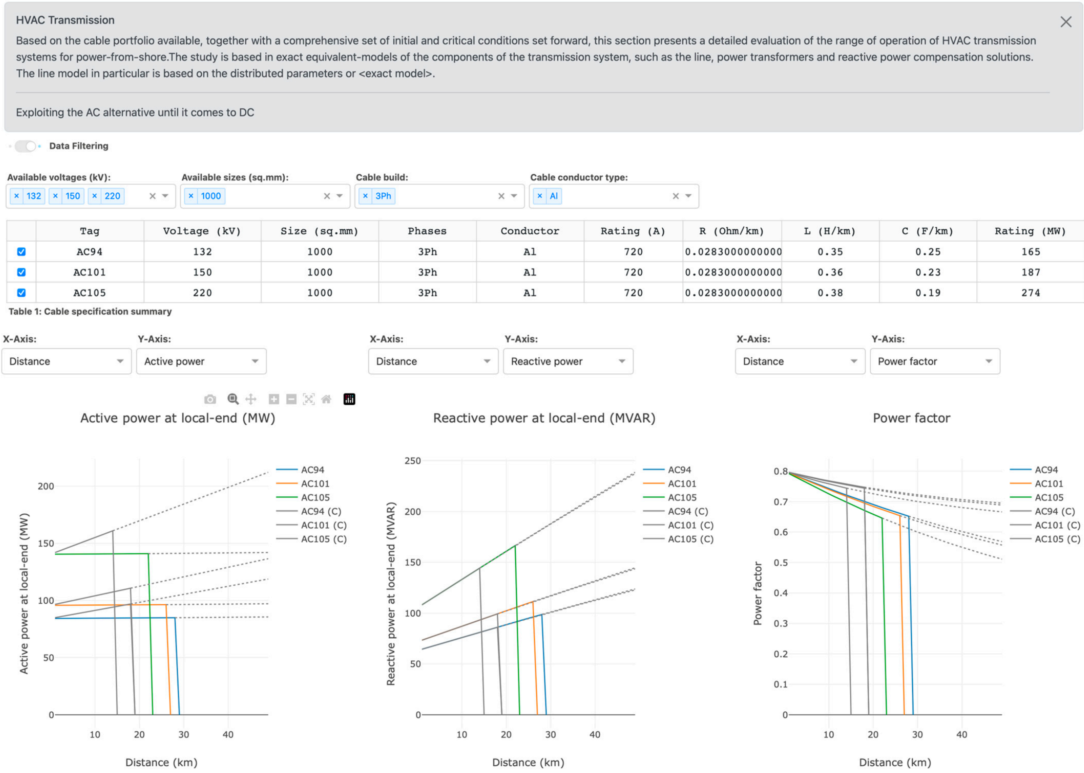


Figure 18. Optioneering interface dashboard (HVAC performance overview).

On the other hand, besides the automatic clustering of the known O&G sites, it was possible to assess other scenarios or ad-hoc case studies. Said sandbox model is a parallel development of the main optimization model, focused on a single use-case scenario, which has the added benefit that specific or particular edge cases can be tested manually, including multiple connection configurations or different levels of reactive power compensation. While Figure 18 shows the multiple degrees of adjustment of the sandbox environment, Figures 19 and 20 shows the example case study results.

