Glosten

WSF MEDIUM VOLTAGE SHORE POWER

FEASIBILITY STUDY

PREPARED FOR

WASHINGTON STATE FERRIES
SEATTLE, WASHINGTON

8 February 2018
FILE NO. 17122.01
REV. –

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Revision History

Section	Rev	Description	Date	Approved
All	P0	Preliminary release for comment.	12/21/17	-
All	-	Initial Issue.	02/09/18	SAC

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Definition of Terms

Basic Charge: A basic charge is a recurring monthly charge that occurs regardless of energy usage. It is used to cover the costs of having an electricity supply.

Cab: An enclosed platform that interfaces between the Passenger Apron and the Passenger Transfer Span. The Cab is adjusted vertically to compensate for tidal changes.

Car Transfer Span: A moveable bridge that connects the Vehicle Apron to the fixed trestle roadway that extends from the shore. The vessel side of the Car Transfer Span is adjusted vertically by a fixed gantry structure to adjust for tidal changes.

Demand Charge: The demand charge is a measurement of the highest power level (kW) drawn from the grid in a given billing cycle. The higher the power, the higher the charge.

Minimum Charge: The minimum charge billed regardless of energy usage to cover the cost of having an electricity supply.

Passenger Apron: The adjustable ramp that spans the gap from the Cab to the vessel for boarding passengers. The passenger apron folds down from the Cab and rests on the passenger deck of the vessel. It is capable of rotating, extending (telescoping), and folding up/down. It rides up and down with the Cab to adjust for tidal changes.

Passenger Transfer Span: The passenger boarding walkway that connects the Cab to the shore.

Slip: The location and associated pilings, wing walls, etc. where the vessel docks during loading and unloading.

Vehicle Apron: An adjustable ramp that folds down from the Car Transfer Span and rests on the lower vehicle deck of the vessel to allow the loading/unloading of vehicles.

Wing Wall: An angled array of reinforced pilings on each side of the vessel end of the car transfer span designed to absorb vessel impacts and guide/center the vessel in the slip.

Executive Summary

Automated shore power connections for vehicle passenger ferries are an emerging technology that enable a ship to be connected to electric power from shore without human contact with the connection device or plug. These systems differ from manual shore power connections in that they do not require the time and process needed for a human to connect the ship to shoreside power manually, which takes at minimum thirty minutes.

With any emerging technology there are unique challenges. Tackling these issues requires close interaction between technology developers and the end users. This has proven true for the current installations of automated shore power systems in Norway and Finland described in this report. These initial pilot applications have been custom designed to accommodate specific voltage and power requirements, as well as terminal infrastructure constraints.

This investigation into automated shore power connections is part of a larger-scale project organized by Washington State Ferries (WSF) to determine the feasibility of converting the three Jumbo Mark II ferries to plug-in hybrids. These ferries primarily serve the Seattle/Bainbridge and Edmonds/Kingston routes. The terminals and vessels examined in this report are shown in the table below.

Table 1 Terminals and vessels

Terminals	Vessels
Colman Dock (Seattle)	M/V Tacoma
Bainbridge	M/V Wenatchee
Kingston	M/V Puyallup
Edmonds	

This report will examine the feasibility of the terminal infrastructure component of the plug-in hybrid conversion. Feasibility of the terminal infrastructure was divided into two sections: terminal-side power infrastructure and ship-to-shore interface. Each of these were assessed on technical feasibility and lifecycle cost. Figure 1 outlines this report's scope of work in the context of the total project scope for hybridizing the ferries.

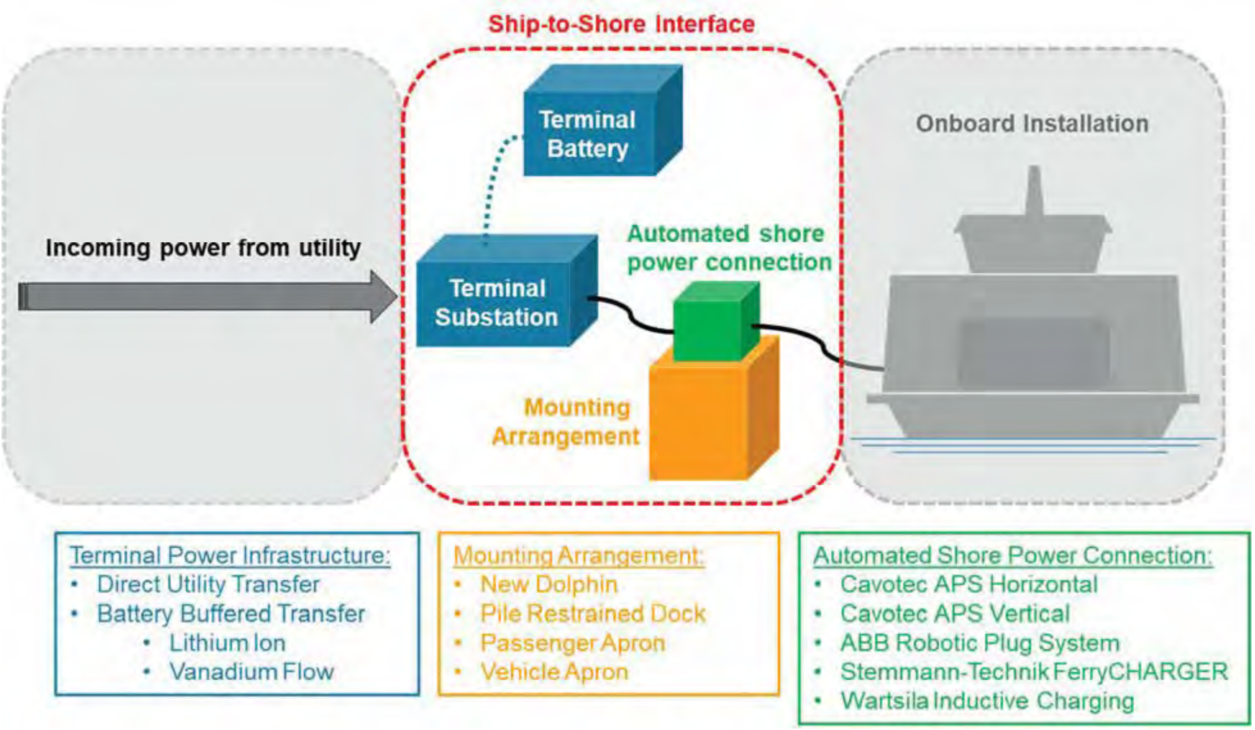


Figure 1 Scope of work diagram

Technical Feasibility

The technical feasibility of each power infrastructure arrangement and each automated shore power connection option is discussed in Section 5 of this report. For terminal power infrastructure options, the primary driver of technical feasibility was availability of real estate at the terminal. The following table outlines each terminal power infrastructure's size requirements and its availability at the terminals studied.

Table 2 Power transfer infrastructure arrangement - real estate requirements

Power Transfer Method	Real Estate Required (ft^2)	Terminal Availability
Direct Utility	720 ft^2 (fence)	Bainbridge, Kingston, Edmonds; Colman Dock not considered due to terminal modifications
	190 ft^2 (building)	
Battery Buffered Lithium-ion batteries	1830 ft^2 (fence + batteries)	Bainbridge, Kingston, Edmonds; Colman Dock not considered due to terminal modifications
	1065 ft^2 (building + batteries)	
Battery Buffered Vanadium-flow batteries	7180 ft^2 (fence + batteries)	Kingston. Other terminal not considered due to lack of space

Automated shore power connection technology was examined based on available "off-the-shelf" commercial solutions. Each technology was evaluated on several criteria. For this summary, the three areas with the most significant technical impact are presented in Table 3.

Table 3 Off-the-shelf compatibility assessment condensed summary

	Cavotec APS Horizontal	Cavotec APS Vertical	Stemmann Technik FerryCHARGER	ABB Robotic Plug System	Wartsila Inductive
Horizontal Reach	Poor	Poor	Poor	Poor	Poor
Vertical Displacement	Moderate	Good	Good	Poor	Poor
Technology Maturity	Prototype	Early Commercial	Early Commercial	Prototype	Early Commercial

Lifecycle Cost

The second element of the shoreside infrastructure assessment was a lifecycle cost analysis. The analysis was performed in accordance with the National Institute of Standards and Technology (NIST) Lifecycle Cost Estimating Manual. Each terminal was examined independently. A summary of costs, shown in Table 4, was developed for each primary power infrastructure arrangement and automated shore power technology option.

Table 4 Terminal power infrastructure lifecycle cost (in millions, 2017 dollars)

	Colman Dock		Bainbridge		Edmonds		Kingston		
	Li-Ion	Direct utility	Li-Ion	Direct utility	Li-Ion	Direct utility	Li-Ion	Vandium Flow	Direct utility
Cavotec APS-Horizontal									
CapEx	8.1	4.1	8.1	4.1	7.1	4.1	7.1	12.0	4.1
Lifecycle	43.2	35.3	33.8	30.4	18.3	16.5	17.2	21.3	14.1
Cavotec APS-Vertical									
CapEx	8.6	4.6	8.6	4.6	7.6	4.6	7.6	12.4	4.6
Lifecycle	43.9	36.0	34.5	31.1	19.0	17.2	17.9	22.0	14.8
Stemmann-Technik FerryCHARGER									
CapEx	8.8	4.8	8.8	4.8	7.8	4.8	7.8	12.6	4.8
Lifecycle	44.2	36.3	34.8	31.4	19.3	17.5	18.2	22.3	15.1
ABB Robotic Plug System									
CapEx	9.9	5.9	9.9	5.9	8.9	5.9	8.9	13.7	5.9
Lifecycle	45.8	37.9	36.4	33.0	20.9	19.1	19.8	23.9	16.7
Wartsila Inductive									
CapEx	12.6	8.6	12.6	8.6	11.6	8.6	11.6	16.5	8.6
Lifecycle	49.8	41.9	40.5	37.1	25.0	23.1	23.8	27.9	20.8
Median									
CapEx	**8.8**	**4.8**	**8.8**	**4.8**	**7.8**	**4.8**	**7.8**	**12.6**	**4.8**
Lifecycle	**44.2**	**36.3**	**34.8**	**31.4**	**19.3**	**17.5**	**18.2**	**22.3**	**15.1**

The lifecycle cost analysis indicated that for all terminals, a direct utility transfer solution (no battery buffering) was the least cost option for terminal power infrastructure. Three technologies were determined to be viable cost options: Cavotec APS-Horizontal, Cavotc APS-Vertical, and Stemmann-Technik's FerryCHARGER system.

Section 1 Introduction

This report is part of a large-scale project sponsored by Washington State Ferries (WSF) to determine the feasibility of converting the Jumbo Mark II ferries from diesel-fueled only to plug-in diesel-electric hybrids. The diesel-electric hybrid power plant will consist of a battery bank and diesel generators. The shipboard battery bank is intended to be sized such that the ferries can use battery power for main propulsion and ship service electrical loads (all non-propulsion electrical loads), with diesel generators as a backup system. The batteries will be charged from shore by a shore connection while the ferries are loading and unloading at the terminals.

Figure 2 shows the scope breakdown and major contributors to the project.

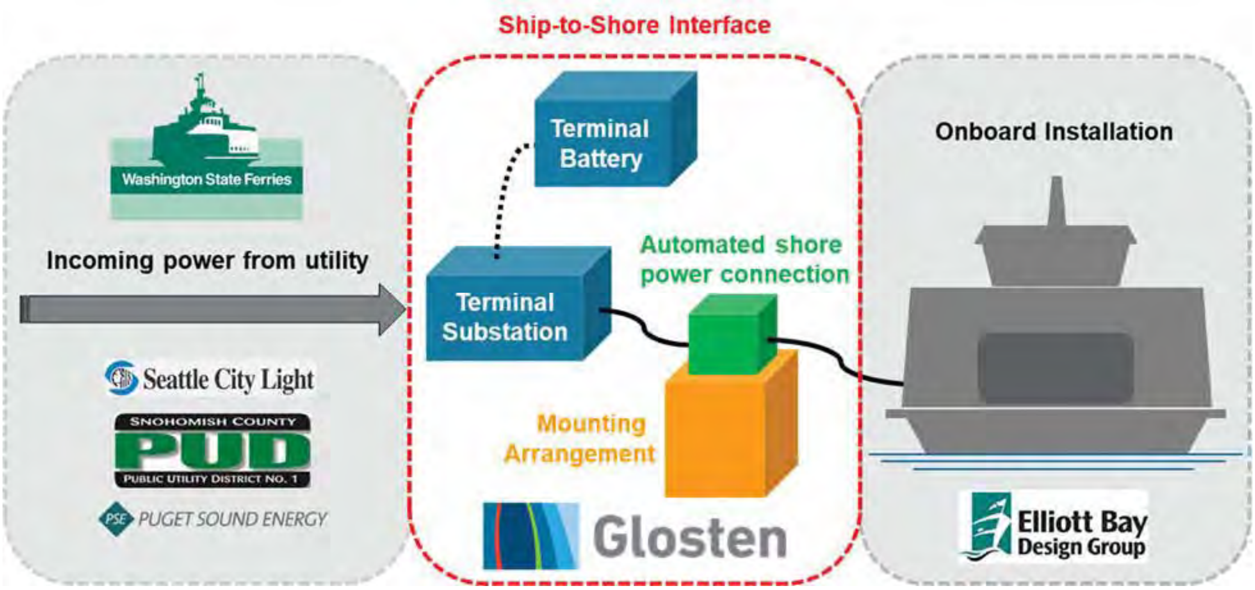


Figure 2 Scope illustration

WSF role was to work directly with the three electric utilities serving the terminals to determine the cost and other impact for brining the required power infrastructure to the terminal. Elliot Bay Design Group (EBDG) studied the impacts and costs of the onboard hybrid conversion. Glosten's contribution to the feasibility study focuses on the terminal infrastructure required to transfer electricity from the utility's electric meter to the electrical point of entry onboard the ferry. The scope of Glosten's effort includes:

- Survey of the state of art for automatic electric ship charging methods.
- Establishing design requirements regarding safety, vessel motions, tidal fluctuations and operational constraints.
- Estimating capital costs and lifecycle costs for the project.

