Electrical Infrastructure Cost Model for Marine Energy Systems

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National Renewable Energy Laboratory

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List of Acronyms

A	ampere
AC	alternating current
AWG	American wire gauge
CSA	cross-sectional area
DC	direct current
HERO WEC	hydraulic and electric reverse osmosis wave energy converter
HVDC	high-voltage direct current
KCMIL	1,000 circular mils
kV	kilovolt
kW	kilowatt
m	meter
MVA	megavolt-ampere
MVAR	megavolt-ampere reactive
MW	megawatt
NREL	National Renewable Energy Laboratory
PBE	Powering the Blue Economy
SAM	System Advisor Model
SVC	static var compensator
WEC	wave energy converter

Executive Summary

The National Renewable Energy Laboratory's Electrical Infrastructure Cost Model is an Excel-based tool designed to estimate the electrical infrastructure costs of marine energy components and subsystems. It incorporates data collected from offshore wind projects, utility projects, and other relevant sources to provide accurate and comprehensive cost projections. The tool allows users to input various parameters (e.g., distance to shore, device rated power, amperage, load characteristics) related to the system array, electrical cables, and substations. By leveraging industry data, cost trends, and technological advancements, the tool generates outputs that include system array sizing, electrical cable specifications and costs, substation specifications and costs, and total electrical infrastructure costs.

One of the notable strengths of the tool is its flexibility in covering multiple-orders-of-magnitude scaled systems, accommodating projects ranging from proof-of-concept or pilot-scale installations to large-scale offshore systems. By collecting data largely from offshore wind reports and utility projects, the model incorporates real-world conditions and accounts for industry-specific factors. It incorporates cost trends and sizing relationships to deliver cost estimations for electrical infrastructure components, such as electrical cables and substation equipment.

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1 Model Description

1.1 Overview and Purpose

The motivation behind the development of the Electrical Infrastructure Cost Model was to create a high-level tool for estimating the electrical infrastructure costs associated with marine energy systems. The funding for this project primarily came from the National Renewable Energy Laboratory's (NREL's) System Advisor Model (SAM) project, where the implementation of this cost model takes place. Additionally, support was extended by the Powering the Blue Economy™ (PBE) initiative in an effort to enhance precision, particularly within the context of smaller-scale systems. The intended use of the model is to assist project developers, researchers, and industry stakeholders in assessing the technical and financial aspects of implementing marine energy projects. It enables users to estimate sizing and costs related to the electrical cables and substations.

As an emerging field with potential for global impact, marine energy faces unique challenges in technological advancements and in its transition toward commercialization. With NREL's expertise in techno-economic analysis, marine energy projects are evaluated not only from a technical standpoint but also from an economic perspective. SAM (2020) showcases NREL's efforts to provide accessible and comprehensive tools that aid decision-making by simulating and evaluating the performance and costs of various renewable energy projects, including marine energy systems. The PBE initiative underscores NREL's dedication to expanding the realm of renewable energy to marine and maritime sectors, recognizing the untapped potential of blue economy technologies.

The cost model considers various user inputs for the system array, electrical specifications, and substation requirements to generate outputs such as system array specifications (i.e., number of devices, rated array capacity), electrical cable specifications (i.e., cable length, voltage, current, gauge), substation specifications (i.e., alternating current [AC] or high-voltage direct current [HVDC], substation voltage rating), and total electrical infrastructure costs. Figure 1 shows a one-line diagram of the model setup. To model a marine energy system within the cost model, users must provide specifications about a single device or a collection of devices forming an array. Note that an array of devices are interconnected through an array cable. For floating (versus fixed) marine energy devices, a riser cable (also known as a dynamic or umbilical cable) is also used to connect each floating device to the array. Subsequently, a terminal cable, serving as the electrical conduit from the array's collection point, links to an offshore substation. The offshore substation functions as the central convergence point for aggregating and converting the electrical output harnessed from the marine energy array and is typically only required for large-scale systems far from shore. The converted power is then channeled via an export cable for transmission to the onshore substation. The onshore substation assumes a pivotal role in the process, adeptly transforming the transmitted electrical energy from the array and effectively distributing it to the designated load or the wider grid network. Note that if substations are not considered, the terminal cable is the cable that connects the array to the load.

The cost model is flexible and can be applied to a wide range of system sizes, from proof-of-concept or pilot-scale projects to large-scale offshore installations. The model's Excel-based format allows users to input relevant parameters and receive detailed cost estimations. Overall, the model provides a robust and versatile approach to estimate the electrical infrastructure costs for marine energy systems, incorporating data from offshore wind projects, utility projects, manufacturers, suppliers, and other relevant sources to deliver cost projections. By leveraging industry data, the model accounts for real-world conditions and factors that impact the electrical infrastructure costs of marine energy systems. Note that when utilizing collected data from sources that present costs in a foreign currency, exchange rates were applied to convert the data into U.S. dollars. To ensure uniformity, all the cost data integrated into this project were adjusted to 2021 U.S. dollars. This process was facilitated by using the respective consumer price index to account for changes in the value of money over time.

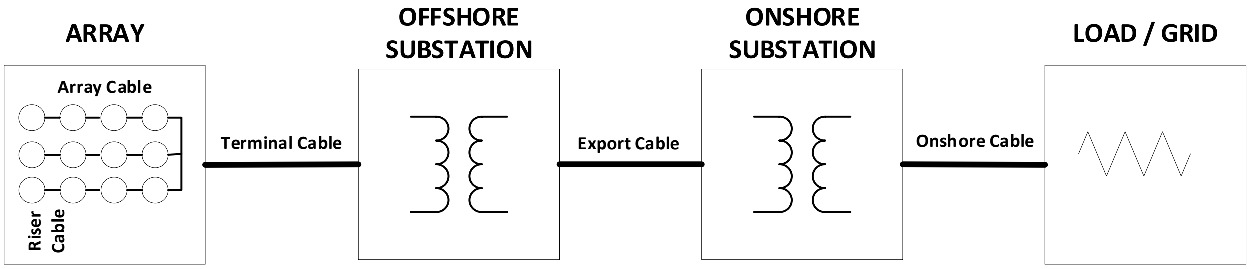

Figure 1. One-line diagram of model setup

1.2 User Inputs

The model requires the user to input several specifications about the system array, electrical cables, and substations. These inputs are used to understand the array size, electrical cabling requirements, and substation sizing to estimate the cost of electrical infrastructure for marine energy systems.

1.2.1 System Array Specifications

The model requires specifications that define the system array. The specifications are used to estimate the rated array capacity and the required length of electrical cables and to determine whether an AC or direct current (DC) system is more suitable. The system array specifications include the following parameters:

Number of Rows – The total number of rows of marine energy devices within the array, determining the horizontal arrangement of devices.

Devices per Row – The number of marine energy devices positioned within each row.

Device Spacing – The distance between individual devices within a row.

Row Spacing – The distance between adjacent rows of devices within the array.

Distance to Shore – The distance between the array and the nearest shoreline.

Water Depth – The depth of the water at which the marine energy devices will be installed.

Note that the model can be used for a single device or an array of devices. For a single device, the user should input one row, one device per row, and 0 meters (m) of device and row spacing.

1.2.2 Electrical Specifications

In addition to the system array specifications, the model also requires the user to input several electrical specifications. These inputs are used to estimate the rated voltage, current, gauge, and cost of the electrical cables. The electrical specifications include the following parameters:

Current Type – The type of current used in the system, which can be three-phase, single-phase, or DC. This information is crucial for determining the appropriate cable and substation characteristics to meet the specific electrical requirements of the system.

Device Rated Power – The maximum continuous power output (or nameplate rating) in kilowatts (kW) of each device under normal operating conditions without overheating or causing damage to the system. This parameter is used in calculating the electrical requirements of the system.

Maximum Current – The maximum current, in amperes (A), that will flow through the cables for determining the electrical characteristics of the cables, such as the cable gauge.

Cable System Overbuild – The amount of extra cable length considered for system installation, expressed as a percentage.

Floating or Fixed Array – Indicating whether the marine energy array is floating or fixed. This information influences the type of cables being considered.

Terminal and Export Cable Redundancy – Specifying whether redundancy is considered for the terminal and export cables. Redundancy refers to having duplicate or backup cables for enhanced reliability.

1.2.3 Substation Specifications

Lastly, the model requires the user to input substation requirements. These inputs are used to estimate the substation ratings and subsystem costs, considering factors such as the capacity of transformers, the type (AC or DC) and ratings of switchgear, and the necessary reactive power equipment. The substation requirements include the following parameters:

Offshore Substation – Specifying whether an offshore substation is included in the marine energy system. This option accounts for the need to have a substation located offshore, closer to the marine energy array to step-up the voltage to reduce transmission losses.

Onshore Substation – Specifying whether an onshore substation is part of the system. This option models an onshore substation, which steps down the voltage to match the grid-side voltage and serves as the connection point between the offshore substation and the local electrical grid or load.

Load/Grid Voltage Level – The load or grid voltage level, in kilovolts (kV), that the onshore substation will be designed to handle.