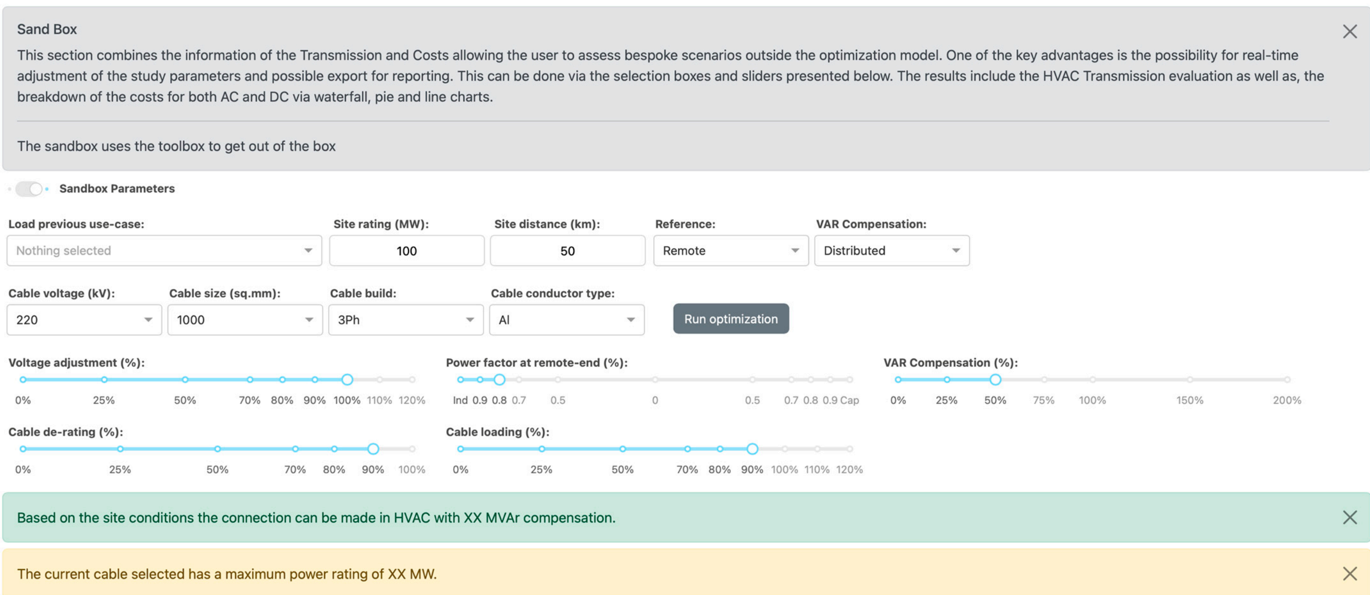


Figure 19. Optioneering interface dashboard (Sandbox; Parameters).