1.1 Shore Power Applications

Shore power connections allow vessels to use electricity from the shoreside grid rather than their onboard diesel generators to power their onboard electric loads. Shore power systems have been installed for vessels such as cruise vessels and cargo ships, allowing them to shut down their onboard diesel-powered generators while in port. To date, these installations use manual connection methods where the physical electrical connect/disconnect process is undertaken by shoreside personnel, typically requiring at least 30 minutes to complete. Figure 3 shows a typical shore power connection for a containership.

Figure 3 Making a typical shore power connection (image from http://www.polb.com/environment/air/shorepower.asp)

In order to transmit the amount of power needed to support the electrical loads on the vessels, the connection typically consists of medium voltage (1kV – 35kV) electrical plugs. For safety reasons, several steps are in place to ensure that both the plug and receptacle do not have power to them while the physical connection is made. For vessels with longer port stays (12+ hours), the time taken to ensure personnel safety is a small portion of the port stay and outweighs the cost and complexity associated with an automatic connection.

More recently, electric ferries in Norway and Finland have been designed to operate completely on shipboard battery power instead of diesel engine power. The shore power connection for these vessels must provide power to recharge the batteries that power them while underway, in addition to powering the electrical loads onboard while they are docked at the terminal. As a result, the size of the shore power connection for these ferries tends to be relatively large compared to vessel size. To mitigate personnel dangers and increase connect/disconnect speed, these ferry operators have begun automating the process of connecting to shore power. Using a device rather than personnel to establish the shore power connection reduces the potential for exposing personnel to live conductors, and it reduces the time required to connect and disconnect from shore, which increases the amount of time that the vessel can be connected to shore power. This operation is similar to the application being explored by WSF, where the vessel is at the dock for less than 30 minutes.

Automated shore power solutions have a limited history, with installations dating back only a few years. Additionally, since much of the automated technology is still in various stages of development, the depth of information that is publicly available for disclosure within this report is limited. This report discusses five automated shore power systems, only two of which have actually been installed and operated.

Table 5 is a brief overview of installed automated shore power systems for fully electric and diesel-electric hybrid ferries. The Jumbo Mark IIs were added to this table to provide context for comparison.

Table 5 **Electric and hybrid ferries using automated shore power connections**

Year	2017	2015	2017	TBD
Vessel	M/F *Elektra* Hybrid diesel-electric by design	M/F *Ampere* Fully electric by design	M/F *Folgefonn* Hybrid diesel-electric by retrofit	Jumbo Mark II
Location	Finland	Norway	Norway	WA, USA
Cars/Passengers	90/0 (4)	120/360 (20)	76/300 (21)	218/2,500
One-way distance (miles)	1.0 (4)	3.5 (20)	1.4 (21)	8.6
One-way sail time (min)	8	20	10	28
Time at terminal (min)	7 (17)	10 (18)	5	20
Charging power (MW)	2 (22)	1.2 (22)	1.2 (21)	10
Charging technology	Cavotec APS Vertical	Cavotec APS Vertical	Wärtsilä-Inductive	TBD

Note: Reference numbers are denoted as superscripts.

Most of the technologies used in the automated shore power installations referenced above assume the vessel will dock parallel to the shore power equipment, as shown in Figure 4. As a result, most designs are focused on mitigating the horizontal and vertical static and dynamic motions of the vessel. For WSF, the ferry terminals are arranged such that the vessel can angle itself in the slip based on wind and weather conditions. This presents an additional design challenge not yet solved in any existing prototype or working commercial installations.

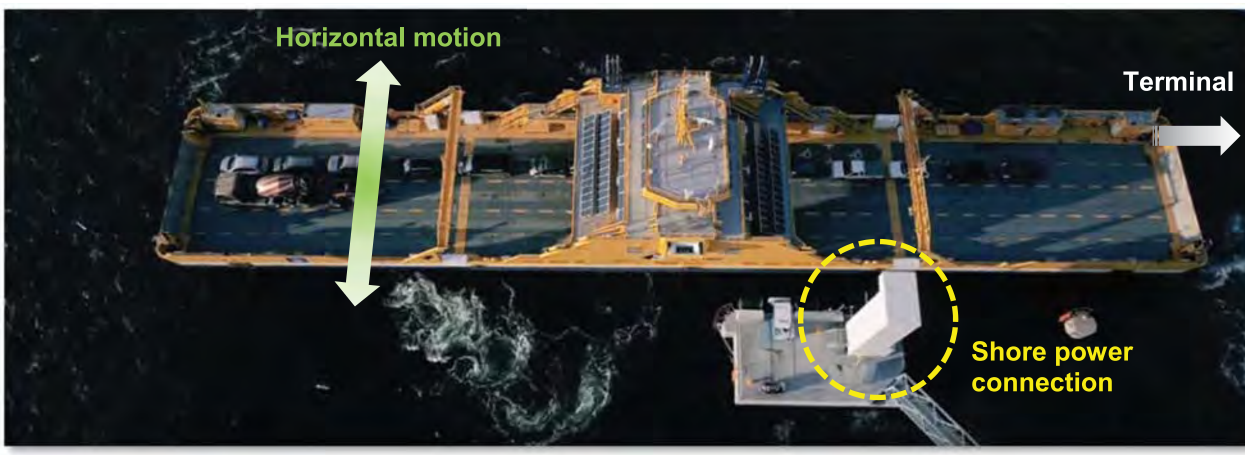


Figure 4 M/V *Elektra* leaving the dock at Parainen terminal, Finland (image from Siemens)

Section 2 Vessels and Terminals

The vessels and terminals examined in this report are the Jumbo Mark II vehicle-passenger ferries, and the terminals they serve: Seattle, Bainbridge, Kingston and Edmonds. The intent of this feasibility study is to determine technical solutions that are compatible with all terminals studied and to provide costs on a per terminal basis. Vessel conversion was not examined in this portion of the report, but some general information is provided in the following section. Each terminal and vessel/terminal interface was investigated to determine design criteria used to analyze technical feasibility. These criteria, in addition to project assumptions, are outlined in the following sections.

2.1 Vessels

This study considers the three WSF Jumbo Mark II vehicle-passenger ferries, the M/V *Puyallup*, M/V *Tacoma*, and M/V *Wenatchee*. The vessel principal particulars are listed in Table 6.

Table 6 Jumbo Mark II principal characteristics

Length overall, molded	460	ft
Breath overall, molded	89.83	ft
Depth of hull at side, molded	25.25	ft
Service speed	18	kts
Passengers	2,500	
Vehicles	202	

The Jumbo Mark II's existing propulsion plant consists of four diesel generators, which supply electrical power to the main propulsion motors, which in turn drive the propellers. Typically, three of the four generators are in use while the vessel is underway.

2.2 Terminals

The terminals examined in this study are those regularly serviced by the Jumbo Mark II ferries: Colman Dock, Bainbridge, Kingston, and Edmonds. It is assumed automated shore power need only be available at the primary slip at each terminal. The primary slip is the northmost slip at each terminal. Furthermore, it is assumed that the installation of automated shore power equipment will be in the same position with respect to the vessel at each terminal. This standardization of location will maximize compatibility between all vessels and terminals studied.

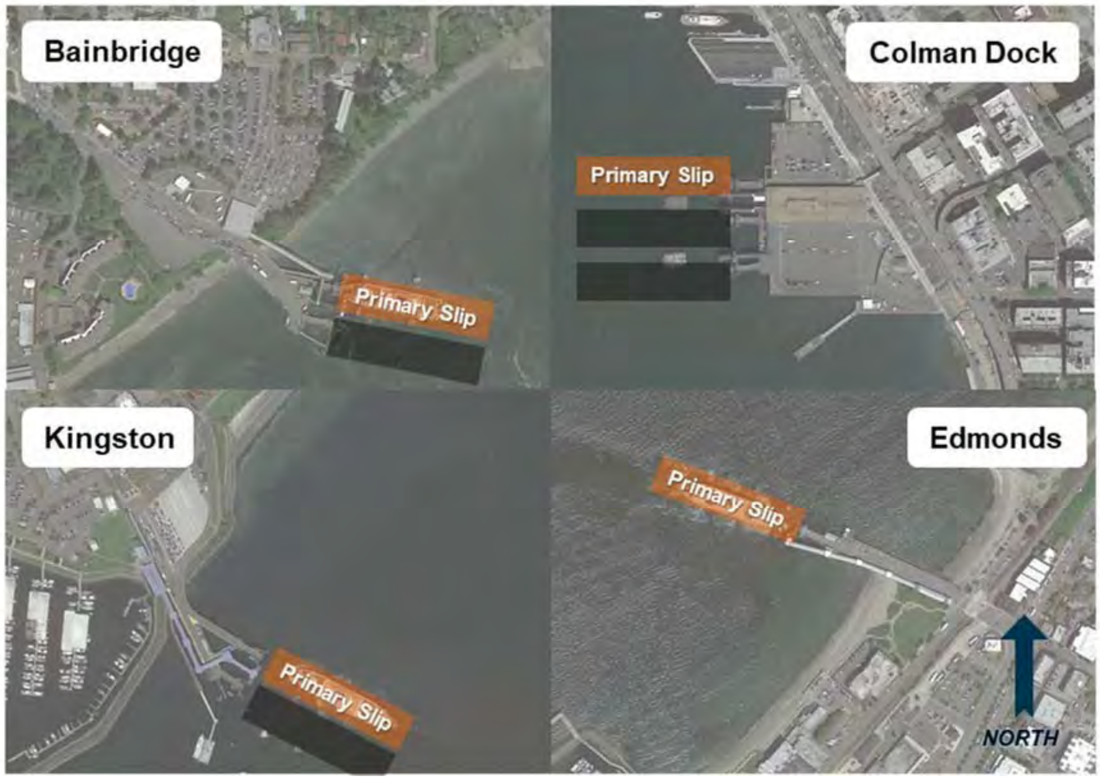


Figure 5 Terminal and slip overview (images from Google Earth)

2.3 Docking Considerations

A key functional requirement of the shore power connection device is the ability to automatically reach the vessel and align the electrical connection prior to completing the connection and initiating charging. The vessel's position relative to the shore connection will change as a function of the various environmental and operational conditions experienced at the time. In the horizontal plane (parallel to the water), the shore power connection device must be able to have an adequate reach to the vessel as well as the ability to compensate for different vessel angles to the dock. In the vertical plane (perpendicular to the water), the device must have adequate travel to compensate for changes in tidal conditions and vessel draft. These motions are considered "static," as they are relatively fixed during each period of time the vessel is connected to shore power. These static ranges of motions were analyzed for each terminal and shore power connection methodology; the results are outlined in the sections below.

2.3.1 Static Horizontal Displacement

Horizontal displacements between the device and the vessel include both a maximum reach, and a maximum angle.

For this analysis it was assumed that the vessel always touches the forward wing walls while at the dock. The resulting approach angle between the two vessel positions at each terminal is presented in Table 7. Colman Dock only has one docking arrangement at the primary slip, pushing against the southern breasting barge; as such there is no reported approach angle.

Table 7 Angular displacement per terminal

Terminal	Maximum Angle
Kingston	7.5°
Bainbridge	6.6°
Edmonds	9.6°
Colman Dock	n/a

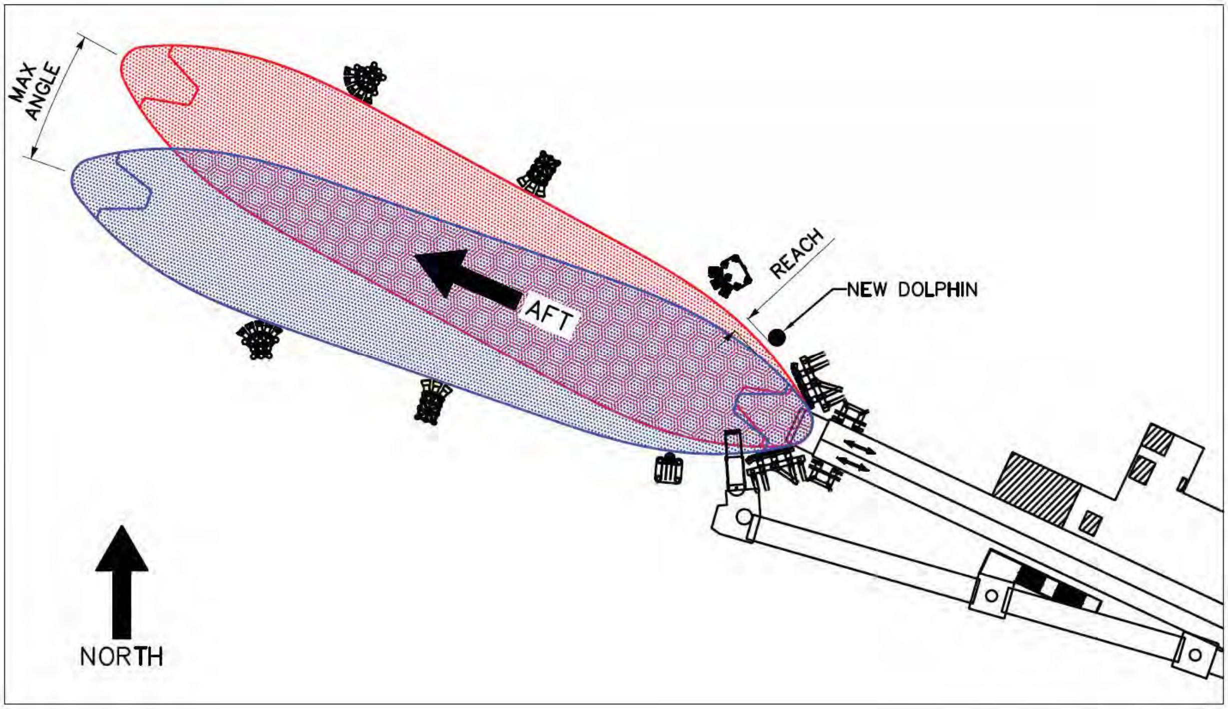


Figure 6 Edmonds terminal, passenger ramp angle calculation method

Reach, the distance between the mounting location and the vessel side, is dependent on the location of the terminal connection devices. The further away the device is placed from the terminal, the larger the required reach becomes due to the angle.