1.3 Model Calculations and Outputs

With the user inputs described above, the model generates outputs that provide estimates and information regarding various aspects of the electrical infrastructure for marine energy systems, including system array sizing, electrical cable specifications and costs, substation specifications and costs, and total electrical infrastructure costs. These outputs assist users in understanding the system array, electrical cable specifications, and substation specifications for marine energy systems.

1.3.1 System Array Specifications

Based on the user inputs of the number of rows, devices per row, device spacing, and row spacing, the model calculates the total number of devices in the array and the rated array capacity. This information helps estimate the power capacity and cable lengths for the marine energy system. Note that this model assumes a square array configuration to estimate the cable lengths.

Number of Devices in the Array – The quantity of marine energy devices that will be installed within the system, taking into account the number of rows and devices per row in the array.

Rated Array Capacity – The maximum power output, in kilowatts, that can be generated by the marine energy system, taking into account the individual device ratings and the overall array configuration.

These outputs offer valuable information about the size and potential power output of the marine energy array. They provide understanding of the capacity and capabilities of the system, aiding in system design, performance assessment, and energy generation predictions.

1.3.2 Electrical Cable Specifications

Using the user inputs for electrical specifications, the model estimates the cable voltage, current, cable gauge, and overall cost of the electrical cables. These outputs provide valuable insights for necessary cable characteristics, system design, and the associated expenses for the electrical infrastructure.

Cable Length – The estimated lengths of each cable (riser, array, terminal, and export) in meters.

Cable Rated Apparent Power – The power-carrying capacity of the electrical cables, in megavolt-amperes (MVA).

Export Cable Type – Determines whether the system is, or should be, designed for AC or HVDC. The user may define a current type, or the model recommends AC or HVDC based on user inputs and the table in Appendix A (Gaillard 2015).

Number of Conductors – The estimated number of conductors for each cable system, depending on current type (AC single-phase, AC three-phase, or DC).

Cable Voltage – The estimated voltage rating of each cable type (Appendix B) in kilovolts.

Cable Current – The estimated maximum current flow through each cable in amperes.

Cable Gauge – The diameter, or cross-sectional area, of each electrical conductor, within each electrical cable. This parameter is expressed in American wire gauge (AWG) or 1,000 circular mils (KCMIL).

Cost per Cable – The estimated cost per cable for each cable system in dollars.

1.3.3 Substation Specifications

The user inputs for the substation specifications help in determining the appropriate substation equipment and infrastructure required for the marine energy system. These outputs assist users in understanding the design considerations, capacity requirements, and associated expenses related to substation infrastructure for the marine energy system.

Substation Type – Determines whether the substations should be designed for AC or HVDC based on the export cable type determined.

Offshore Substation Rating – The estimated rated voltage, in kilovolts, of the offshore substation, which facilitates in stepping up the array voltage and transmits power to the onshore substation for distribution with reduced losses.

Onshore Substation Rating – The estimated rated voltage, in kilovolts, of the onshore substation, which steps down the voltage to the grid-side voltage and acts as the connection point between the offshore substation and the local electrical grid, or load.

Substation Costs – The estimated capital costs (installation not included), in dollars, associated with the substation infrastructure and equipment, including transformers, switchgear, protection systems, and other necessary components.

1.3.4 Electrical Infrastructure Costs

Cost data for substation equipment and infrastructure, as well as subsea electrical cables, were collected from offshore wind projects, cable manufacturers, suppliers, and journal papers and reports (cited throughout this report, where applicable). The data serves as a foundation for understanding cost drivers and trends, sizing relationships, and industry practices. The cost trends developed for the various electrical components are incorporated into the model, and the mathematical relationships are used to estimate the costs of the components and equipment to estimate the total electrical infrastructure costs for the marine energy system. The total electrical cost is a summation of the following:

Array Cable System Cost – Summation of the riser cable (for a floating system) and array cable costs.

Export Cable System Cost – Summation of the terminal cable and export cable costs.

Cable Protection – Optional user input, if known.

Offshore Substation Cost – Total offshore substation cost, if considered for the system design.

Onshore Substation Cost – Total onshore substation cost, if considered for the system design.

Onshore Transmission Infrastructure Cost – Optional user input, if known.

Other Electrical Infrastructure Cost – Optional user input, if known.

1.4 Component Formulas

1.4.1 Electrical Infrastructure Cost Model

1.4.1.1 Electrical Cable Specifications

Rated Apparent Power – The apparent power (*S*), expressed in megavolt-amperes, is the total usable power in a system. For three-phase systems, the relationship between real power (*P*), expressed in kilowatts, and apparent power is as follows:

$$S = \frac{P}{\sqrt{3} \times PF} \tag{1}$$

Where *PF* is the power factor, which is a unit of measurement to indicate the efficiency of an electrical system and represented as a ratio of the real power absorbed by the load to the apparent power flowing in the circuit (Eaton undated). Depending on the type of cable, the model utilizes either the device rated power (kW) or the rated array capacity (kW), and the assumed power factor of 0.95 to estimate the rated apparent power for each cable (DNV GL 2015; Gaillard 2015). This is summarized in Table 1.

Table 1. Rated Apparent Power Estimation for Cables

Cable Type	Power Factor (*PF*)	Real Power, *P* (kW)	Apparent Power Equation
Riser Cable	0.95	Device rated power	$S = \frac{Device\ rated\ power}{\sqrt{3} \times PF}$
Array Cable	0.95	Device rated power × devices per row	$S = \frac{Device\ rated\ power \times devices\ per\ row}{\sqrt{3} \times PF}$
Terminal Cable	0.95	Rated array capacity	$S = \frac{Rated\ array\ capacity}{\sqrt{3} \times PF}$
Export Cable	0.95	Rated array capacity	$S = \frac{Rated\ array\ capacity}{\sqrt{3} \times PF}$

Voltage Level – For this cost model, data pertaining to subsea electrical cable costs was collected from diverse sources, including offshore wind projects as well as reputable cable manufacturers and suppliers (Wire and Cable Your Way undated; Nassau Electrical Supply undated; Rexel undated; Gaillard 2015; Gonzalez-Rodriguez 2017; Collin et al. 2017; Rodrigues et al. 2016; Xiang, Merlin, and Green 2016; Rosenauer 2014; Smart et al. 2016; Green et al. 2007). The data provided valuable insights into the cost factors influencing cable pricing. Note that the cost data only include procurement costs of cables; installation and burial factors are not represented in the costs. As shown in Figure 2, the data revealed that the relative cost-effectiveness of cable voltage ratings is contingent upon the MVA rating. By utilizing the MVA rating as a pivotal criterion, the cost model determines the cable voltage rating that yields the most cost-efficient outcome. See Appendix B for more details on the methodology used for estimating cable voltage levels.

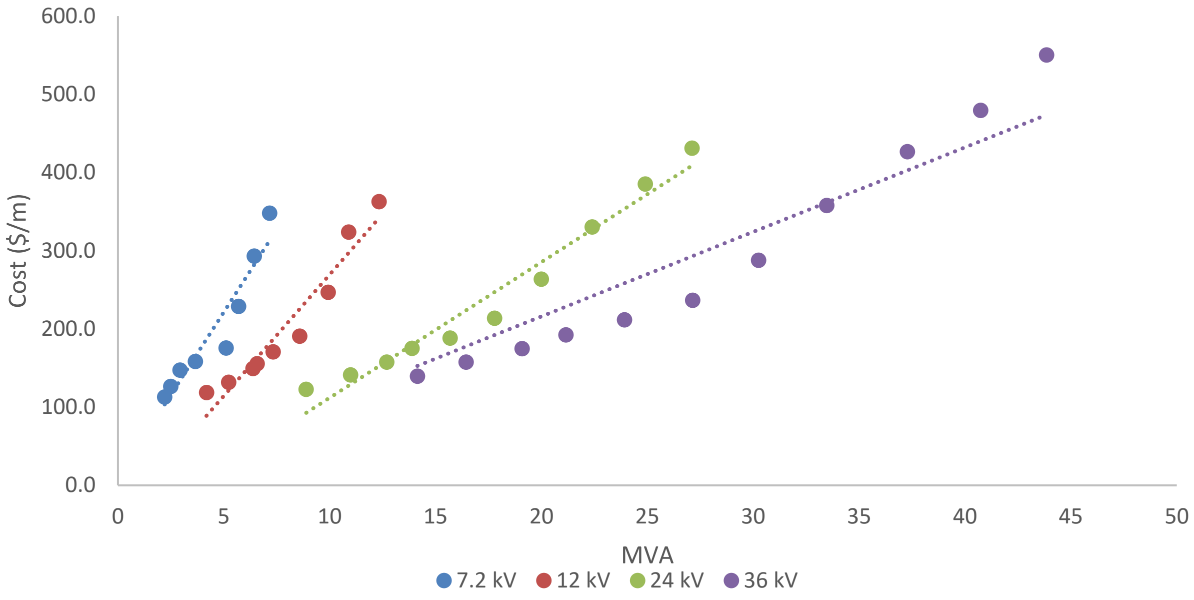

Figure 2. Relationship between cable rated power (MVA) and cost ($/m) for various voltage levels.