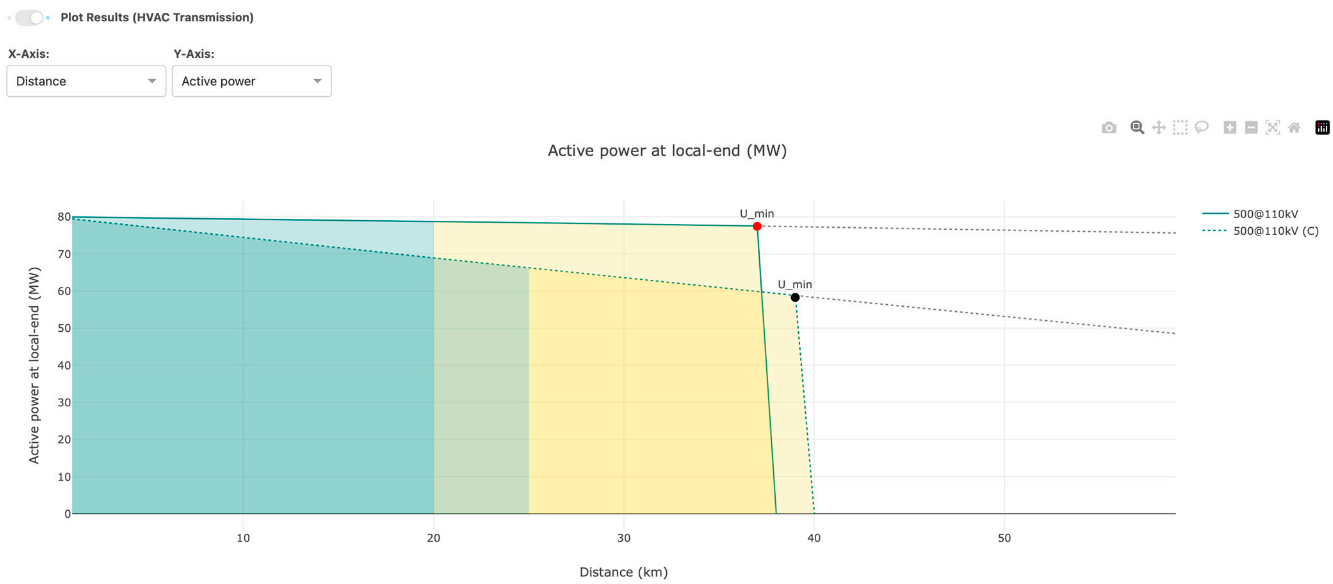


Figure 20. Optioneering interface dashboard (Sandbox; Results).

The variables available included load and no-load voltage, load and no-load current, power rating, voltage and current angles, and power factor. Other features, such as a cost breakdown of HVAC and HVDC proposals, as well as a break-even comparison of both, are also included in the application.

5. Conclusions

This work has covered the transmission and cost models for offshore HVAC & HVDC systems and presents an optioneering model aimed at reducing the development costs and time for said type of infrastructure and validating a potential standardization.

First, the bundled power transmission and cost model proved reliable in the standardization exercises performed, consistently outputting three AC envelopes (66, 110, and 132 kV) and one DC envelope (80 kV).

Considering the extent of the candidate sample, the AC and DC cable portfolio, plus the possible variations in terms of the number of cables per phase and the reactive power adjustment used in the AC alternative, the results are very satisfactory. Though 88% of the candidates are recommended for a DC configuration, the AC envelopes could be expanded to include 220 and 275 kV and cater to a larger part of the sample.

Later, from a DC-only perspective, the model managed to consistently show a range of 3 equally sized power envelopes of 50 MW at 80 kV that could have all the proposed candidates allocated. It should be noted that both the AC and the DC clustering showed a cost deviation of only 1–3% from baseline whilst narrowing both the pool of voltages (in AC) and the set of power envelopes (for DC) that correspond to 5% of the initial DC cable portfolio sample.

It is, therefore, concluded that offshore transmission systems can be successfully standardized with a minor impact on the overall deployment cost. Having that said, the strategy to improve the cost of offshore infrastructures is tied to the consistent and efficient use of DC. On the actual optimization capital amount brought by using a more restricted set of options, since the development costs play a small role in the overall offshore CAPEX, it is difficult to properly evaluate without further research on the detailed costing of OHVS and cables. Certainly, coupling these learnings with OWFs could further bring out the cost efficiencies searched for in this research.

Future work is expected to extend the implementation of the traditional GA features, such as improved cross-over and mutation methods that can mold and fine-tune the rating/voltage envelopes. Another alternative suggested is to use a generic/wide-range power/voltage tuple envelope that can also be used in the mutation process to identify key critical criteria in the grid connection calculation that could be factored in while outlining the power/voltage envelopes being proposed.

Author Contributions: Conceptualization, T.A.A. and R.C.; methodology, T.A.A. and R.C.; software, T.A.A.; validation, T.A.A., R.C., P.J.S. and A.J.P.; formal analysis, R.C., P.J.S. and A.J.P.; investigation, T.A.A.; resources, T.A.A., R.C., P.J.S. and A.J.P.; data curation, T.A.A.; writing—original draft preparation, T.A.A.; writing—review and editing, R.C.; visualization, T.A.A., R.C., P.J.S. and A.J.P.; supervision, R.C., P.J.S. and A.J.P.; project administration, R.C., P.J.S. and A.J.P.; funding acquisition, R.C., P.J.S. and A.J.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by national funds through FCT—Fundação para a Ciência e a Tecnologia, under the projects UIDB/50021/2020, UIDB/00066/2020 and UIDB/00308/2020.