To provide an indication of order of magnitude of reach distance, we examined the maximum reach for a new dolphin mounted solution. The dolphin was positioned based on engineering judgement, at 4 ft from the vessel side at the north docking position. The reach values, reported in Table 8, indicate the minimum and maximum reach required to connect to the vessel in the south docking position. These values were used to broadly determine how each technology can accommodate reach.

Table 8 Estimated design reach per terminal

Terminal	Min	Max
Kingston	4'	9'
Bainbridge	4'	8'
Edmonds	4'	10'
Colman Dock	4'	n/a

2.3.2 Static Vertical Displacement

The static vertical displacement is a combination of vessel draft and tidal level. The design tidal range is 21 ft, which is the maximum value reported in Reference 27 for the terminals examined.

Tidal ranges for each terminal are reported in Table 9. Variations in vessel draft are assumed to be small relative to the tidal range and are not included in this study.

Table 9 Design tidal ranges (Reference 27)

Terminal	Minimum Tide (ft)	Maximum Tide[1] (ft)	Total (ft)
Kingston	-4.88	15.24	20.12
Bainbridge	-4.98	15.68	20.66
Edmonds	-4.83	15.10	19.93
Colman Dock	-4.88	15.68	20.56

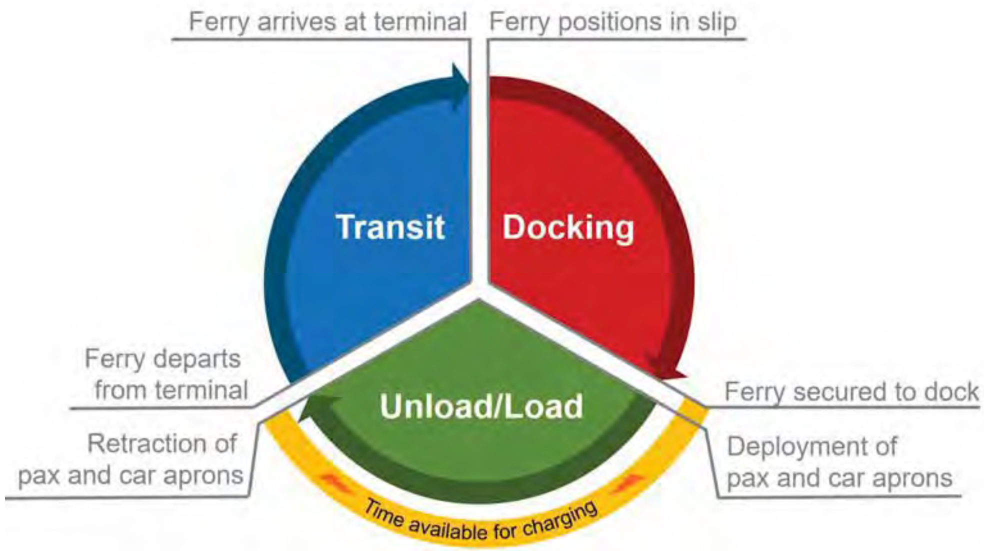
(1) Includes predicted sea level rise

2.3.3 Dynamic Motions

Normal docking operations occur in partially protected waters where the wind and wave forces are small. It is assumed that in case of extreme weather conditions, the vessel will not attempt to connect to shore power and instead will utilize its onboard diesel generator(s), some of which will be retained after conversion. Considering these factors, the likelihood of vessel dynamic motions falling outside of the operating limits of the technology analyzed in this study is low. As such, the effects of dynamic motions were not considered in this study.

Section 3 Operational Profile

The primary function of the Jumbo Mark II ferries is to move vehicles and passengers between terminals. To maintain operational efficiency within the fleet, passenger and vehicle unload/load operations have been standardized. There are three standard operational phases, which occur in a continuous cycle throughout the day: Transit, Docking, and Unload/Load. For the purposes of this report, the three phases are described in Figure 7.



Transit: The time in which the vessel has departed the dock and is underway.

Docking: The time in which the vessel has navigated to the desired docking position and is settling and securing to the dock.

Unload/Load: The time in which vehicles and passengers are being loaded and unloaded. The deployment and retraction of the passenger and vehicle apron mark the commencement and conclusion of this phase. During loading and unloading, the vessel uses its propellers to maintain docking position. This is referred to in this report as "pushing the dock."

Figure 7 Vessel operational phases

3.1 Time Available for Charging

The time available for charging the ferry's batteries is during the Unload/Load phase of the operation, which is calculated here as the difference between the estimated arrival time and the published departure time. Arrival times were estimated based on a 28-minute crossing time for Seattle-Bainbridge, as per WSF direction. Crossing times for Edmonds-Kingston runs were also provided by WSF.

Figure 8 shows the time at terminal for all daily trips on the published WSF Fall 2017 schedule by arrival terminal. A two-vessel schedule for both routes, Seattle-Bainbridge and Edmonds-Kingston, was assumed. Based on the Fall 2017 schedule and guidance from WSF, the total amount of time available for the entire charging operation was assumed to be 20 minutes.

About twenty percent of the Fall 2017 terminal visits are shorter than 20 minutes. According to the schedule, these instances occur in the early morning and late evening, as shown in Figure 9. If a vessel does not receive a full charge, the diesel generators will provide supplemental power once the ferry's batteries reach a predetermined lower limit state of charge. WSF has tentatively indicated that they intend to remove only two of the onboard diesel generators from each vessel, in which case it will be possible to supplement the battery power by running one of the remaining diesel generators during instances when battery power levels are drawn down more than can be replenished through charging.

The proposed charging profile is described in Section 3.2.

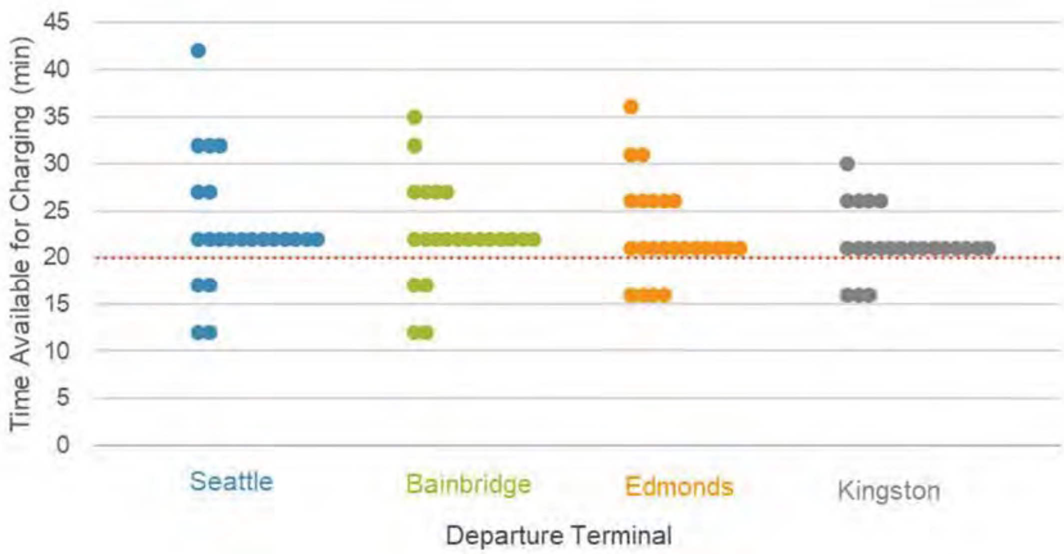


Figure 8 Number of terminal visits per day by time available for charging based on published Fall 2017 schedule

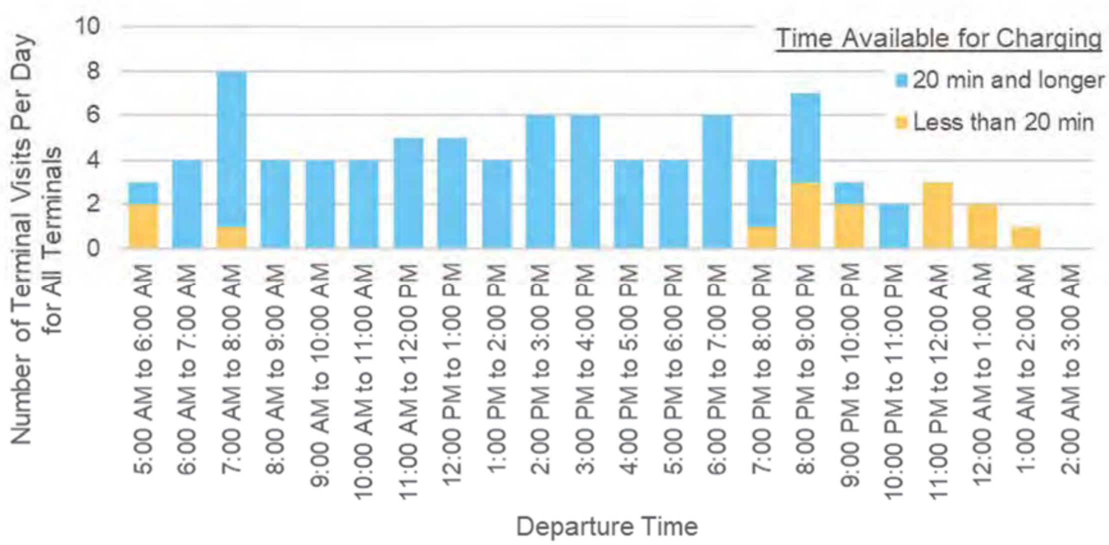


Figure 9 Number of terminal visits per day by time of day and time available for charging for all terminals based on published Fall 2017 schedule

Navigational data collected onboard the M/V *Tacoma* (Seattle-Bainbridge run) and the M/V *Puyallup* (Kingston-Edmonds run) was provided by WSF to show current transit and docking times for the month of September 2017. The data, provided in Appendix D and Appendix E, show a much greater variation in docking time than presented in Figure 8. There are a few methods of addressing this variation, which are outlined in the Table 10. For the remainder of this report, we will assuming a charging time of 20 minutes and a power as described in Section 3.3.

Table 10 Schedule variation mitigation method evaluation

Option	Benefits	Drawbacks
Modify schedule to allow for minimum of 20 minutes at dock	• Allows for single plug solution (shorter charging time may require two plugs) • Minimizes size/cost of charging and power infrastructure (shorter charge time requires larger equipment) • No change to Elliot Bay Design Group (EBDG) design fuel consumption and emissions, Reference 31	• Possible public relations issues
Increase utility power to allow full charge in a more limited time	• No change to EBDG design fuel consumptions and emissions, Reference 31	• Requires dual plug solution • May require modification to power infrastructure and technology
Run diesel generators to compensate for reduction in energy recovery	• Allows for single plug solution (shorter charging time may require two plugs) • Minimizes size/cost to charging and power infrastructure (shorter charge time requires larger equipment)	• Increased emissions and fuel consumption

3.2 Charging Profile

Charging a vessel's batteries involves several activities, all of which need to be accomplished in the design time available for charging, assumed here to be 20 minutes total. The assumed charging process is:

1. **1.5 min:** Mechanically *and* electrically connect vessel to shore power.
2. **1 min:** Ramp up to full charging power to reduce the strain on the utility grid.
3. **15 min:** Charge batteries at full charging power.
4. **1 min:** Ramp down to zero charging power to reduce the strain on the utility grid.
5. **1.5 min:** Mechanically *and* electrically disconnect vessel from shore power.

Out of a 20-minute window, these assumptions leave *15 minutes* for charging at full power. The charging profile is shown graphically in Figure 10.

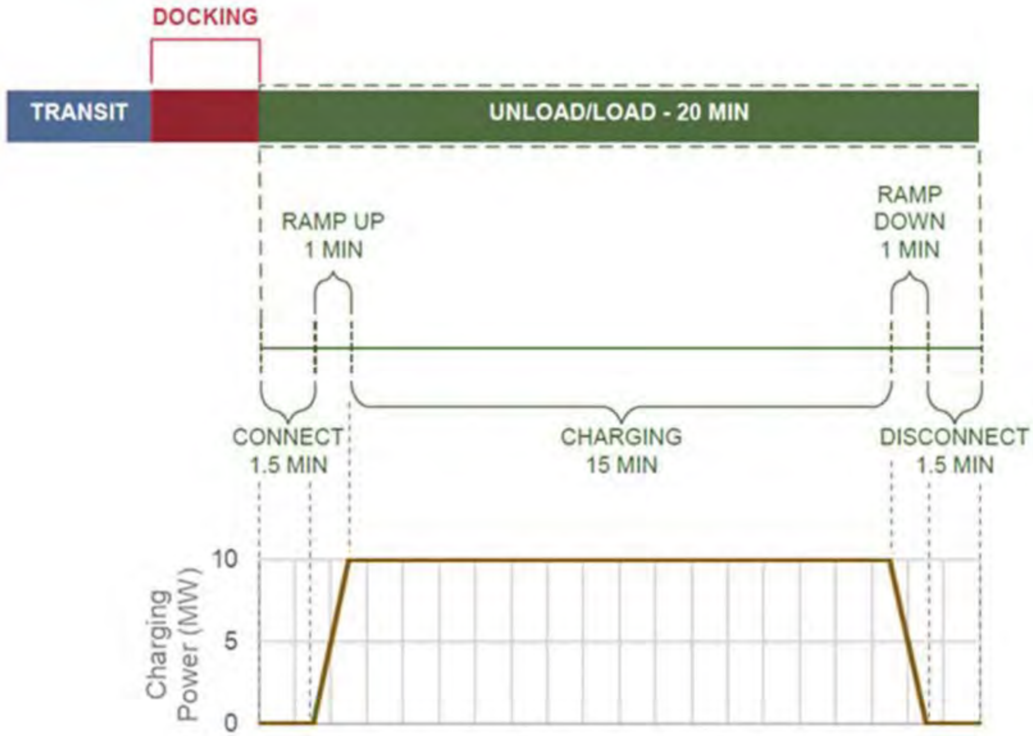


Figure 10 Charging profile

It is possible that some automatic shore power connection technologies may allow for initiating the shore power connection during the docking phase, which increases the available charging time. However, to provide the most conservative power requirements, a docking-phase connection is not considered in this study.