Not shown: data points for 0.6 kV, 1 kV, 2 kV, 66 kV, 72.5 kV, 145 kV, 220 kV, 400 kV.

Rated Current – The rated current of each cable is used to determine the cable specifications, such as conductor gauge. The model calculates the rated current for each cable, taking into account the electrical outputs of the devices, row configurations, or collection point within the marine energy system. As described in Table 2, the rated current for the riser cable is based on the maximum current output of each marine energy device. The rated current for the array cable is determined by summing the currents of all the devices within each row of the array. This provides an estimation of the total current flowing through the cable, considering the electrical output of each device within the row. The terminal cable's rated current is based on the current at the collection point of the array. This value represents the combined current of all the devices within the array, considering the electrical output of each device. The export cable's rated current is based on the current flow between the offshore and onshore substations.

Table 2. Parameters Used for Calculating Rated Current of Each Cable Type

Cable Type	Parameters Used for Calculations
Riser Cable	Maximum current output of each device (per device)
Array Cable	Maximum current output of devices within each row (summed)
Terminal Cable	Maximum current at the collection point of the array (combined maximum current of all devices within the array)
Export Cable	Maximum current at the offshore substation (maximum current at the collection point of the array)

Cross-Sectional Area – To determine the cross-sectional area (CSA) of each cable based on the estimated current ratings, a linear relationship can be established using a cable gauge conversion chart (Newark undated; Ayixa 2020). This chart provides data on the ampacity (A) and CSA

(mm^2) for various cable sizes. The linear relationship between ampacity and CSA can be represented by the following equation:

$$CSA = 0.3551 \times Ampacity + 0.0001 \tag{2}$$

Equation (2) indicates that as the ampacity increases, the CSA of the cable also increases (Figure 3). It is important to note that the actual cable selection and sizing process should consider additional factors such as cable material, insulation type, temperature rating, and local regulations. However, for the purpose of estimation within the cost model, the linear relationship based on the ampacity and CSA can provide a reasonable approximation.

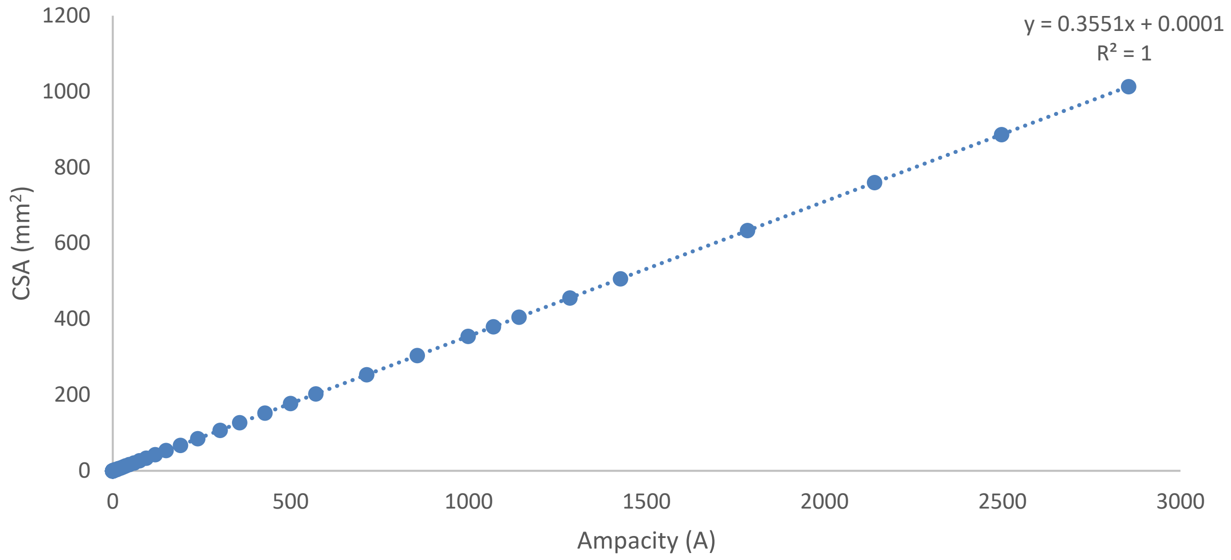

Figure 3. Relationship between cable ampacity (A) and cross-sectional area (mm^2)

Gauge – Selecting the appropriate cable gauge is crucial for various applications, as it ensures that the conductor can handle the required current load without becoming a bottleneck or posing safety risks. Different electrical components and systems, such as power cables, wiring in buildings, and electronics, have specific gauge requirements based on their intended use and the amount of current they will carry. AWG, also referred to as Brown & Sharpe Gage, is the standardized means within the United States for indicating the cross-sectional dimensions of round, solid conductors (Wesco undated). The cost model integrates the industry standard cable gauge conversion chart to map the CSA of each cable to a specific gauge size per this method. Cable gauges are typically represented by whole numbers and range from 4/0 to 40 AWG, and the model considers the 44 commonly known sizes within this range. However, wires larger than 4/0 are expressed in KCMIL, which is a unit of area derived from the diameter of a circle, where 1 circular mil is the area of a circle with a diameter of 1 mil (1/1,000 of an inch) (Wesco undated). By incorporating both the gauge sizes and KCMIL measurements, the model ensures comprehensive coverage of various wire sizes encountered in electrical cable systems. This approach ensures that the electrical infrastructure costs adhere to industry standards and account for the appropriate wire sizes to meet the system's electrical demands.

Cable Type – The choice between an AC and HVDC export cable system depends on several key factors, including the distance to shore and the installed capacity (refer to Appendix A). As learned from offshore wind projects, AC export cable systems are commonly used for smaller systems with shorter distances to shore. For these arrays, AC cables offer advantages, such as lower conversion losses and simpler installation and maintenance procedures. For larger-scale systems that are further offshore, HVDC export cable systems are typically favored. HVDC technology allows for lower transmission losses over long distances because it can maintain a stable voltage level. While HVDC systems generally have higher initial investment costs, they offer benefits in terms of improved transmission efficiency and reduced grid congestion. Incorporating insights derived from offshore wind projects, the cost model integrates the guidance provided in Appendix A. This table, designed to account for distance to shore and rated array capacity, serves as a benchmark for making informed decisions regarding the optimal choice of transmission system for marine energy projects.

1.4.1.2 Electrical Cable Costs

As previously mentioned, this model incorporates collected cable cost data from offshore wind projects, utility projects, suppliers, and other relevant sources. The data have been analyzed to establish the relationship between the cost per meter per conductor ($/m/conductor) and the CSA of the cable. By plotting these two variables and applying a linear trendline (Figure 4), the cost relationship (in $/m/conductor) is determined to be:

$$Cost\ per\ length\ per\ conductor\ = 0.3476 \times CSA \tag{3}$$

To calculate the cost per cable using this relationship, the model multiplies the estimated cost per meter per conductor value by the cable length (in meters) and the number of conductors, where the number of conductors is determined based on the user input for the current type. For a single-phase system, the model assumes two conductors, a three-phase system assumes four conductors, and DC assumes two conductors. By performing this calculation, the model provides an estimation of the cost per cable in dollars, considering the cable length, number of conductors, and the established cost trends derived from the collected data. This approach ensures that the cost estimation aligns with real-world cost drivers and reflects the specific characteristics of the marine energy system being analyzed.

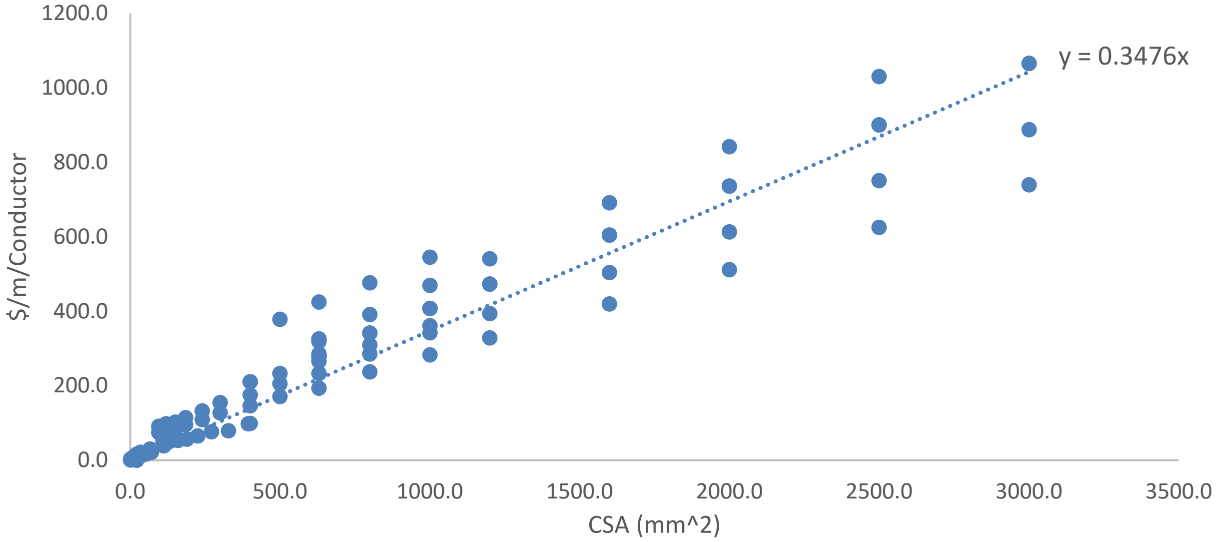

Figure 4. Cost trend for subsea electrical cables

1.4.2 Substation Cost Model

Integrated within the electrical infrastructure model is a substation cost model, which takes into consideration the user inputs and the electrical outputs from the model to appropriately size substation components and equipment. Substations play a vital role in converting and transmitting the electrical energy generated by the marine energy array, enabling its integration into the local electrical grid or load. By considering substation requirements, the model determines the appropriate substation equipment and infrastructure needed for the marine energy system, as well as the component ratings and associated costs. The cost estimations for the substation components are based on cost trends and relationships developed from data collected from various offshore wind projects and project developers.