Data Availability Statement: The data presented in this study are openly available in multiple repositories. The sources of the data have been included in the references whenever applicable.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

List of Abbreviations

Acronym	Full Name
AC	Alternated Current
ARM	Association Rule Mining
BL	Baseline
CAPEX	Capital Expenditure
DC	Direct Current
DFIG	Doubly-fed Induction Generator
EPCI	Engineering, Procurement, Construction and Installation
FCM	Fuzzy C-Means
GA	Genetic Algorithm
H2	Hydrogen
HVAC	High Voltage Alternated Current
HVDC	High Voltage Direct Current
MILP	Mixed-Integer Linear Programming
MST	Minimum Spanning Tree
MV	Medium Voltage
O&G	Oil and Gas
OHVS	Offshore High Voltage Substation(s)
OS	Optimal Solution
OSS	Offshore Substations
OWF	Offshore Wind Farm
PFS	Power from Shore
POC	Point-of-Connection
PSO	Particle Swarm Optimization
SCR	Short-circuit Rating
STATCOM	Static Synchronous VAR Compensation
SVC	Static Var Compensation
VAR	Reactive Power
VSC	Voltage-Sourced Converter
WTG	Wind Turbine Generator

List of Variables

Variable	Variable Name/Description	Units
P	Active power requirement/envelop of the candidate	MW
$C_{AC\ w/VAR}$	Total cost using AC solution inc. Reactive Compensation (for candidate)	USD
C_{MVA}	Cost factor per unit of Apparent Power	USD/MVA
d	Distance of the candidate site to shore	M
C_{km}	Cost factor per unit of Kilometer	USD/km
Q	Reactive power requirement/envelop of the candidate	MVAr
C_{VAR}	Cost factor per unit of Reactive Power (VAR system)	USD/MVAr
C_{Others}	Other costs (lump-sum)	USD
BL	Baseline solution	-
OS	Optimum solution	-
C_{AC}	Total cost using AC solution (for candidate)	USD
$C_{AC\ w/VAR}$	Total cost using AC solution including Reactive Compensation (for candidate)	USD
C_{DC}	Total cost using DC solution (for candidate)	USD
C_{OFFTrb}	Total cost offshore on-board gas turbine generation (for candidate)	USD
U_r	Voltage at reception (remote-end or offshore)	kV
I_r	Current at reception (remote-end or offshore)	A
Z_L	Longitudinal Impedance	Ω/km
Y_T	Transverse Admittance	S
U_e	Voltage at emission (local-end or onshore)	kV
I_e	Current at emission (local-end or onshore)	A
ABCD	Transmission line model coefficients	-
I_{DC}	Line Current	A_{DC}
U_{DC}	Line Voltage	kV_{DC}
R_L	Resistance per-km (DC cable)	Ω/km
P_{DC}	Active Power Flow	MW

Appendix A

Table A1. HVAC transmission model reference values [1].

Parameter	Units	Value
Rated voltage	%	100
Cable de-rating	%	80
Cable loading	%	80
Power factor	N/A	1.0

Table A2. HVAC transmission critical values [1].

Parameter	Units	Value
Minimum nominal voltage	%	0.9
Maximum nominal voltage	%	105
No-load current	%	100
Minimum no-load voltage	%	0.95
Maximum no-load voltage	%	105
Static stability maximum angle	°	30

Table A3. HVAC offshore transmission reference costs [1].

Parameter	Units	Value
Land cable (supply and installation)	MUSD/MVA.km	4.4
Submarine cable (supply and installation)	MUSD/MVA.km	4.6
Onshore substation (EPCI)	MUSD/MW	0.054
Offshore substation (EPCI)	MUSD/MW	0.194
VAR compensation (SVC-type)	MUSD/MVAr	0.1
Development and other costs	%	10.0

Table A4. HVDC offshore transmission reference costs [1].