3.3 Power Requirements

The total power required to charge the vessel was calculated based on the current power usage during both the vessel's transit and docking, unloading, and loading at the terminal.

The design energy requirement is based on a typical transit from Bainbridge to Seattle, since the energy consumed on this route is greater than the energy consumed on the Edmonds-Kingston route. A one-way trip from Bainbridge to Seattle has an average energy consumption of 2,200 kWh, per WSF. The charging time at full power is 15 minutes, so the total power required for the transit is 2,200 kWh ÷ 0.25 hrs, or 8,800 kW.

The power required while at the dock was estimated to be 400 kW for the ship service load and 800 kW for pushing the dock.

This yields a total of ten megawatts required to replace the energy consumed during transit as well as to supply power while the ferry is at the dock. This is depicted in Figure 11 and summarized in Table 11 below.

Table 11 Power summary

Power Demand	Route: Seattle-Bainbridge	Route: Edmonds – Kingston
Crossing energy/charge time (kW)	8,800	6,400
Ship service load (kW)	400	400
Pushing the dock (kW)	800	800
Total required power (kW)	10,000	7,600

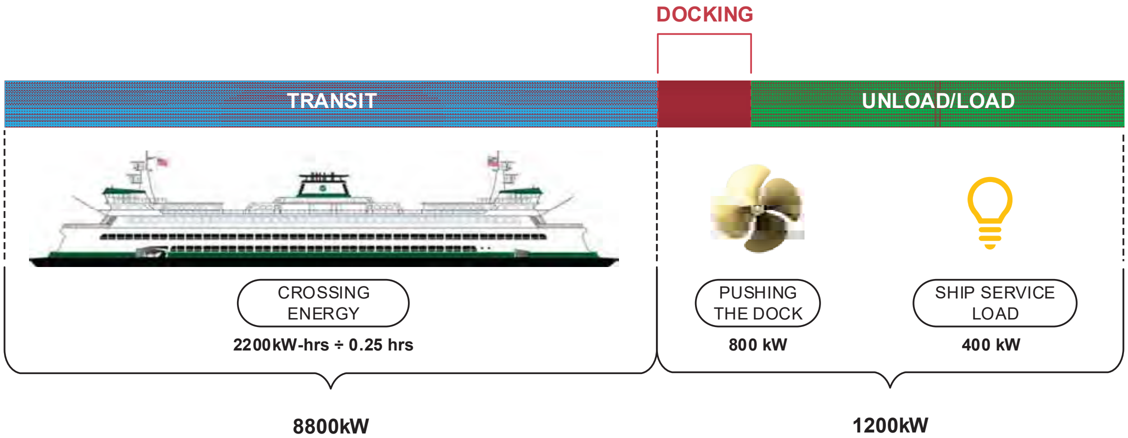


Figure 11 Seattle – Bainbridge Power calculation

Section 4 Ship-to-Shore Interface

Ship-to-shore interface is defined as the equipment and methods used to transfer power from the utility to the vessel. For this section, we have broken down the equipment requirements into four discussion sections:

- power (incoming utility power and power transfer method);
- terminal power infrastructure;
- automated connection technology;
- technology mounting arrangement.

These components are outlined in Figure 12.

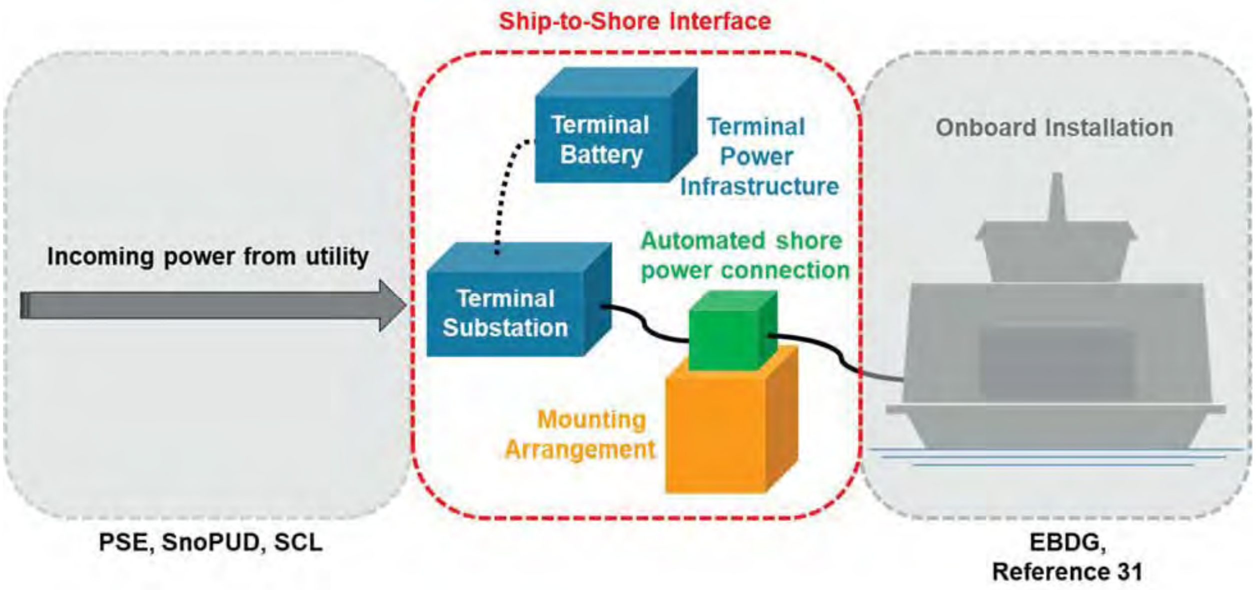


Figure 12 Terminal infrastructure components

4.1 Power

4.1.1 Incoming Power

Incoming power is considered in detail in a study undertaken by PSE, SnoPUD, and SCL as a separate component of the overall WSF study; for purposes of this report, only incoming voltages are considered. Table 12 lists the electrical power available at each terminal, as indicated by the local utility companies.

Table 12 Available utility power (provided by WSF)

Terminal	Utility	Voltage (kV)	Power Available (MW)
Colman Dock	Seattle City Light	26.0	10+
Bainbridge	Puget Sound Energy	12.4	10
Edmonds	Snohomish County PUD	12.4	10, with new substation
Kingston	Puget Sound Energy	12.4	10

Since three of the four terminals have power available at 12.4kV, this was chosen as the supply voltage to eliminate the need for a transformer at those locations. Colman Dock will require a transformer to step down the 26kV utility voltage to the design 12.4kV.

The vessel propulsion system and the batteries will be at a lower voltage than the incoming shore power. Voltage step down, isolation, and power conversion will occur onboard the vessel as needed, after the power is transferred from shore. To accommodate 10 MW of power, the electrical current at 12.4kV is approximately 465 Amps. The power can be transferred through a single standard, commercially available, 500-Amp shore power plug.

4.1.2 Power Transfer Method

Two methods of power transfer from utility meter to the automated shore power connection were considered for this application: direct utility transfer and battery-buffered transfer. Direct utility transfer is the direct transfer of power from the utility to the automated shore power connection. For battery-buffered transfer, the incoming utility power is transformed to a lower voltage and used to charge a terminal battery bank, which is used to charge the vessel. Power from the batteries may be supplemented with utility power, as needed, when the vessel is connected to shore power. The two methods are compared in Table 13 and discussed in greater detail in the following sections.

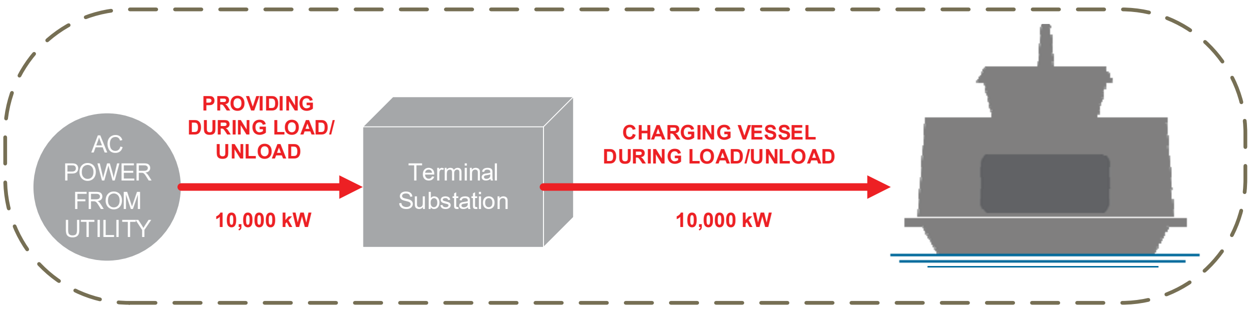


Figure 13 10MW direct utility transfer power flow

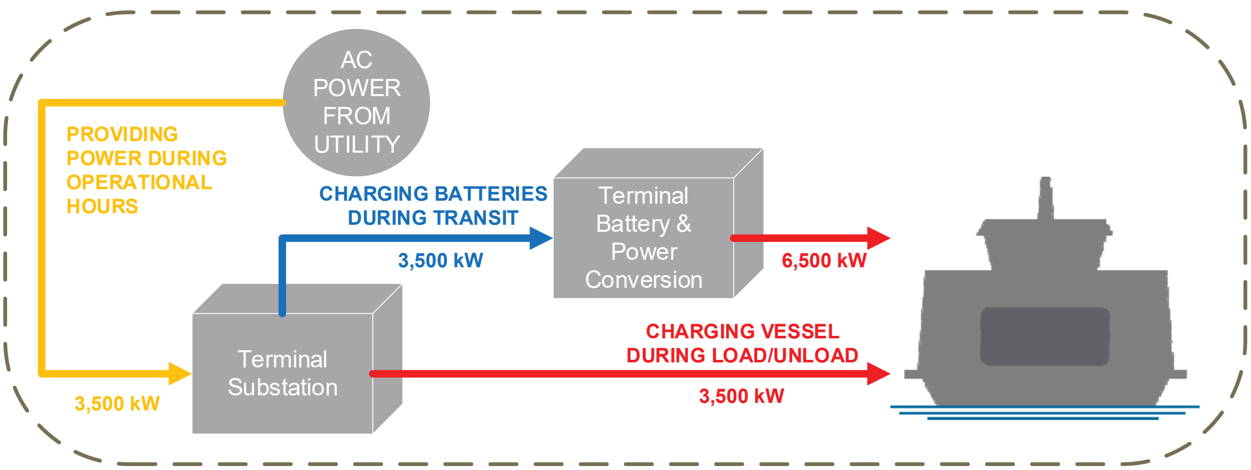


Figure 14 10MW battery buffered transfer power flow

Table 13 Comparison of power transfer methods

	Power Transfer Method	
	Direct Utility Transfer	Battery-buffered Transfer
Required terminal footprint	~720 ft^2	Greater than 720 ft^2
Utility demand	Periodic high demand	Steady
Efficiency	Greater than 98% efficient[1]	~85-90% efficient[2]

1. Assuming no step-down transformer (true for all terminals except Colman Dock)
2. Assuming AC/DC/AC power conversion and voltage transformers (step-down/up)

4.1.2.1 Direct Utility Transfer

Direct utility transfer requires a terminal substation. In this method of power transfer, the terminal substation equipment consists of disconnects, circuit protection, and power and safety monitoring equipment.

The primary disadvantage of direct utility transfer is that all the power required to charge the vessel is supplied by the utility during the time the vessel is loading/unloading and connected to the charging system. This results in a cyclical high-power demand, which increases the utility's monthly demand charge. Monthly demand charges are calculated as rate ($/kW) multiplied by the peak demand of the month; consequently, the higher the peak demand, the higher the demand charge. The monthly demand charge is in addition to the cost of electricity ($/kWh).

4.1.2.2 Battery-buffered Transfer

Battery-buffered transfer requires a significant amount of additional equipment beyond a terminal substation and batteries. Since batteries operate on direct current (DC) and at a much lower voltage than the utility power, this solution will require power conversion equipment (inverters and rectifiers) to convert the AC power to DC and then back to AC. It will also require transformers to step the voltage down to the level needed for the batteries, then back up to 12.4kV for transfer to the vessel. Various other equipment items will also be needed, such as switchgear, disconnects, circuit protection, and power and safety monitoring equipment. All of this equipment adds cost, requires space, and results in a large loss of efficiency (~10-15%).