1.4.2.1 Substation Rating

The information derived from the export cable voltage rating is of paramount importance in determining the rating for the onshore and offshore substation. The export cable voltage rating reflects the maximum voltage capacity at which the power is transmitted from the marine energy farm to the substation. Based on this rating, the cost model ensures that the offshore substation is appropriately sized to handle the voltage level and efficiently manage the electrical transmission process (refer to Appendix C). For the onshore substation, the cost model compares the export cable voltage rating with the onshore cable voltage rating, which is determined based on the user's input for the load/grid voltage level (refer to Appendix D). It selects the higher voltage rating between the two, as this represents the critical point of voltage capacity in the entire electrical infrastructure. The onshore substation is then designed and rated to match the higher voltage level to accommodate the power flow from the marine energy farm effectively. By utilizing information from the export cable voltage rating and comparing it to the onshore cable voltage rating, the cost model optimizes the design and capacity of both the offshore and onshore substations.

1.4.2.2 Substation Base / Foundation Cost

The foundation cost accounts for the expenses related to constructing the stable base and support structure for both the onshore and offshore substations.

Offshore Substation – Offshore platforms are specialized structures used to house electrical equipment for the offshore substation, such as converters and switchgear, above the water level; they are designed to withstand the challenging marine environment. The cost model utilizes offshore platform data collected from various offshore wind projects to estimate the foundation cost (Regional Group North Sea 2011; Härtel et al. 2017; Smart 2016). Based on the cost curve shown in Appendix F, the cost relationship implemented in the model for the offshore substation foundation (in $) is as follows:

$$Cost_{Base,offshore} = \frac{\$303.09}{\text{kV}} \times rated\ array\ capacity\ (\text{kW}) \tag{4}$$

Onshore Substation – For onshore substations, the first component is the base cost without any equipment. The cost model uses base cost data collected from a reputable infrastructure development construction firm for a new substation, assuming flat, barren land with relatively easy site access (Pletka et al. 2014). Based on the cost curve shown in Appendix F, the cost relationship implemented in the model for the onshore substation foundation (in $) is as follows:

$$Cost_{Base,onshore} = \frac{\$6{,}533.1}{\text{kV}} \times substation\ voltage\ rating\ (\text{kV}) \tag{5}$$

1.4.2.3 AC Electrical Equipment

Circuit Breakers – Circuit breakers are essential protective devices that interrupt electric currents during fault conditions to prevent damage to the electrical equipment and ensure the safety and reliability of the substation. Based on the cost curve presented in Appendix F, the cost relationship implemented in the model for circuit breakers (in $) is as follows (MISO 2020):

$$Cost_{Circuit\ Breakers} = \frac{\$818.42}{\text{kV}} \times \text{kV} \tag{6}$$

AC Switchgear – AC switchgear serves as the central control and distribution system for electrical power within the substation, enabling the efficient switching, protection, and control of electrical circuits. Based on the cost curve presented in Appendix F, the cost relationship implemented in the model for AC switchgear (in $) is as follows (Gaillard 2015; Regional Group North Sea 2011):

$$Cost_{Switchgear} = \frac{\$14{,}018}{\text{kV}} \times \text{kV} \tag{7}$$

Transformer – Transformers facilitate voltage transformation and power distribution, converting electrical energy to the required voltage levels for efficient transmission from the offshore or onshore substation to the grid. Based on the cost curve presented in Appendix F, the cost relationship implemented in the model for transformers (in $) is as follows (Lazaridis 2005):

$$Cost_{Transformer} = \frac{\$11{,}879}{\text{kV}} \times \text{kV} \tag{8}$$

Shunt Reactor – Shunt reactors are used to compensate for capacitive reactive power and maintain voltage stability, ensuring a balanced and smooth power flow within the substation and the electrical grid. Based on the cost data presented in Appendix G, an average of the cost per megavolt-ampere reactive ($/MVAR) was calculated, and the cost relationship implemented in the model for shunt reactors (in $) is as follows (Elliott et al. 2016; Friday and Luckett 2016; MISO 2020; Pletka et al. 2014; Regional Group North Sea 2011):

$$Cost_{Shunt\ Reactor} = \frac{\$35{,}226}{\mathrm{MVAR}} \times \mathrm{MVAR} \tag{9}$$

Series Capacitor – Series capacitors are employed to enhance transmission power capacity and improve voltage regulation, reducing power losses and enhancing the efficiency of power transfer within the substation. Based on the cost data presented in Appendix G, an average of the cost per megavolt-ampere reactive was calculated, and the cost relationship implemented in the model for series capacitors (in $) is as follows (Pletka et al. 2014; MISO 2020; Regional Group North Sea 2011):

$$Cost_{Series\ Capacitor} = \frac{\$22{,}047}{\mathrm{MVAR}} \times \mathrm{MVAR} \tag{10}$$

Static Var Compensator – Static var compensators, also known as SVCs, regulate reactive power to stabilize voltage levels, enhance power quality, and control voltage fluctuations, supporting the reliable operation of the substation and the connected electrical grid. Based on the cost data presented in Appendix G, an average of the cost per megavolt-ampere reactive was calculated, and the cost relationship implemented in the model for SVCs (in $) is as follows (MISO 2020; Pletka et al. 2014; Regional Group North Sea 2011):

$$Cost_{Static\ Var\ Compensator} = \frac{\$105{,}060}{\mathrm{MVAR}} \times \mathrm{MVAR} \tag{11}$$

1.4.2.4 DC Electrical Equipment

HVDC Converter Station – HVDC converter stations act as interfaces that convert AC power to DC for transmission over HVDC cables and convert it back to AC at the receiving end. These components play a crucial role within HVDC transmission systems, facilitating the transfer of electrical power over long distances between AC networks. The HVDC converter stations typically consist of AC transformers, AC filters, phase reactor(s), DC converter, DC capacitor(s), and DC reactor(s), which collectively ensure controlled power conversion. The data collected are shown in Appendix F, and the cost trend implemented in the model for an HVDC converter station (in $) is as follows (Härtel et al. 2017; Pletka et al. 2014; MISO 2020):

$$Cost_{HVDC\ Converter\ Station} = \frac{\$142.61}{\mathrm{kW}} \times \mathrm{kW} \tag{12}$$

1.4.2.5 Total Substation Cost

As illustrated in Appendix H, if the substation is AC, the total cost of both the onshore and offshore substations is calculated as the sum of two main components: the foundation cost and the AC electrical equipment cost, which includes the capital expenses associated with circuit breakers, switchgear, transformers, and reactive power compensation equipment needed for the AC system.

On the other hand, if the substation is DC, the total cost of the onshore and offshore substations is determined by summing the foundation cost and the HVDC converter station cost. The foundation cost remains the same as in the AC system assumption, covering the expenses related to constructing the foundation or base for both substations. However, instead of the AC electrical equipment, the HVDC converter station cost is considered, which incorporates the expenses associated with the specialized equipment and components used for the conversion of electrical power from AC to DC and vice versa.

2 Output Examples

In order to demonstrate and evaluate the model's performance and accuracy across various scales, two distinct cases are examined. In both cases, an adequate amount of detailed information has been provided for each respective system. This approach facilitates a fair comparison between the case outputs and the predictions from the cost model, allowing for a discerning evaluation of the model's ability to generate cost and sizing estimates that align with real-world scenarios.

2.1 Case 1: Small-Scale Wave Energy Converter Deployment (HERO WEC)

Case 1 represents a wave energy converter (WEC) designed and fabricated by NREL and deployed at Jennette's Pier in North Carolina's Outer Banks in August 2022 (Nakhai, McGilton, and Jenne 2022). The hydraulic and electric reverse osmosis wave energy converter (HERO WEC) comprises one WEC rated at 2 kW with a maximum current of 60 A. The deployment site had a water depth of 50 m. The terminal cable, which is the electrical line from the device to the load, has four conductors for the three-phase system, is 150 m in length, and is rated at 4 AWG, 0.6 kV. The input and output specifications for the HERO WEC are listed in Table 3.