Parameter	Units	Value
Land cable (supply and installation)	MUSD/MVA.km	1.5
Submarine cable (supply and installation)	MUSD/MVA.km	1.5
Onshore substation (EPCI)	MUSD/MW	0.137
Offshore substation (EPCI)	MUSD/MW	0.277
Development and other costs	%	10.0

References

1. Antunes, T.A.; Castro, R.; Santos, P.J.; Pires, A.J. Standardization of Power-from-Shore Grid Connections for Offshore Oil & Gas Production. *Sustainability* **2023**, *15*, 5041. [CrossRef]
2. Vrana, T.K.; Mo, O. Optimal Operation Voltage for Maximal Power Transfer Capability on Very Long HVAC Cables. *Energy Procedia* **2016**, *94*, 399–408. [CrossRef]
3. Zhao, F.; Wang, X.; Zhou, Z.; Kocewiak, Ł.; Svensson, J.R. Comparative study of battery-based STATCOM in grid-following and grid-forming modes for stabilization of offshore wind power plant. *Electr. Power Syst. Res.* **2022**, *212*, 108449. [CrossRef]
4. Bian, Z.; Xu, Z.; Xiao, L.; Dong, H.; Xu, Q. Selection of optimal access point for offshore wind farm based on multi-objective decision making. *Int. J. Electr. Power Energy Syst.* **2018**, *103*, 43–49. [CrossRef]
5. Tan, H.; Li, H.; Yao, R.; Zhou, Z.; Liu, R.; Wang, X.; Zheng, J. Reactive-voltage coordinated control of offshore wind farm considering multiple optimization objectives. *Int. J. Electr. Power Energy Syst.* **2021**, *136*, 107602. [CrossRef]
6. Raza, M.; Collados, C.; Gomis-Bellmunt, O. Reactive power management in an offshore AC network having multiple voltage source converters. *Appl. Energy* **2017**, *206*, 793–803. [CrossRef]
7. Liu, G.; Fan, M.; Wang, P.; Zheng, M. Study on Reactive Power Compensation Strategies for Long Distance Submarine Cables Considering Electrothermal Coordination. *J. Mar. Sci. Eng.* **2021**, *9*, 90. [CrossRef]
8. Rahman, S.; Khan, I.; Alkhammash, H.I.; Nadeem, M.F. A Comparison Review on Transmission Mode for Onshore Integration of Offshore Wind Farms: HVDC or HVAC. *Electronics* **2021**, *10*, 1489. [CrossRef]
9. Montilla-Djesus, M.E.; Arnaltes, S.; Castronuovo, E.D.; Santos-Martin, D. Optimal Power Transmission of Offshore Wind Power Using a VSC-HVdc Interconnection. *Energies* **2017**, *10*, 1046. [CrossRef]
10. Ryndzionek, R.; Sienkiewicz, Ł. Evolution of the HVDC Link Connecting Offshore Wind Farms to Onshore Power Systems. *Energies* **2020**, *13*, 1914. [CrossRef]
11. Gulski, E.; Anders, G.; Jongen, R.; Parciak, J.; Siemiński, J.; Piesowicz, E.; Paszkiewicz, S.; Irska, I. Discussion of electrical and thermal aspects of offshore wind farms' power cables reliability. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111580. [CrossRef]
12. Gulski, E.; Jongen, R.; Rakowska, A.; Siodla, K. Offshore Wind Farms On-Site Submarine Cable Testing and Diagnosis with Damped AC. *Energies* **2019**, *12*, 3703. [CrossRef]
13. Offshore Renewable Energy Catapult, Guide to an Offshore Windfarm, Guide to an Offshore Windfarm. 2019. Available online: https://guidetoanoffshorewindfarm.com/wind-farm-costs (accessed on 23 December 2023).
14. Zhao, X.; Liu, Y.; Wu, J.; Xiao, J.; Hou, J.; Gao, J.; Zhong, L. Technical and economic demands of HVDC submarine cable technology for Global Energy Interconnection. *Glob. Energy Interconnect.* **2020**, *3*, 120–127. [CrossRef]
15. Lakshmanan, P.; Liang, J.; Jenkins, N. Assessment of collection systems for HVDC connected offshore wind farms. *Electr. Power Syst. Res.* **2015**, *129*, 75–82. [CrossRef]
16. Korompili, A.; Wu, Q.; Zhao, H. Review of VSC HVDC connection for offshore wind power integration. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1405–1414. [CrossRef]
17. Stan, A.; Costinaș, S.; Ion, G. Overview and Assessment of HVDC Current Applications and Future Trends. *Energies* **2022**, *15*, 1193. [CrossRef]
18. Fjellstedt, C.; Ullah, I.; Forslund, J.; Jonasson, E.; Temiz, I.; Thomas, K. A Review of AC and DC Collection Grids for Offshore Renewable Energy with a Qualitative Evaluation for Marine Energy Resources. *Energies* **2022**, *15*, 5816. [CrossRef]
19. Smailes, M.; Ng, C.; Mckeever, P.; Shek, J.; Theotokatos, G.; Abusara, M. Hybrid, Multi-Megawatt HVDC Transformer Topology Comparison for Future Offshore Wind Farms. *Energies* **2017**, *10*, 851. [CrossRef]