One advantage of the battery-buffered transfer method is the elimination of cyclical, high-power demand required by direct utility transfer. The batteries flatten out the demand on the utility power and reduce the demand charges imposed by the utilities. The battery buffered solution also allows a smaller power connection from the utility, which could be an advantage for some applications.

4.2 Terminal Power Infrastructure

4.2.1 Terminal Substation

For both the direct utility transfer and battery-buffered transfer methods, an electrical equipment enclosure, a power meter, and switchgear are required at each terminal.

The electrical equipment is estimated to have a 65-inch by 100-inch (45 ft^2) footprint. The enclosure will be required to have a safety perimeter installed to satisfy regulations. The safety perimeter can be a fence or an enclosed building. A fence requires a 10-foot clear setback on all sides and implies that the equipment will not be protected by an enclosed building. An enclosed building safety perimeter allows the equipment to be installed against one wall, with a 5-foot clear setback from the other three walls. Diagrams of the fence and enclosed building footprints are shown in Figure 15.

All equipment within the safety perimeter, and the safety perimeter itself, will be referred to herein as the "terminal substation."

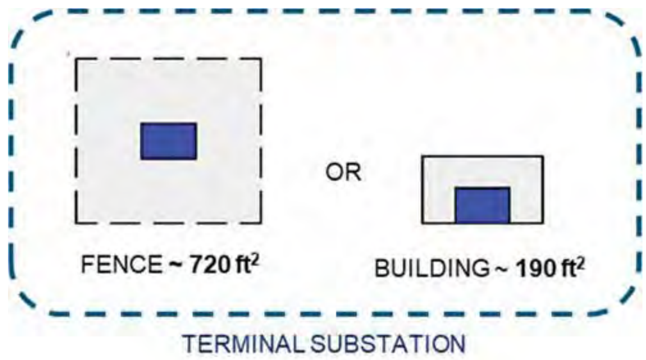


Figure 15 Terminal substation footprints

Although both safety perimeters are acceptable, the building containment option allows for a significant reduction in required space. Where not constrained by space limitations, the fence solution is more common due to its lower cost of installation.

The described containments apply to all terminals except Colman Dock. Colman Dock will require a step-down transformer to reduce the incoming voltage to the 12.4 kV design transfer voltage. This will add approximately 250 ft^2 of additional space.

4.2.2 Terminal Battery

For the battery-buffered transfer, a terminal battery bank is required. Batteries are typically optimized for either power *or* energy. Power batteries are optimized to discharge power very quickly where electrical loads are high and the discharge time is limited. Energy batteries are optimized to store electrical energy efficiently and are less efficient when power is discharged too quickly. The required footprint of the battery bank is highly dependent on battery type. For this study a power battery and energy battery were examined: lithium-ion and vanadium-flow batteries, respectively.

4.2.2.1 Lithium-ion Batteries

Lithium-ion batteries are the most common battery used in power applications, for example in electric vehicles. There are a variety of battery chemistries in the lithium-ion battery family. Table 14, adapted from Reference 28, describes the various types of lithium-ion battery chemistries and their applications. Lithium-ion batteries can be designed as either power or energy batteries.

Table 14 Lithium-ion battery chemistries

Type	Battery Chemistry	Typical Uses	Example Applications
NCA	Nickel cobalt aluminum	Cars	Toyota Prius plug-in hybrid, Tesla
NMC	Nickel manganese cobalt oxide	Stationary energy storage systems, consumer goods, cars, and buses	Nissan Leaf, Chevrolet Bolt, Proterra, New Flyer, Tesla Grid Storage
LMO	Lithium manganese oxide	Cars	Nissan Leaf
LTO	Lithium titanate	Cars and buses	Honda Fit, Proterra
LFP	Lithium iron phosphate	Stationary energy storage systems, cars, buses, trucks	BYD, TransPower, Siemens, Nova Bus, Volvo

It is assumed that the lithium-ion batteries would be housed in an enclosed building with a 540-square foot footprint, as shown in Figure 16. Transformers and power conversion equipment are required to convert the utility AC voltage to the DC battery voltage, and then from the DC battery voltage to AC transfer voltage. This equipment would be housed in the same containment as the terminal substation equipment.

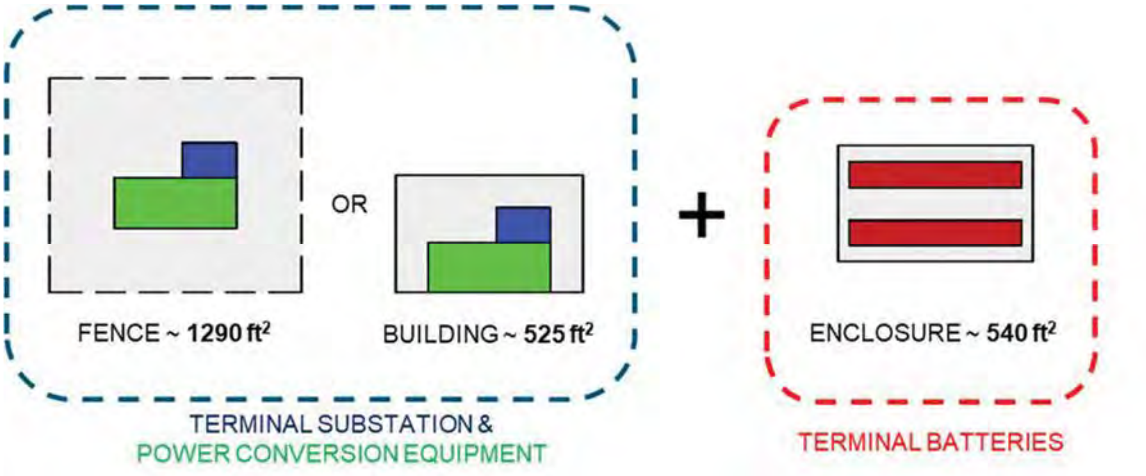


Figure 16 Terminal lithium-ion battery, substation, and power conversion equipment footprint

Estimates of the lithium-ion battery buffers at each terminal were developed by creating a battery operating profile from the Fall 2017 sailing schedule at each terminal and the energy required to recharge the ferry during each docking. These operating profiles assume a steady power demand from the utility and a cycling state of charge on the battery. The profiles were optimized to minimize the power demand while maintaining the battery state of charge within a relatively constant band throughout the day. The battery operating profiles were provided to Spear Power Systems (Spear), who sized the battery system for each terminal to provide a 6-year service life. At the end of the service life, battery replacement is required. Battery buffer sizes estimated by Spear are shown in Table 15. Sample battery profiles are provided in Appendix C.

Table 15 Battery buffer size estimate for lithium-ion batteries

Terminal	Battery Type	Service Life (years)	Energy (kWh)	Incoming power[1] (kW)
Kingston	NMC	6	3,979	1,350
Bainbridge	NMC	6	5,223	3,100
Edmonds	NMC	6	3,979	1,350
Colman Dock	NMC	6	5,223	3,100

1. Incoming steady power available (demanded) from the utility after power conversion losses of the battery power systems (90% efficiency)

4.2.2.2 Vanadium-flow Batteries

Vanadium-flow batteries are typically used in energy storage applications, such as large-scale utility substations. These installations typically have slow discharge rates, ranging from 2 to 8 hours, and are less subject to space constraints.

Each vanadium-flow battery string is comprised of power conversion equipment and four 20-foot standard battery containers, as shown in Figure 17. Typically, two strings are installed facing one another. To reduce footprint, strings can be stacked, increasing the height of the battery bank from 9.5’ to 19’. Because these batteries are typically much larger than lithium-ion batteries, it was determined that Kingston is the only location that may have enough space for this equipment. Figure 18 shows the footprint requirements for Kingston Terminal, which would utilize 9 strings, double stacked.

Figure 17 Uni Energy Technology (UET) vanadium flow battery string

String and footprint requirements for each terminal are outlined in Table 16.

Table 16 Space requirements for vanadium-flow batteries

Terminal	Required Number of Strings	Required Footprint (acres)	Required Footprint (ft^2)
Colman Dock (Seattle)	11	0.21	9,150
Bainbridge	11	0.21	9,150
Edmonds	9	0.17	7,410
Kingston	9	0.17	7,410

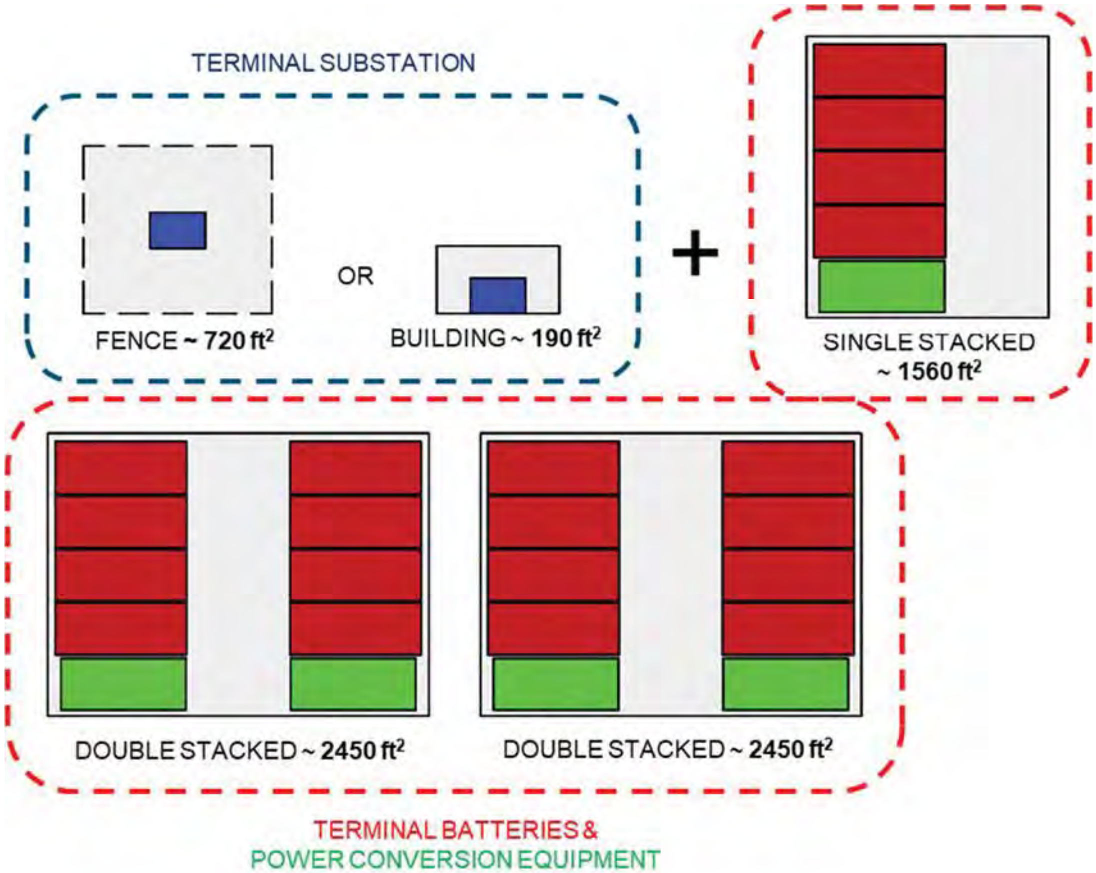


Figure 18 Vanadium flow battery, terminal substation and power conversion equipment footprint

Vanadium flow batteries, such as those provided by UniEnergy Technology (UET), have several advantages over lithium-ion batteries. The batteries are capable of an enormous number of full charge-discharge cycles with almost no degradation. UET estimates that the batteries would have a 20-year life in this application. Another advantage is that the batteries are very good at storing large amounts of energy. A lithium-ion battery capable of storing a comparable amount of energy would likely be much more expensive. Finally, the batteries are able to charge and discharge to 100% of rated capacity without harming the batteries. Lithium-ion batteries for similar applications of energy storage would be designed to use only a fraction of their rated capacity, because repeated deep-discharge cycles shorten their life.

However, for this application it is not necessary to store large amounts of energy relative to the amount of power required. Therefore, the vanadium flow battery was determined to be a mismatch for this application.

4.3 Automated Shore Power Connection Technologies

Various automated shore power technologies are commercially available and at various stages of deployment and development. A survey of available technologies was performed and is summarized below.

4.3.1 Cavotec Automated Plug-in System (APS) - Vertical

The Cavotec APS-Vertical system is a tower that allows for the descent of a large plug into a shipboard receptacle, as shown in Figure 19. Plug height is controlled by a cable winch that automatically adjusts for tide levels. The plug's distance from the ship is controlled by a linearly actuating arm at the top of the tower. The shipside receptacle is housed within a custom hatch affixed to the side of the ship's hull that, when moored, opens to allow the plug to drop inside and connect, as shown in Figure 20. After the ship is secured at the dock, the connection is made, and charging begins in less than one minute. The power supply of the vertical APS system can be varied to meet design requirements.

There are two existing installations of the Cavotec APS-Vertical system, one in Finland on the M/V *Ampere*, and the most recent in Norway on the M/V *Elektra*.