Note: Although the device is floating (not bottom-fixed), a riser cable was not deployed with the system, so the input to specify a floating array is selected as "No" to avoid modeling a riser cable. Also, to achieve a terminal cable length of 150 m, a distance to shore of 100 m must be entered as an input, since the model considers water depth in the cable length calculation. Lastly, as outlined in Section 1, since there were no substations for this system, the model considers the terminal cable as the cable that connects the array to the load (as opposed to an export cable).

Table 3. Input and Output Specifications for HERO WEC

Inputs		
System Array Specifications		
Number of rows	1	
Devices per row	1	
Device spacing (m)	0	
Row spacing (m)	0	
Distance to shore (m)	100	
Water depth (m)	50	
Electrical Specifications		
Current type	AC - Three Phase	
Device rated power (kW)	2	
Maximum current (A)	60	
Cable system overbuild (%)	0	
Floating array? (Y/N)	No	
Build terminal cable redundancy? (Y/N)	No	
Build export cable redundancy? (Y/N)	No	
Substation Specifications		
Offshore substation? (Y/N)	No	
Onshore substation? (Y/N)	No	
Load / grid voltage?	N/A	
Outputs		
	Actual Output	**Model Output**
Cable Ratings		
Terminal Cable Rated Current (A)	90	60
Terminal Cable Gauge (AWG)	4	4
Terminal Cable Voltage Rating (kV)	0.6	0.6
Costs		
Terminal Cable Cost ($)	4,450	4,444

2.2 Case 2: Fixed-Bottom Offshore Wind Reference Project

Case 2 represents an offshore reference project from NREL’s *2021 Cost of Wind Energy Review* report (Stehly and Duffy 2022). This project is designed to be a representative example of upcoming offshore wind projects expected in the North Atlantic region of the United States. For this reference project, the wind power plant comprises 75 wind turbines, each with a capacity of 8 megawatts (MW), resulting in a total capacity of 600 MW for the entire plant. The rotor diameter is 159 m, which is used to determine the spacing between turbines in the array (assumed 10x rotor diameter). This example is for a fixed-bottom configuration, assuming a water depth of 34 m and distance to shore of 50,000 m. The array cable system, which is the electrical line from the array to the offshore substation, is rated at 66 kV. The export cable from the offshore substation, which transfers power to the landfall, is rated at 220 kV. The input and output specifications for the offshore wind reference project are listed in Table 4.

Table 4. Inputs and Outputs for the Offshore Wind Reference Project

Inputs		
System Array Specifications	**From Report**	**From Model**
Number of rows	Given: 75 turbines	5
Devices per row	Given: 75 turbines	15
Device spacing (m)	Given: rotor diameter 159 m	1,590 (rotor diameter×10)
Row spacing (m)	Given: rotor diameter 159 m	1,590 (rotor diameter×10)
Distance to shore (m)	50,000	50,000
Water depth (m)	34	34
Electrical Specifications		
Current type	Not disclosed	AC - Three Phase
Device rated power (kW)	8,000	8,000
Maximum current (A)	Not disclosed	100
Cable system overbuild (%)	Not disclosed	0
Floating array? (Y/N)	No (Fixed)	No
Build terminal cable redundancy? (Y/N)	Not disclosed	No
Build export cable redundancy? (Y/N)	Not disclosed	No
Substation Specifications		
Offshore substation? (Y/N)	Not disclosed	Yes
Onshore substation? (Y/N)	Not disclosed	Yes
Load / grid voltage?	Not disclosed	kV ≥ 220
Outputs		
Cable Ratings	**Case Output**	**Model Output**
Array cable voltage level (kV)	66	66
Terminal cable voltage level (kV)	66	66
Export cable voltage level (kV)	220	220
Array cable rated current (A)	Not disclosed	1,500
Terminal cable rated current (A)	Not disclosed	7,500
Export cable rated current (A)	Not disclosed	9,000
Array cable gauge (KCMIL)	1,250	1,000
Terminal cable gauge (KCMIL)	2,000	2,000
Export cable gauge (KCMIL)	2,000	2,000
Costs		
Array cable system cost ($)	70,200,000	87,138,608
Export cable system cost ($)	232,200,000	207,508,053
Total electrical infrastructure cost ($)	415,800,000	511,749,475

3 Discussion and Suggestions for Future Work

The implementation of the Electrical Infrastructure Cost Model has provided valuable insights into estimating the financial aspects of marine energy projects. However, it is important to acknowledge that certain discrepancies between model outputs and real-world applications can arise due to a range of factors. Notably, the exclusion of installation costs, cable protection costs, and costs of cable connectors, which can vary significantly depending on site-specific conditions and technologies, might contribute to these differences. Additionally, uncertainties surrounding electrical specifications, such as cable characteristics and substation equipment, can introduce variations between the model's estimates and actual costs.

To enhance the model's accuracy and applicability, several avenues for future work are worth exploring. A continuous refinement of cost curves through the inclusion of additional data points can improve the model's predictive power. Ensuring the model remains up-to-date with the latest developments can enhance its utility and relevance. Gathering more data on the various electrical components, cable protection features, and electrical subsystems can help capture a broader range of scenarios and improve the precision of cost estimates. Furthermore, incorporating advanced scenarios that account for various installation challenges and factors, such as seabed conditions, can offer a more comprehensive perspective on project costs. Integrating these complexities can provide users with a clearer understanding of potential cost fluctuations and uncertainties.

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Appendix A. Method for Assuming Export Cable Type

Table A-1. Method for Assuming Export Cable Type. Data from Gaillard (2015).

Installed Capacity (kW)	Distance to Shore (m)												
	30,000	**40,000**	**50,000**	**60,000**	**70,000**	**80,000**	**90,000**	**100,000**	**110,000**	**120,000**	**130,000**	**140,000**	**150,000**
200,000	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	HVDC
300,000	AC	AC	AC	AC	AC	AC	AC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC
400,000	AC	AC	AC	AC	AC	AC	AC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC
500,000	AC	AC	AC	AC	AC	AC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC
600,000	AC	AC	AC	AC	AC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC
700,000	AC	AC	AC	AC	AC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC
800,000	AC	AC	AC	AC	AC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC
900,000	AC	AC	AC	AC	AC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC
1,000,000	AC	AC	AC	AC	AC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC
1,100,000	AC	AC	AC	AC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC
1,200,000	AC	AC	AC	AC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC	HVDC

Appendix B. Method for Estimating Cable Voltage Levels

Table B-1. Method for Estimating Cable Voltage Levels

Type of Cable	MVA	Voltage (kV)	Rated Power per Device (MVA) Range
Riser Cable	0	0.6	0 ≤ MVA < 0.03
	0.03	1	0.03 ≤ MVA < 1
	1	2	1 ≤ MVA < 3
	3	7.2	3 ≤ MVA < 5
	5	12	5 ≤ MVA < 9
	9	24	9 ≤ MVA < 14
	14	36	MVA ≥ 14
Type of Cable	**MVA**	**Voltage (kV)**	**Rated Power per Row (MVA) Range**
Array Cable	0	0.6	0 ≤ MVA < 0.03
	0.03	1	0.03 ≤ MVA < 1
	1	2	1 ≤ MVA < 3
	3	7.2	3 ≤ MVA < 5
	5	12	5 ≤ MVA < 9
	9	24	9 ≤ MVA < 14
	14	36	14 ≤ MVA < 30
	30	66	30 ≤ MVA < 40
Type of Cable	**MVA**	**Voltage (kV)**	**Rated Power per Row (MVA) Range**
Terminal Cable	0	0.6	0 ≤ MVA < 0.03
	0.03	1	0.03 ≤ MVA < 1
	1	2	1 ≤ MVA < 3
	3	7.2	3 ≤ MVA < 5
	5	12	5 ≤ MVA < 9
	9	24	9 ≤ MVA < 14
	14	36	14 ≤ MVA < 30
	30	66	30 ≤ MVA < 40
Type of Cable	**MVA**	**Voltage (kV)**	**Rated Power per Array (MVA) Range**
Export Cable (AC)	0	0.6	0 ≤ MVA < 0.03
	0.03	1	0.03 ≤ MVA < 1
	1	2	1 ≤ MVA < 3
	3	702	3 ≤ MVA < 5
	5	12	5 ≤ MVA < 9
	9	24	9 ≤ MVA < 14
	14	36	14 ≤ MVA < 30
	30	66	30 ≤ MVA < 40
	40	72.5	40 ≤ MVA < 121
	121	145	121 ≤ MVA < 250
	250	220	250 ≤ MVA < 550
	550	400	MVA ≥ 550
Type of Cable	**MW**	**Voltage (kV)**	**Rated Power per Array (MW)**
Export Cable (HVDC)	0	150	0 < MW < 500
	500	300	MW ≥ 500