20. Zuo, T.; Zhang, Y.; Meng, K.; Dong, Z.Y. Collector System Topology for Large-Scale Offshore Wind Farms Considering Cross-Substation Incorporation. *IEEE Trans. Sustain. Energy* **2019**, *11*, 1601–1611. [CrossRef]
21. Wang, B.; Wang, X.; Qian, T.; Ning, L.; Lin, J. A fast dimension reduction framework for large-scale topology optimization of grid-layout offshore wind farm collector systems. *Int. J. Electr. Power Energy Syst.* **2023**, *149*, 109066. [CrossRef]
22. Wu, Y.; Xia, T.; Wang, Y.; Zhang, H.; Feng, X.; Song, X.; Shibasaki, R. A synchronization methodology for 3D offshore wind farm layout optimization with multi-type wind turbines and obstacle-avoiding cable network. *Renew. Energy* **2021**, *185*, 302–320. [CrossRef]
23. Hou, P.; Hu, W.; Chen, Z. Offshore substation locating in wind farms based on prim algorithm. In Proceedings of the 2015 IEEE Power & Energy Society General Meeting, Denver, CO, USA, 26–30 July 2015; pp. 1–5. [CrossRef]
24. Paul, S.; Rather, Z.H. A novel approach for optimal cabling and determination of suitable topology of MTDC connected offshore wind farm cluster. *Electr. Power Syst. Res.* **2022**, *208*, 107877. [CrossRef]
25. Hardy, S.; Van Hertem, D.; Ergun, H. Application of Association Rule Mining in offshore HVAC transmission topology optimization. *Electr. Power Syst. Res.* **2022**, *211*, 108358. [CrossRef]
26. Jiang, D.; Wu, B.; Yang, X.; Van Gelder, P. A fuzzy evidential reasoning based approach for submarine power cable routing selection for offshore wind farms. *Ocean Eng.* **2019**, *193*, 106616. [CrossRef]
27. Gao, X.; Yang, H.; Lin, L.; Koo, P. Wind turbine layout optimization using multi-population genetic algorithm and a case study in Hong Kong offshore. *J. Wind. Eng. Ind. Aerodyn.* **2015**, *139*, 89–99. [CrossRef]
28. González, J.S.; García, L.T.; Payán, M.B.; Santos, J.R.; Rodríguez, G.G. Optimal wind-turbine micro-siting of offshore wind farms: A grid-like layout approach. *Appl. Energy* **2017**, *200*, 28–38. [CrossRef]
29. De Kuyffer, E.; Shen, K.; Martens, L.; Joseph, W.; De Pessemier, T. Offshore windmill and substation maintenance planning with Distance, Fuel consumption and Tardiness optimisation. *Oper. Res. Perspect.* **2023**, *10*, 100267. [CrossRef]
30. Bin Ahmad, I.; Schnepf, A.; Ong, M.C. An optimisation methodology for suspended inter-array power cable configurations between two floating offshore wind turbines. *Ocean Eng.* **2023**, *278*, 114406. [CrossRef]