Figure 19 Cavotec APS-Vertical shown without housing (left) and with housing (right)

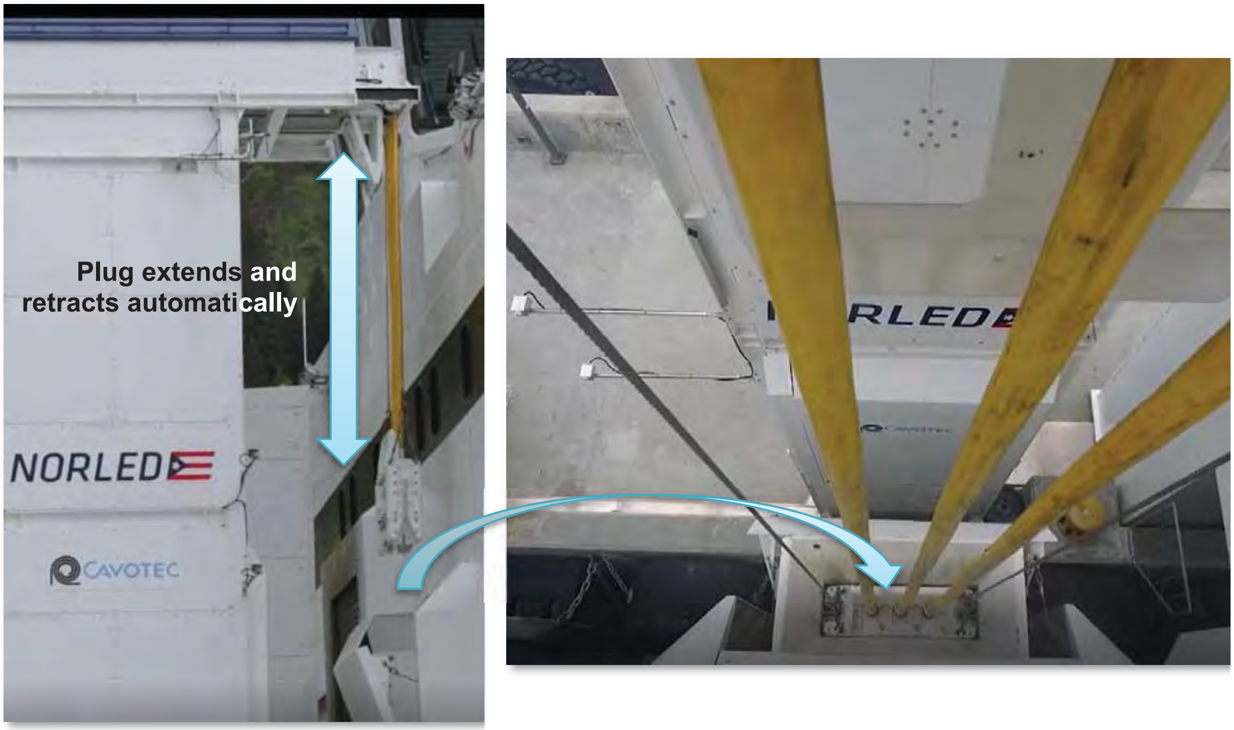


Figure 20 Cavotec APS-Vertical system plug mating with onboard receptacle

4.3.2 Cavotec APS – Horizontal

Cavotec is developing a new type of APS that operates in a horizontal orientation. The system is still in development and currently has no operable installations. Information on this system is not publicly available but some information was provided to Glosten under protection of a non-disclosure agreement (NDA).

Cavotec APS-Horizontal is an automated system capable of high-power (multi-megawatt) transfer and is composed of a plug and receptacle. The system can compensate for static changes in vertical displacements due to tides or draft, static horizontal displacements, and angular alignment. It has a small form factor and offers a cable connection between the shore and the vessel.

The plug and receptacle are commercially available, off-the-shelf components. Based on preliminary evaluation, this solution is considered a low risk regarding regulatory approval.

4.3.3 ABB Robotic Plug System

ABB's shore connection technology is centered around the IRB 7600, a fully autonomous robotic arm first manufactured in 2001. The shore-mounted arm has many degrees of freedom, giving it a large sphere of functionality in all directions. The arm uses laser guidance to find the receptacle on the vessel. To account for tidal variation, the existing design has both low and high receptacles on the vessel, thereby limiting the vertical reach that would be required by the arm. Figure 21 shows the system under construction for HH Ferries.

A pilot installation was completed in 2016 for the ferries M/F *Aurora* and M/F *Tycho Brahe*. However, the system is still being fine-tuned and commissioned, and no new information regarding functionality of the system or operation of the converted ferries has been made publicly available in the last few months.

The technology is based on proven industrial robotic technology and conventional high-power plugs. The technology holds great promise, but there is no operational history in a marine application.

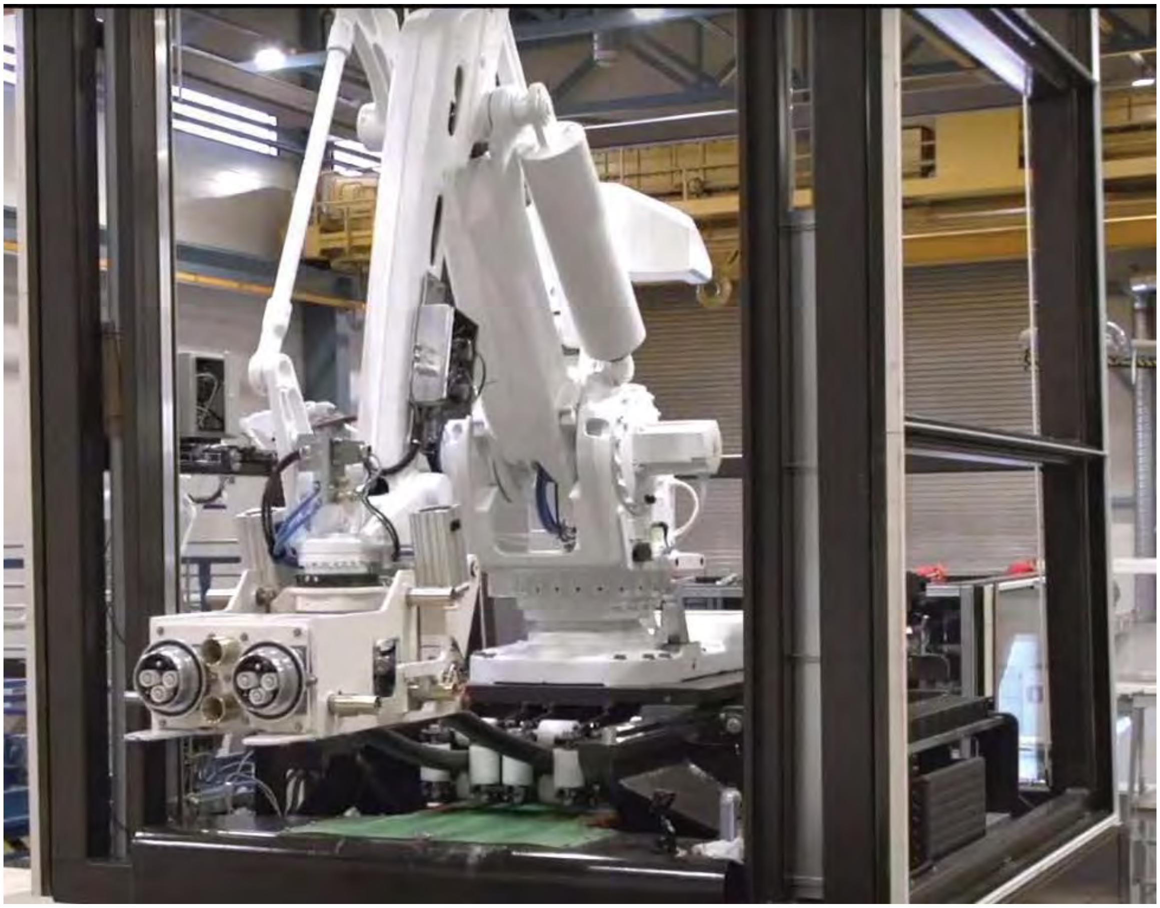


Figure 21 ABB Robotic Plug System under construction for HH ferries (Reference 26)

4.3.4 Wärtsilä Inductive Charging

Inductive charging is a wireless charging technology that does not require physical contact between the device and the vessel. This technology works by placing two electrical coils close enough together for an electromagnetic field generated in one coil to transfer energy to the other. The specific device under consideration is manufactured by Wärtsilä Marine Solutions and can deliver up to 2.5 MW of power with an efficiency of at least 95% across about half a meter (19 inches) of open space. The unit requires an area of approximately 2 square meters (~22 ft^2) or 1.25MW/m^2 (~230kW/ft^2).

On shore, a robotic arm carrying the charged induction coil allows for precise adjustment of the system so it can properly interface with the vessel. Onboard the vessel, a receiving coil is mounted directly to the side of the hull, over which the charging coil is placed. After the vessel is secured at the dock, the system activates, lines up the coils, and commences charging in seconds (Reference 21). The existing technology operates at 690VAC. For higher power applications such as for WSF, multiple units would be required, possibly assembled into an array.

Figure 22 Wartsila Inductive Charging system (on the right) employed on the M/F *Folgefonn*; on the left of the platform is a Cavotec vacuum mooring system that is used with the wireless charger

4.3.5 Stemmann-Technik FerryCHARGER

FerryCHARGER is an automated shore power connection system manufactured by Stemmann-Technik. The high-power version of the system utilizes a plug and receptacle to make the power connection between the shore and the vessel. The system accommodates static displacements by extending and travelling vertically within a tower mounted on the shore or pier.

After the vessel has been secured at the dock, the FerryCHARGER is deployed, and charging initiates in less than 7 seconds. The existing FerryCHARGER has a vertical operational range of about 15 feet and a horizontal reach of 1.3 feet. It also contains sensors and controls to properly adjust for dynamic motions during charging. The current model of FerryCHARGER has power options available up to 8 MW (Reference 7).

Figure 23 Stemmann-Technik FerryCHARGER plug and receptacle

There has been one pilot system commissioned, and there are 16 on order as of December 2017. The current commissioned installation, on the *M/V Ampere,* is a lower power application which utilizes a pantograph charging mechanism, rather than a plug and receptacle system. Stemmann-Technik has a proven history of providing multi-megawatt shore power systems on numerous vessels, and was one of the first to successfully deploy an automated shore power system.

4.4 Mounting Methods

One of the most challenging aspects of providing an automated charging system for any hybrid or battery powered vessel is spanning the gap between the pier (or shore) and the vessel. There are physical considerations such as compensating for the vessel movements, logistical considerations to avoid interfering with passenger and vehicle loading, engineering and controls issues requiring sensors and motors to automatically align the electrical equipment, and finally safety concerns to protect the wellbeing of the passengers and comply with regulatory requirements.

For automated shore power projects to be successful, mounting solutions need to allow for streamlined integration of the shore power plug with existing terminal infrastructure and vessel connection locations.

Examined mounting arrangements are described in the following sections and illustrated in Figure 24. Mounting option suitability for each technology is shown in

Table 17.

Table 17 Mounting platform suitability for different technologies

Technology	Feasible Mounting Platform			
	New dolphin	Floating pile restrained dock	Passenger apron	Vehicle apron
Cavotec APS-Vertical	✓	✓		
Cavotec APS-Horizontal	✓	✓	✓	
ABB Robotic Plug System	✓	✓		
Wärtsilä Inductive	✓	✓		✓
Stemmann-Technik FerryCHARGER	✓	✓		

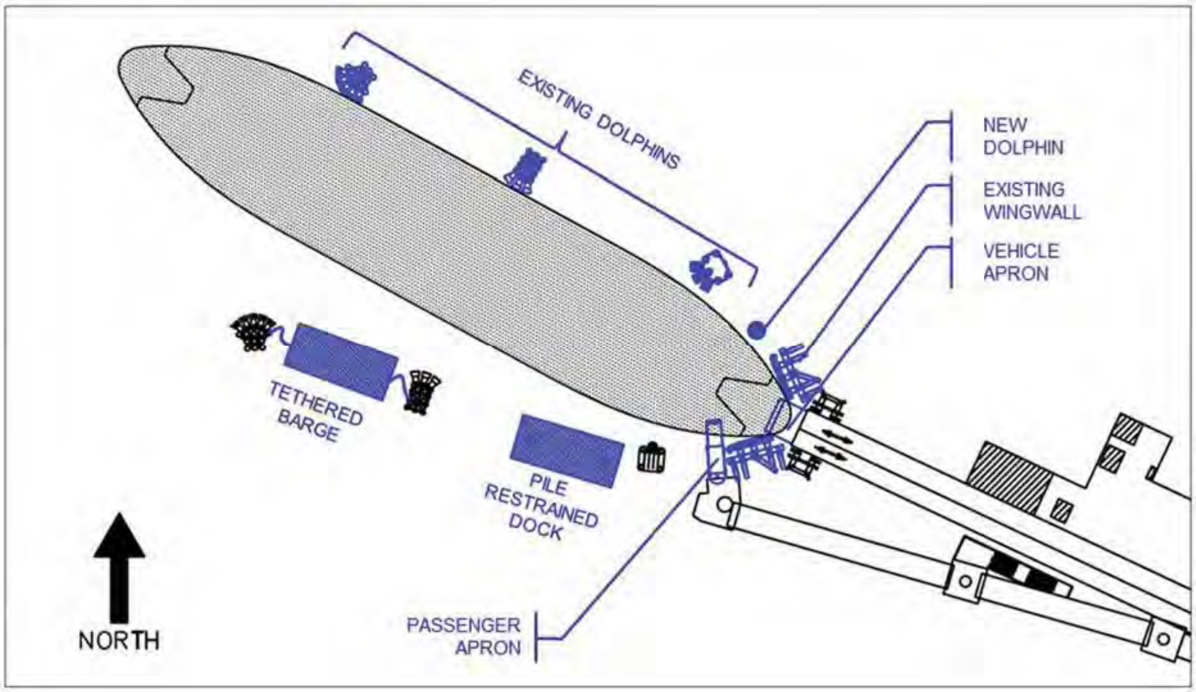


Figure 24 Mounting arrangement options, Edmonds shown

4.4.1 New Dolphin

A new dolphin mounting arrangement would require installation of a large pile near the existing wingwalls. A platform and catwalk would be designed and installed to support the automated shore power connection device and foundation, and to allow room for maintenance. This platform would be similar in size to the passenger cab. The optimal location for the new dolphin is near the existing wingwalls, minimizing the design challenges created by the docking arrangement.