Appendix C. Substation Specification Options

Table C-1. Substation Specification Options

Cable Voltage (kV)	Substation Rating
0.6	0.6 kV AC Substation
1	1 kV AC Substation
2	2 kV AC Substation
7.2	8 kV AC Substation
12	15 kV AC Substation
24	25 kV AC Substation
36	46 kV AC Substation
66	69 kV AC Substation
72.5	115 kV AC Substation
145	161 kV AC Substation
220	230 kV AC Substation
400	415 kV AC Substation
150	161 kV HVDC Substation
300	345 kV HVDC Substation

Appendix D. Method for Assuming Onshore Cable and Substation Voltage

Table D-1. Method for Assuming Onshore Cable and Substation Voltage

User Input: Load/Grid Voltage Level	Voltage Range	Assumed Onshore Cable Voltage (kV)	Assumed Substation Rating
Ultralow Voltage (ULV)	kV ≤ 2	2	2 kV AC Substation
Extra-Low Voltage (ELV)	2 ≤ kV < 7.2	7.2	8 kV AC Substation
Low Voltage (LV)	7.2 ≤ kV < 36	36	46 kV AC Substation
Medium Voltage (MV)	36 ≤ kV < 72.5	66	69 kV AC Substation
High Voltage (HV)	72.5 ≤ kV < 145	145	161 kV AC Substation
Extra-High Voltage (EHV)	145 ≤ kV < 220	220	230 kV AC Substation
Ultrahigh Voltage (UHV)	kV ≥ 220	400	415 kV AC Substation

Appendix E. American Wire Gauge Conversion Chart

Table E-1. American Wire Gauge Conversion Chart. Data from Newark (undated) and Ayixa (2020).

Ampacity (A)	Conductor cross section (mm^2)	AWG / KCMIL	Conductor Diameter (in.)	Conductor Diameter (mm)	Ohms (per 1,000 ft)	Ohms (per km)
0.0137	0.00487	40	0.0031	0.07874	1049	3440
0.0175	0.00621	39	0.0035	0.0889	831.8	2728
0.0228	0.00811	38	0.004	0.1016	659.6	2163
0.0289	0.0103	37	0.0045	0.1143	523.1	1715
0.035	0.0127	36	0.005	0.127	414.8	1360
0.044	0.0159	35	0.0056	0.14224	329	1079.12
0.056	0.0201	34	0.0063	0.16002	260.9	855.752
0.072	0.0255	33	0.0071	0.18034	206.9	678.632
0.091	0.0324	32	0.008	0.2032	164.1	538.248
0.113	0.0401	31	0.0089	0.22606	130.1	426.728
0.142	0.0507	30	0.01	0.254	103.2	338.496
0.182	0.0647	29	0.0113	0.28702	81.83	268.4024
0.226	0.08	28	0.0126	0.32004	64.9	212.872
0.288	0.102	27	0.0142	0.36068	51.47	168.8216
0.361	0.128	26	0.0159	0.40386	40.81	133.8568
0.457	0.162	25	0.0179	0.45466	32.37	106.1736
0.577	0.205	24	0.0201	0.51054	25.67	84.1976
0.729	0.259	23	0.0226	0.57404	20.36	66.7808
0.92	0.327	22	0.0253	0.64516	16.14	52.9392
1.2	0.412	21	0.0285	0.7239	12.8	41.984
1.5	0.519	20	0.032	0.8128	10.15	33.292
1.8	0.653	19	0.0359	0.91186	8.051	26.40728
2.3	0.823	18	0.0403	1.02362	6.385	20.9428
2.9	1.04	17	0.0453	1.15062	5.064	16.60992
3.7	1.31	16	0.0508	1.29032	4.016	13.17248
4.7	1.65	15	0.0571	1.45034	3.184	10.44352
5.9	2.08	14	0.0641	1.62814	2.525	8.282
7.4	2.63	13	0.072	1.8288	2.003	6.56984
9.3	3.31	12	0.0808	2.05232	1.588	5.20864
12	4.17	11	0.0907	2.30378	1.26	4.1328
15	5.26	10	0.1019	2.58826	0.9989	3.276392
19	6.63	9	0.1144	2.90576	0.7921	2.598088
24	8.37	8	0.1285	3.2639	0.6282	2.060496
30	10.6	7	0.1443	3.66522	0.4982	1.634096
37	13.3	6	0.162	4.1148	0.3951	1.295928
47	16.8	5	0.1819	4.62026	0.3133	1.027624
60	21.1	4	0.2043	5.18922	0.2485	0.81508
75	26.7	3	0.2294	5.82676	0.197	0.64616
94	33.6	2	0.2576	6.54304	0.1563	0.512664
119	42.4	1	0.2893	7.34822	0.1239	0.406392
150	53.5	0 (1/0)	0.3249	8.25246	0.0983	0.322424
190	67.4	00 (2/0)	0.3648	9.26592	0.0779	0.255512

Ampacity (A)	Conductor cross section (mm^2)	AWG / KCMIL	Conductor Diameter (in.)	Conductor Diameter (mm)	Ohms (per 1,000 ft)	Ohms (per km)
239	84.9	000 (3/0)	0.4096	10.40384	0.0618	0.202704
302	107	0000 (4/0)	0.46	11.684	0.049	0.16072
357	126.7	250	-	-	-	-
428	152	300	-	-	-	-
499	177.3	350	-	-	-	-
571	202.7	400	-	-	-	-
714	253.4	500	-	-	-	-
856	304	600	-	-	-	-
999	354.7	700	-	-	-	-
1,070	380	750	-	-	-	-
1,142	405.4	800	-	-	-	-
1,284	456	900	-	-	-	-
1,427	506.7	1,000	-	-	-	-
1,784	633.4	1,250	-	-	-	-
2,141	760.1	1,500	-	-	-	-
2,497	886.7	1,750	-	-	-	-
2,854	1,013.4	2,000	-	-	-	-

Appendix F. Cost Curves for Substation Infrastructure and Equipment

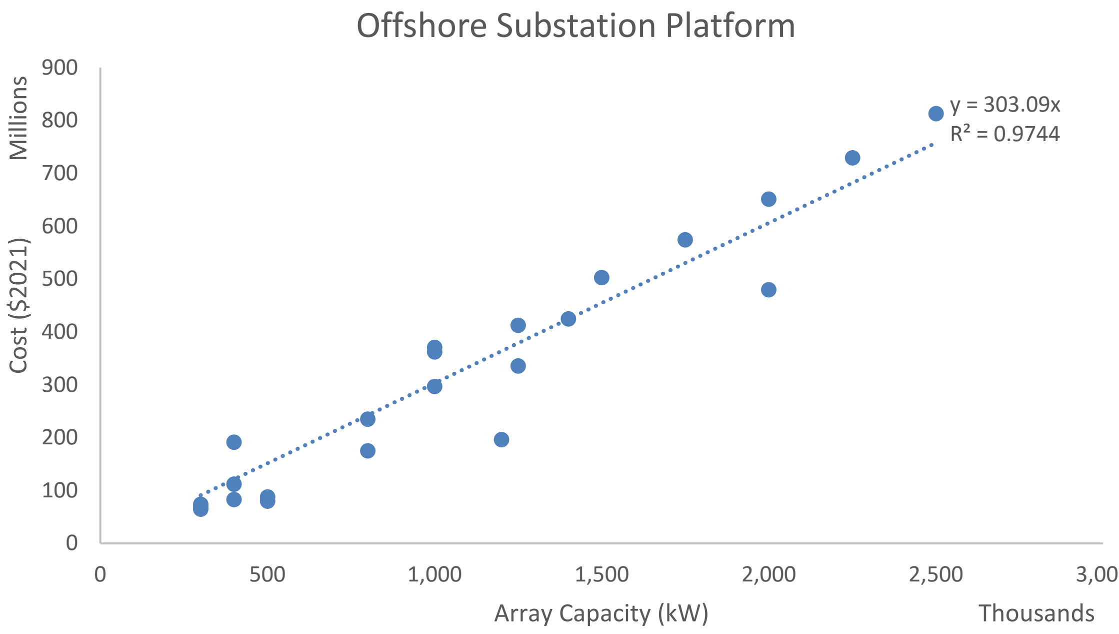

Figure F-1. Cost curve for offshore substation platform. Data from Regional Group North Sea (2011), Härtel et al. (2017), and Smart (2016).