31. Pinto, R.T.; Rodrigues, S.F.; Wiggelinkhuizen, E.; Scherrer, R.; Bauer, P.; Pierik, J. Operation and Power Flow Control of Multi-Terminal DC Networks for Grid Integration of Offshore Wind Farms Using Genetic Algorithms. *Energies* **2012**, *6*, 1–26. [CrossRef]
32. Jin, R.; Hou, P.; Yang, G.; Qi, Y.; Chen, C.; Chen, Z. Cable routing optimization for offshore wind power plants via wind scenarios considering power loss cost model. *Appl. Energy* **2019**, *254*, 113719. [CrossRef]
33. Pérez-Rúa, J.-A.; Das, K.; Cutululis, N.A. Optimum sizing of offshore wind farm export cables. *Int. J. Electr. Power Energy Syst.* **2019**, *113*, 982–990. [CrossRef]
34. Liu, Y.; Fu, Y.; Huang, L.-L.; Ren, Z.-X.; Jia, F. Optimization of offshore grid planning considering onshore network expansions. *Renew. Energy* **2021**, *181*, 91–104. [CrossRef]
35. Dong, T.; Brakelmann, H.; Anders, G. Analysis method for the design of long submarine cables. *Renew. Sustain. Energy Rev.* **2023**, *171*, 113029. [CrossRef]
36. Årdal, A.R.; Undeland, T.; Sharifabadi, K. Voltage and Frequency Control in Offshore Wind Turbines Connected to Isolated Oil Platform Power Systems. *Energy Procedia* **2012**, *24*, 229–236. [CrossRef]
37. Korpås, M.; Warland, L.; He, W.; Tande, J.O.G. A Case-Study on Offshore Wind Power Supply to Oil and Gas Rigs. *Energy Procedia* **2012**, *24*, 18–26. [CrossRef]
38. Kim, A.; Kim, H.; Choe, C.; Lim, H. Feasibility of offshore wind turbines for linkage with onshore green hydrogen demands: A comparative economic analysis. *Energy Convers. Manag.* **2023**, *277*, 116662. [CrossRef]
39. Zhang, H.; Tomasgard, A.; Knudsen, B.R.; Svendsen, H.G.; Bakker, S.J.; Grossmann, I.E. Modelling and analysis of offshore energy hubs. *Energy* **2022**, *261*, 125219. [CrossRef]
40. Antunes, T.A.; Castro, R.; Santos, P.J.; Pires, A.J.; Foehr, M. Optimized Electrification of Subsea Oil & Gas Infrastructures Based in Genetic Algorithm. In Proceedings of the 10th Doctoral Conference on Computing, Electrical and Industrial Systems (DoCEIS), Costa de Caparica, Portugal, 8–10 May 2019; pp. 214–223. [CrossRef]
41. Paiva, J.P.S. *Redes de Energia Eléctrica: Uma Análise Sistémica*; IST Press: Lisboa, Portugal, 2007.
42. Ikotun, A.M.; Ezugwu, A.E.; Abualigah, L.; Abuhaija, B.; Heming, J. K-means clustering algorithms: A comprehensive review, variants analysis, and advances in the era of big data. *Inf. Sci.* **2023**, *622*, 178–210. [CrossRef]