4.4.2 Pile Restrained Dock

The pile restrained dock solution would be a floating platform, likely concrete, designed and installed such that two piles restrain it in the horizontal plane. This dock would accommodate tidal changes by moving vertically along the piles. Docks like this are commonly found in marinas and ferry terminals.

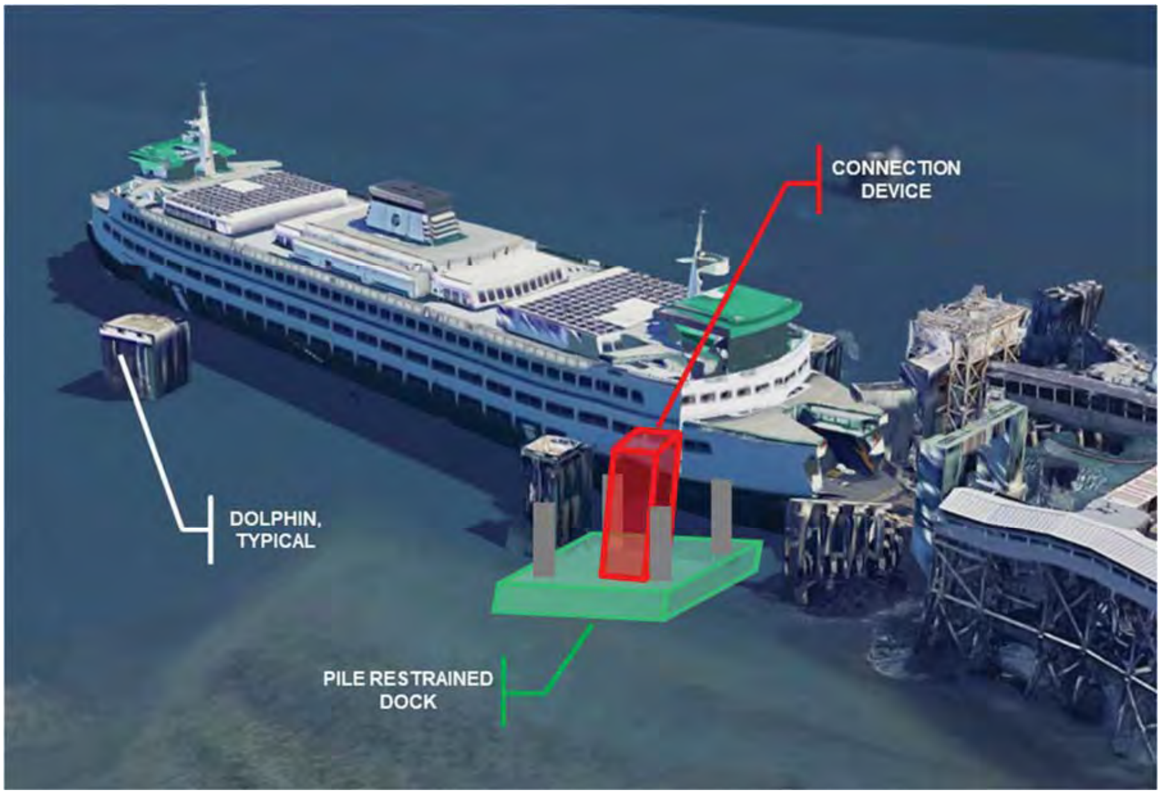


Figure 25 Pile restrained dock mounting arrangement sketch (background image from Google Earth)

4.4.3 Passenger Apron

The existing passenger apron already accommodates the full required range of motion in order to safely and reliably connect the passenger ramp to the vessel. One option that has been considered is to mount the automated shore power connection technology below the passenger apron such that it could utilize the existing system for the gross positioning between the pier and the vessel. It is not yet clear if the existing passenger apron could be adapted, or if a new passenger apron would need to be designed to accommodate the automated connection technology. While this mounting method would limit the weight and size of the connection mechanism, it has the advantage of leveraging an existing platform design.

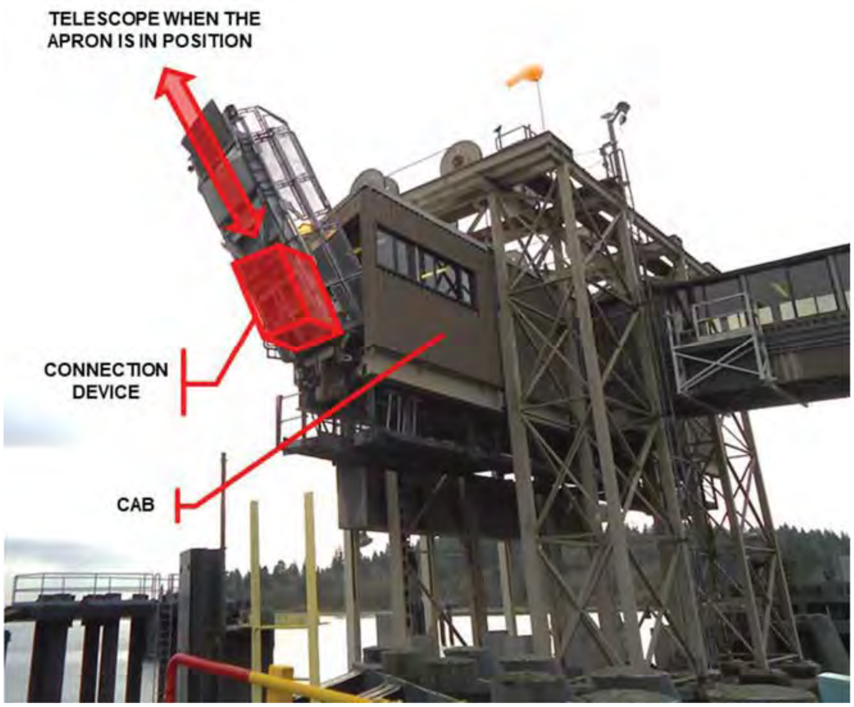


Figure 26 Passenger apron mounting arrangement sketch, Kingston terminal shown

4.4.4 Wing Wall

Attaching the connection device to the existing wing wall structure was considered, as it would potentially not require any new piles. A wing wall arrangement method would require that a mounting platform be designed and integrated with the existing wingwall structure. The platform would need to withstand significant loads, as the vessel consistently pushes against the structure.

4.4.5 Vehicle Apron

The vehicle apron mounting method would require that the connection device be installed below the apron, out of the way of vessel contact. Once the vessel pushes against the wingwall, the apron would be lowered onto the vessel and a connection could be made. This mounting arrangement requires the connection device to be thin enough to be integrated under the apron structure. Similarly, the vessel side connection device would need to be small enough to fit in the steering gear room of the vessel, below the vehicle deck.

A wireless (inductive) charger could potentially be integrated into the underside of the vehicle apron. While the existing vehicle apron has a large enough area to support inductive charging, a new vehicle apron will most likely need to be installed at all terminals to provide greater structural stability and a more optimal mounting method for the inductive chargers. Because of limited space onboard the vessel for infrastructure and the vehicle apron's proximity to the vessel's water line, the other charging technologies were not considered practical in this location.

4.4.6 Tethered Barge

A tethered barge mounting method would utilize a small barge which would be fixed with mooring lines to maintain position. Adequate slack in the mooring lines would allow the barge to rise and fall with the tides. Tethered barges (floating dolphins) already exist at several terminals, including Colman Dock and Mukilteo Ferry Terminal.

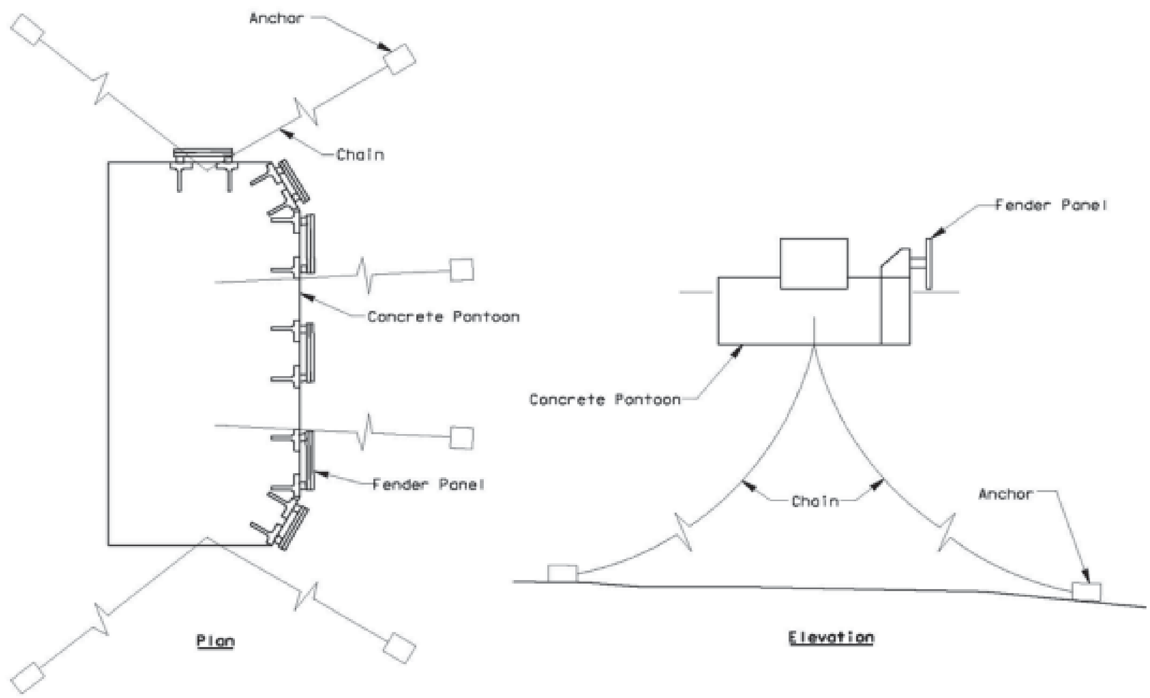


Figure 27 Tethered barge (floating dolphin) example, Reference 27

4.4.7 Existing Dolphins

Utilizing the existing dolphins to mount charging infrastructure would potentially minimize or eliminate the need to add new infrastructure or drive piles. However, the existing dolphins are not optimally located for a shore power connection. The existing dolphins are located such that achieving the required horizontal reach to make a power transfer connection is not realistic for existing technologies, so this option was therefore not seriously considered.

Section 5 Feasibility Review

The feasibility review evaluated the terminal requirements only; onboard considerations are addressed in a separate study.

The design requirements for shore power, and the degree to which the design requirements are met, are shown in Table 18. The automated shore power technologies, power transfer options, and mounting methods, are evaluated separately and discussed in the following sections.

Table 18 Design requirements and fulfillment

Design Requirement Description	Design Requirement	Availability
Utility power	10 MW	Available at all terminals
Utility voltage	12.4kV	Available at all terminals except at Colman Dock; a step-down transformer is required at Colman Dock (26kV to 12.4kV)
Time to charge	20 minutes	80% of trips allow at least 20 minutes of charging time based on published sailing schedules

5.1 Power Transfer Method

Real estate area requirement is the design driver that most significantly impacts power transfer technical feasibility; all power transfer options can provide enough power during the allowable time to charge the vessel. The following table shows the required real estate area for each power transfer option and the availability of this real estate at each terminal.

Table 19 Power Transfer Method Technical Feasibility

<table>
<tr><th>Power Transfer Method</th><th>Real Estate Required (ft^2)</th><th>Terminal Availability</th></tr>
<tr><td rowspan="2">Direct Utility</td><td>720 ft^2 (fence)</td><td rowspan="2">Bainbridge, Kingston, Edmonds; Colman Dock not considered</td></tr>
<tr><td>190 ft^2 (building)</td></tr>
<tr><td rowspan="2">Battery Buffered
Lithium-ion batteries</td><td>1830 ft^2 (fence + batteries)</td><td rowspan="2">Bainbridge, Kingston, Edmonds; Colman Dock not considered</td></tr>
<tr><td>1065 ft^2 (building + batteries)</td></tr>
<tr><td rowspan="2">Battery Buffered
Vanadium-flow batteries</td><td>7180 ft^2 (fence + batteries)</td><td rowspan="2">Kingston</td></tr>
<tr><td>6650 ft^2 (building + battery batteries)</td></tr>
</table>

5.2 Mounting Method

Evaluations of mounting options are presented in Table 20.

Table 20 Comparison of mounting methods

Mounting Platform	Overall Suitability	Benefits	Drawbacks
New dolphin	Good	• Flexible placement options at all terminals • Possible to place close to shore to minimize cable runs	• Requires new pile cluster design and installation
Pile Restrained Dock	Good	• Adjusts for tidal range • Provides room for equipment longitudinal travel	• Requires new piles and dock design and installation
Existing dolphin	Poor	• Does not require new pile cluster design and installation; potential cost savings	• Far from shore • Not optimally placed for shore power connection
Passenger apron	Moderate	• Already compensates for vessel position and motion • Close to shore	• Limited space available • Likely requires new apron design at all terminals
Vehicle apron	Moderate	• Already compensates for vessel position and motion • Close to shore	• Limited space available • Heavily-trafficked area • Likely requires new apron design at all terminals
Wing wall	Poor	• Close to shore	• Serves as fendering so experiences regular vessel contact • Tall structure
Tethered barge	Poor	• Flexible placement options at all terminals • Adjusts for tidal range	• Far from shore • Complex and costly system

5.3 Automated Shore Power Technology

Automated shore power technologies are new and are still under development. The review of available technology showed that there are no off-the-shelf solutions that will meet the requirements of WSF; each technology requires customization. Glosten has evaluated each technology based on how well suited it is for the Jumbo Mark II conversion project. The areas in which the technologies are evaluated and compared are:

- Range of horizontal reach;
- Vertical displacement range;
- Electrical compatibility;
- Technology maturity; and
- Regulatory risk.