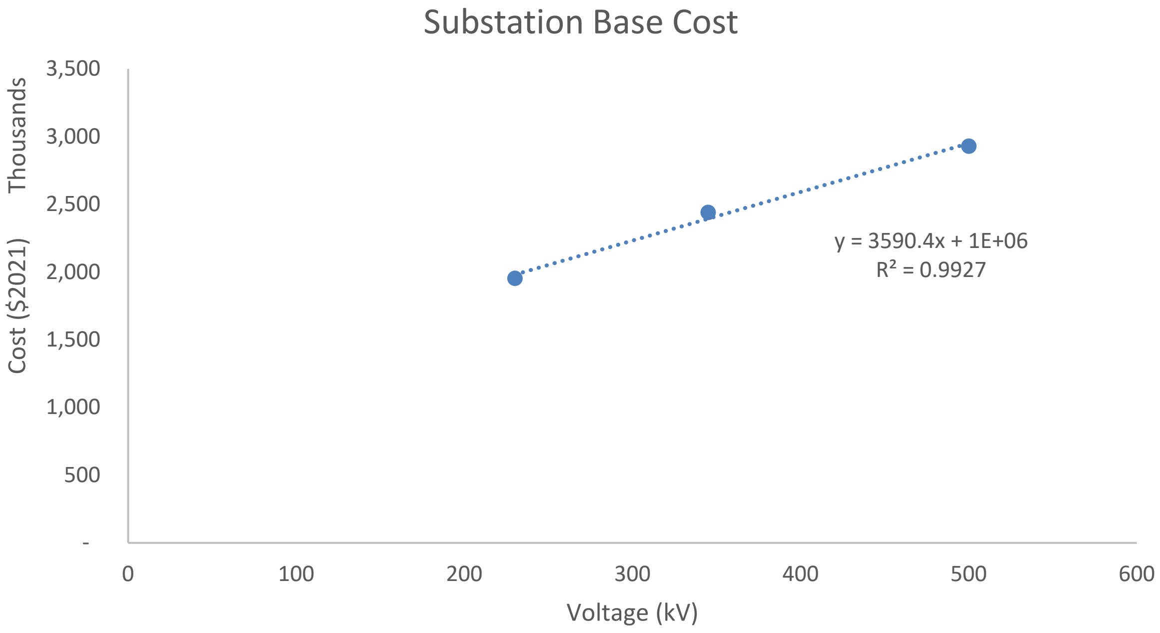

Figure F-2. Cost curve for substation base. Data from Pletka et al. (2014).

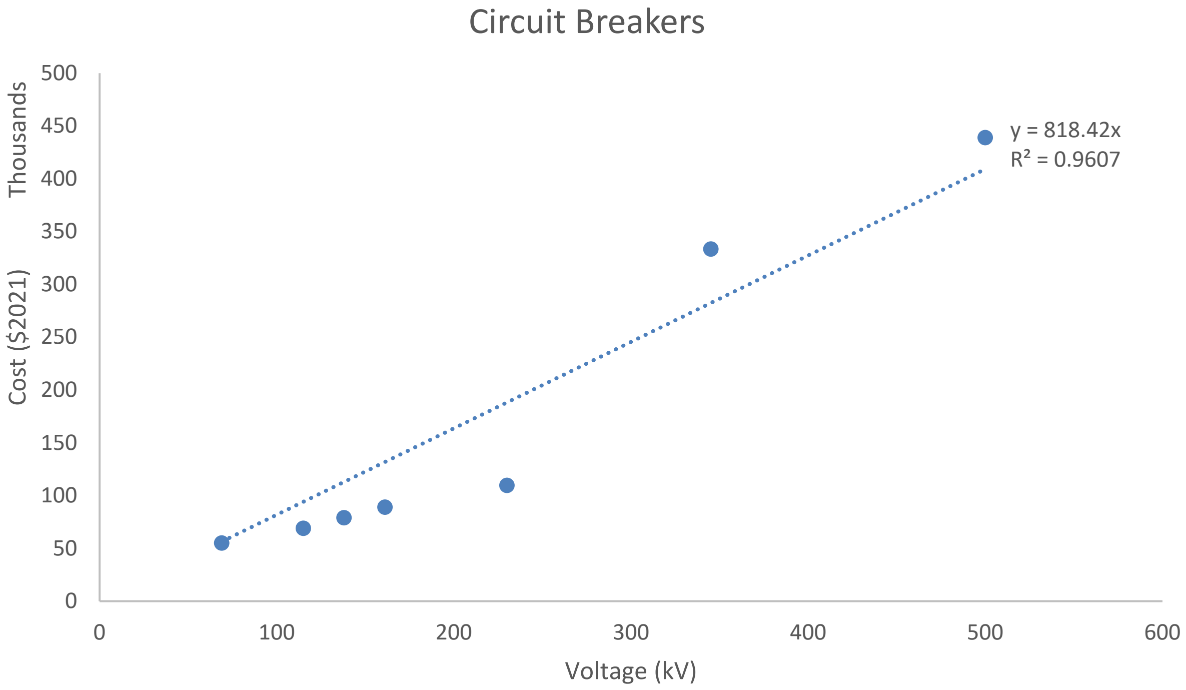

Figure F-3. Cost curve for circuit breakers. Data from MISO (2020).

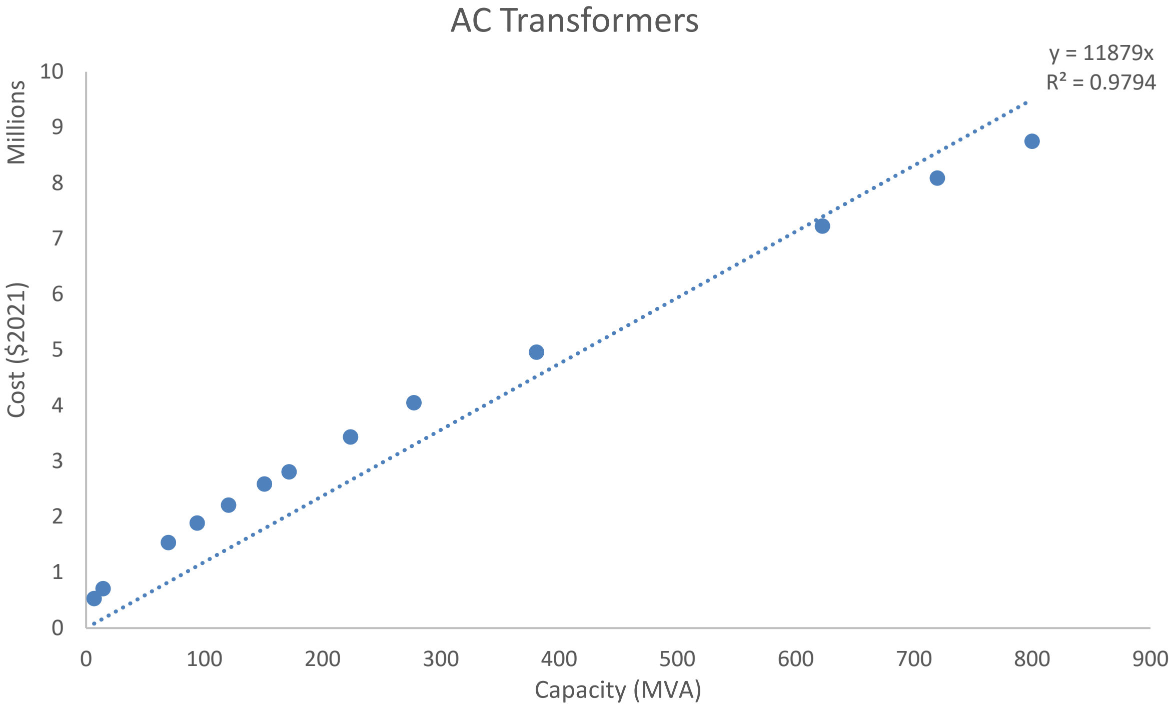

Figure F-4. Cost curve for AC transformers. Data from Lazaridis (2005).

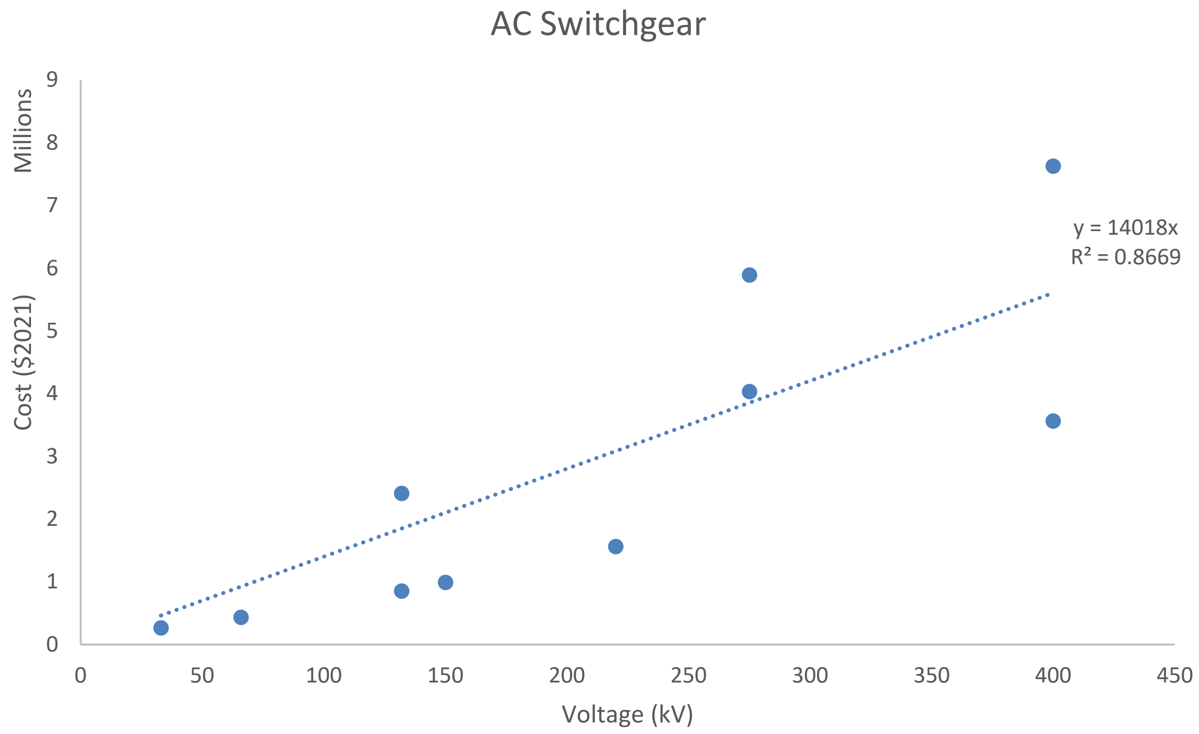

Figure F-5. Cost curve for AC switchgear. Data from Gaillard (2015) and Regional Group North Sea (2011).

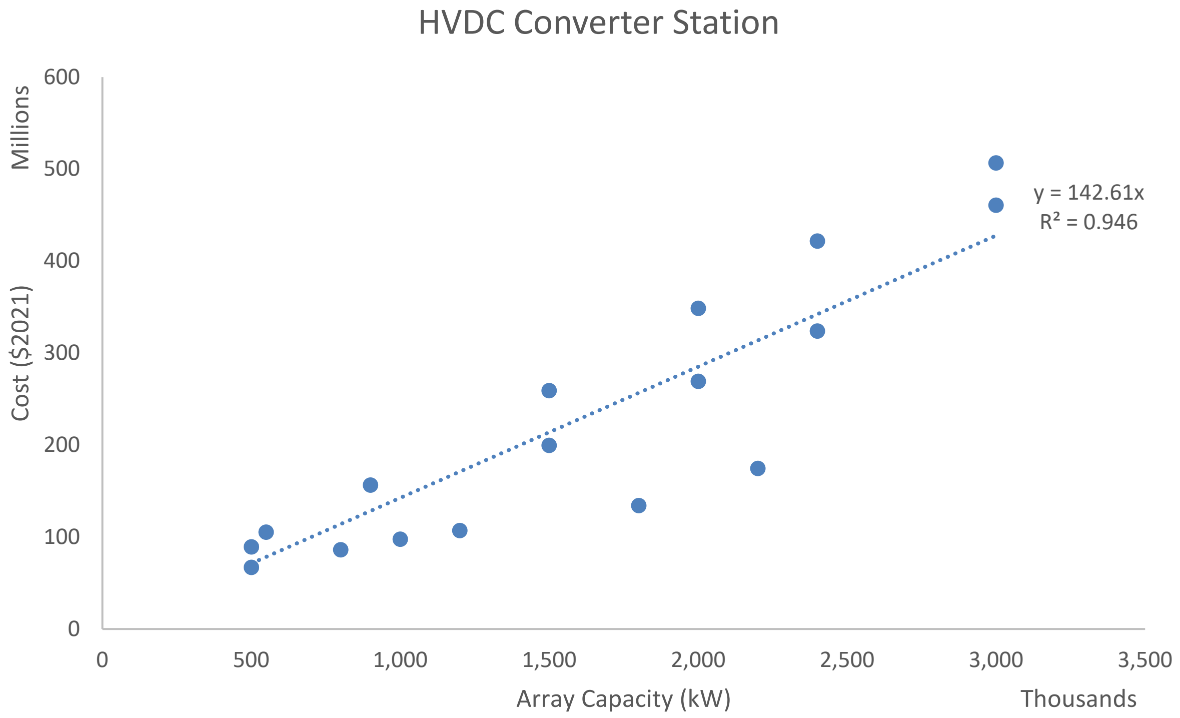

Figure F-6. Cost curve for HVDC converter station. Data from Härtel et al. (2017), Pletka et al. (2014), and MISO (2020).

Appendix G. Reactive Power Compensation Component Cost Data

Table G-1. Reactive Power Compensation Component Cost Data. Data from Elliott et al. (2016), Friday and Luckett (2016), MISO (2020), Pletka et al. (2014), and Regional Group North Sea (2011).

Shunt Reactor		Series Capacitor		Static Var Compensator	
Voltage (kV)	**Cost ($2021/MVAR)**	**Voltage (kV)**	**Cost ($2021/MVAR)**	**Voltage (kV)**	**Cost ($2021/MVAR)**
69	14,568	230	35,488	69	103,210
115	14,568	345	11,848	115	103,210
138	14,568	500	11,848	138	103,210
161	14,568	69	10,732	161	103,210
230	14,568	115	10,732	230	103,210
345	14,568	138	10,732	345	103,210
500	14,568	161	10,732	500	103,210
230	23,697	230	10,732	500	100,316
345	23,697	345	10,732	345	100,316
500	23,697	500	10,732	230	100,316
220	23,048	-	77,188	230	88,514
33	53,571	-	53,067	230	100,316
132	91,837			230	111,527
220	55,102			115	166,406
275	38,775			250	103,444
400	30,612			400	103,232
33	57,398			500	103,285
132	97,959			600	103,258
220	59,694			-	77,188
275	40,816			-	120,606
400	32,143				
13	20,975				
275	48,242				
400	22,191				
Average Cost:	**35,226**	**Average Cost:**	**22,047**	**Average Cost:**	**105,060**

Appendix H. Substation Cost Model

Table H-1. Substation Cost Model

OFFSHORE SUBSTATION			
Parameter	**Component**	**Description**	**Formula**
Foundation	Offshore Platform	Structure that provides a base for an offshore substation to be built on.	303.09 x (rated array capacity, kW)
AC Electrical Equipment	Circuit Breakers	Automatically operated protective device that stops flow of current in the case of a system overload.	818.42 x (substation voltage, kV)
	AC Switchgear	Equipment used to control, protect and disconnect the high voltage connection.	14,018 x (substation voltage, kV)
	Transformer	Equipment used to step up/down voltage of the power system.	11,879 x (export cable rated apparent power per array, MVA)
	Shunt Reactor	Equipment used to regulate voltage and reactive power flows to improve stability of the power system.	35,226 x (MVAR)
	Series Capacitor	Equipment used to regulate voltage and reactive power flows to improve stability of the power system.	22,047 x (MVAR)
	Static Var Compensator	Equipment used to regulate voltage and reactive power flows to improve stability of the power system.	105,060 x (MVAR)
DC Electrical Equipment	HVDC Converter Station	Typically includes: AC Transformer, AC filters, phase reactor, DC converter, DC capacitors, DC reactors)	142.61 x (rated array capacity, kW)
TOTAL COST	**Offshore AC Substation**	Transforms voltage from low to high (or reverse) to transmit power from one destination to another.	Foundation Cost ($) + AC Electrical Equipment Cost ($)
	Offshore HVDC Substation	Converts AC power to DC power for systems that use HVDC export cables.	Foundation Cost ($) + DC Electrical Equipment Cost ($)
ONSHORE SUBSTATION			
Parameter	**Component**	**Description**	**Formula**
Foundation	Base (New Substation)	New substation base cost, without any equipment.	6,533.1 x (substation voltage, kV)
AC Electrical Equipment	Circuit Breakers	Automatically operated protective device that stops flow of current in the case of a system overload.	818.42 x (substation voltage, kV)
	AC Switchgear	Equipment used to control, protect and disconnect the high voltage connection.	14,018 x (substation voltage, kV)
	Transformer	Equipment used to step up/down voltage of the power system.	11,879 x (export cable rated apparent power per array, MVA)
	Shunt Reactor	Equipment used to regulate voltage and reactive power flows to improve stability of the power system.	35,226 x (MVAR)
	Series Capacitor	Equipment used to regulate voltage and reactive power flows to improve stability of the power system.	22,047 x (MVAR)
	Static Var Compensator	Equipment used to regulate voltage and reactive power flows to improve stability of the power system.	105,060 x (MVAR)
DC Electrical Equipment	HVDC Converter Station	Typically includes: AC Transformer, AC filters, phase reactor, DC converter, DC capacitors, DC reactors)	142.61 x (rated array capacity, kW)
TOTAL COST	**Onshore AC Substation**	Transforms voltage from low to high (or reverse) to transmit power from one destination to another.	Foundation Cost ($) + AC Electrical Equipment Cost ($)
	Onshore HVDC Substation	Converts AC power to DC power for systems that use HVDC export cables.	Foundation Cost ($) + DC Electrical Equipment Cost ($)