A summary of the off-the-shelf compatibility is provided in Table 21.

Table 21 Off-the-shelf compatibility assessment summary

	Cavotec APS Horizontal	Cavotec APS Vertical	Stemmann Technik FerryCHARGER	ABB Robotic Plug System	Wartsila Inductive
Horizontal Reach	Poor	Poor	Poor	Poor	Poor
Vertical Displacement	Moderate	Good	Good	Poor	Poor
Electric Compatibility	Yes	Yes	Yes	Yes	No
Technology Maturity	Prototype	Early Commercial	Early Commercial	Prototype	Early Commercial
Regulatory Risk	Low	Low	Low	Low	Medium

5.3.1 Horizontal Reach

All technologies under consideration have the capability to compensate automatically for some amount of horizontal displacement between the vessel and the shore. However, none provide enough horizontal reach to accommodate the variability in vessel docking angle at Bainbridge, Edmonds, and Kingston, which is discussed in Section 2.3. The degree to which each technology can meet the horizontal displacement requirements is presented in Table 22 in terms of the off-the-shelf suitability of the technology.

Table 22 Off-the-shelf technology suitability - horizontal reach

Technology	Suitability for Jumbo Mark II Conversion Range of Horizontal Reach
Cavotec APS-Horizontal	Poor; requires significant customization
Cavotec APS-Vertical	Poor; requires significant customization
Stemmann-Technik FerryCHARGER	Poor; requires significant customization
ABB Robotic Plug System	Poor; requires significant customization
Wärtsilä Inductive	Poor; requires significant customization

5.3.2 Vertical Displacement

All technologies under consideration have the capability to automatically adjust for vertical changes between the vessel and the shore to compensate for changing tides and draft.

Table 23 Off-the-shelf technology suitability - vertical displacement range

Technology	Suitability for Jumbo Mark II Conversion Vertical Displacement Range
Cavotec APS-Horizontal	Moderate; requires some customization
Cavotec APS-Vertical	Good; requires minimal customization
Stemmann-Technik FerryCHARGER	Good; requires minimal customization
ABB Robotic Plug System	Poor; requires significant customization
Wärtsilä Inductive	Poor; requires significant customization

5.3.3 Electrical Power Compatibility

As discussed in Section 4.1.1, the charging voltage between the shore and the ship is assumed to be standardized at 12.4kV, since three of the four terminals can be supplied with this voltage directly from the utility. This eliminates the need for a step-down transformer, and the space and cost associated with that additional equipment.

Table 24 Off-the-shelf technology suitability - electrical compatibility

Technology	Suitability for Jumbo Mark II Conversion Electrical Compatibility
Cavotec APS-Horizontal	The equipment is compatible with the required voltage
Cavotec APS-Vertical	The equipment is compatible with the required voltage
Stemmann-Technik FerryCHARGER	The equipment is compatible with the required voltage
ABB Robotic Plug System	The equipment is compatible with the required voltage
Wärtsilä Inductive	The equipment is not compatible with the required voltage

5.3.4 Technology Maturity

All of the devices under consideration are early-stage technologies. However, most are derived from well-established technologies that have been adapted for the requirements of battery-powered ferries (i.e. marine environment, high power, automated connections, etc.). Some are still in the testing stages and are not yet in full operation, and some have been installed and operated successfully at vessel terminals. Three technology development stages are defined below.

- Prototype or early implementation: The device is under development or has little or no operational experience.
- Early commercial: The device has been successfully operated on one or more routes and is being actively marketed.
- Mature practice or technology: The technology has been widely used and proven on many vessels. The advantages and limitations are well understood.

Table 25 Off-the-shelf technology suitability - technology maturity

Technology	Suitability for Jumbo Mark II Conversion Technology Maturity
Cavotec APS-Horizontal	Prototype or early implementation
Cavotec APS-Vertical	Early commercial
Stemmann-Technik FerryCHARGER	Early commercial
ABB Robotic Plug System	Prototype or early implementation
Wärtsilä Inductive	Early commercial

5.3.5 Regulatory Risk

The approval process for new technologies and applications takes time and money, and is not guaranteed to succeed. While shore power has been used for years and is well understood by regulators, in recent years there has been increased application of high-powered shore plugs in ports for large vessels to reduce pollution. This has sparked a variety of new innovations and has paved the way for automated high-power charging. However, many new risks are introduced with automated charging, especially for passenger vessels.

Regulators are primarily concerned with the safety of the passengers and crew. However, there are also issues related to grid stability that cannot be ignored when high power, short duration charging connections are in use. Some of the technologies and standards for automated shore power are adapted from other industrial applications that are not familiar to the marine regulatory community, and will likely require education of the regulators.

Table 26 Off-the-shelf technology suitability-regulatory risk

Technology	Suitability for Jumbo Mark II Conversion Regulatory Risk
Cavotec APS-Horizontal	Low risk, connection technology is well established in the marine industry
Cavotec APS-Vertical	Low risk, connection technology is well established in the marine industry
Stemmann-Technik FerryCHARGER	Low risk, connection technology is well established in the marine industry
ABB Robotic Plug System	Low risk, connection technology is well established in the marine industry
Wärtsilä Inductive	Medium risk, technology is new to the marine industry, but well established in other industrial applications

Section 6 Cost Estimate

A 40-year lifecycle cost estimate was developed for each automated shore power connection and each terminal power infrastructure option to determine the economic feasibility of each option considered. The lifecycle cost analysis developed for each automated shore power connection option investigates the cost of each technology at a single terminal. It is assumed the lifecycle cost of each technology is the same for each terminal. The analysis completed for the terminal power infrastructure options, however, was performed for each terminal. A summary matrix is provided to compare all available terminal power infrastructure and automated shore power connection options for each terminal. Detailed lifecycle cost analyses may be found in Appendix F.

The lifecycle cost analysis was performed in accordance with the National Institute of Standards and Technology (NIST) Lifecycle Cost Estimating Manual, Reference 29. A real discount rate of 4% was used to calculate future savings into 2017 dollars, as directed by WSF. The real discount rate combines the effects of interest and expected inflation. Energy prices were converted to 2017 dollars using discount factors derived from regional tables provided by NIST's annual update, Reference 30.

A summary matrix of lifecycle cost per terminal is provided in the table below.

Table 27 Ship-to-shore lifecycle cost summary, 2017 dollars (in millions)

	Colman Dock		Bainbridge		Edmonds		Kingston		
	Li-Ion	Direct utility	Li-Ion	Direct utility	Li-Ion	Direct utility	Li-Ion	Vandium Flow	Direct utility
Cavotec APS-Horizontal									
CapEx	8.1	4.1	8.1	4.1	7.1	4.1	7.1	12.0	4.1
Lifecycle	43.2	35.3	33.8	30.4	18.3	16.5	17.2	21.3	14.1
Cavotec APS-Vertical									
CapEx	8.6	4.6	8.6	4.6	7.6	4.6	7.6	12.4	4.6
Lifecycle	43.9	36.0	34.5	31.1	19.0	17.2	17.9	22.0	14.8
Stemmann-Technik FerryCHARGER									
CapEx	8.8	4.8	8.8	4.8	7.8	4.8	7.8	12.6	4.8
Lifecycle	44.2	36.3	34.8	31.4	19.3	17.5	18.2	22.3	15.1
ABB Robotic Plug System									
CapEx	9.9	5.9	9.9	5.9	8.9	5.9	8.9	13.7	5.9
Lifecycle	45.8	37.9	36.4	33.0	20.9	19.1	19.8	23.9	16.7
Wartsila Inductive									
CapEx	12.6	8.6	12.6	8.6	11.6	8.6	11.6	16.5	8.6
Lifecycle	49.8	41.9	40.5	37.1	25.0	23.1	23.8	27.9	20.8
Median									
CapEx	**8.8**	**4.8**	**8.8**	**4.8**	**7.8**	**4.8**	**7.8**	**12.6**	**4.8**
Lifecycle	**44.2**	**36.3**	**34.8**	**31.4**	**19.3**	**17.5**	**18.2**	**22.3**	**15.1**

6.1 Terminal Power Infrastructure Lifecycle Cost

6.1.1 Capital Investment

Capital investment costs for direct utility transfer were assumed to be equal for each terminal. This is in part due to the large number of unknowns and the unique design complexity for each terminal. Battery buffered capital investments costs were calculated based on the power and cycle demands on each run.

6.1.2 Operational Costs

Operation costs were divided into three categories: electrical grid costs (i.e. payments to electric utility), maintenance costs, and replacement costs.

6.1.2.1 Electrical Grid

Electrical grid costs were determined as a function of demand charge, electricity rates, and basic or minimum charges for each terminal. In cases where demand charge varies by month (peak and non-peak) and average charge was used. In cases where demand charges varied by time of day (peak and non-peak), the peak charge was used. The following table outlines the rate schedules used for each utility.

		SnoPUD	PSE	CityLight
Electrical Rate	*(USD$/kWh)*	$ 0.0579	$ 0.052527	$ 0.0712
Demand Charge[1]	*(USD$/kW)*	$ 4.22	$ 2.95	$ 2.33
Minimum Charge	*(USD$/month)*	$ 8,517	-	$ 878
Basic Charge	*(USD$/month)*	-	$ 353	-
Rate Schedule	-	36	46	LGC
Terminals	-	ED	KI, BI	SEA

1. Charges were averaged when peak and non-peak varied by month. Weighted charges were used when peak and non-peak charges varied by time of day

6.1.2.2 Maintenance

Maintenance cost for direct utility transfer were estimated based on expected maintenance cycles for the shore power infrastructure equipment at Seattle's Pier 91, which has a similar sized shore power connection for cruise ships. Costs for this maintenance were estimated based on best engineering judgement. Battery maintenance costs were determined based on vendor supplied recurring costs and annual costs incurred by WSF personnel.

6.1.2.3 Replacement

Replacement costs for lithium-ion batteries were assumed to occur every 6 years, with capital cost falling over time. Historically, lithium-ion battery prices have reduced at aggressive rates. According to a study done by the California EPA Air Resources Board, it was determined that medium battery costs for lithium-ion batteries will reduce by 70% in 2030, Reference 28. The median values trendline found in the study was used in the lifecycle cost analysis for the ship side feasibility study, Reference 31, and thus will also be used here. Replacement costs over the lifecycle were calculated as a percentage of the initial investment costs following this trend, as shown in Figure 28.

Vanadium flow batteries were replaced once over the 40 year lifecycle, 20 years after initial installation. The replacement cost was calculated as 30% of initial capital cost, discounted to 2017 dollars.

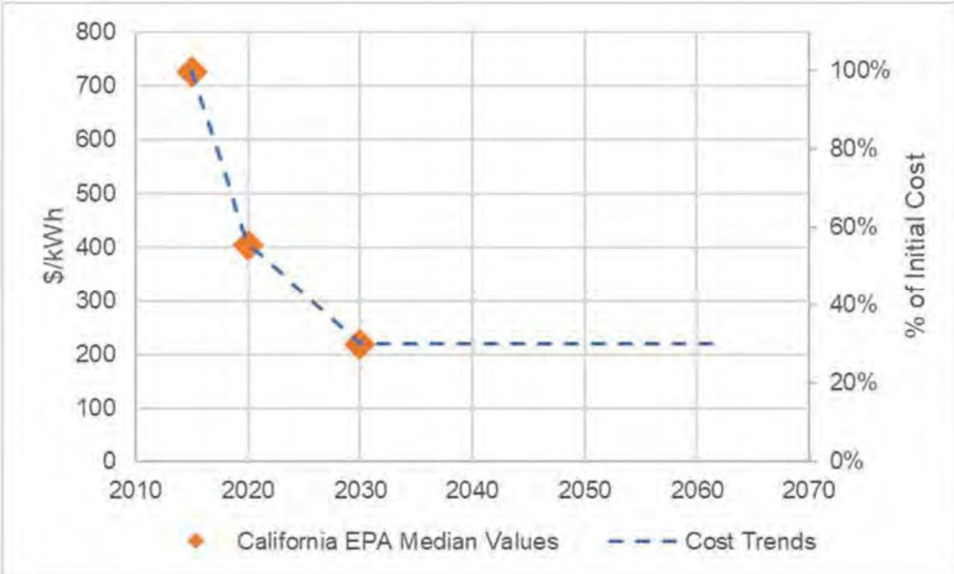


Figure 28 Projected lithium-ion battery cost reduction, adapted from Reference 28.

6.1.2.4 Battery Disposal

With the increasing use and propagation of lithium-ion batteries in electric vehicles and other energy storage applications, environmental and economic impacts of disposal are an emerging area of interest. It has been proposed that lithium-ion batteries have a significant residual value for other energy storage applications, after the conventional design life (typically 80% of initial capacity) has expired. Additionally, the market is responding to the need for disposal of expended battery packs. A recycling market is emerging that could develop into a significant industry capable of at least partially addressing the availability of expended batteries. While the environmental issues are a legitimate social concern, this was not a primary focus of this feasibility study. No residual value or disposal expenses are currently included in this lifecycle cost analysis for lithium-ion batteries. This is an area recommended for further study as more information becomes available.

Likewise, other large format batteries are emerging in the market, such as vanadium flow batteries. Discussions with vendors indicate that there are potential advantages with this technology in terms of cost and environmental impact for expended batteries, although there was insufficient data available to quantify the impact. As such, this lifecycle analysis has not assumed any residual value or disposal expenses for vanadium flow batteries.

6.1.3 Results

6.1.3.1 Power Infrastructure Lifecycle Cost

Lifecycle costs for all power infrastructure options per terminal are presented in Figure 29.

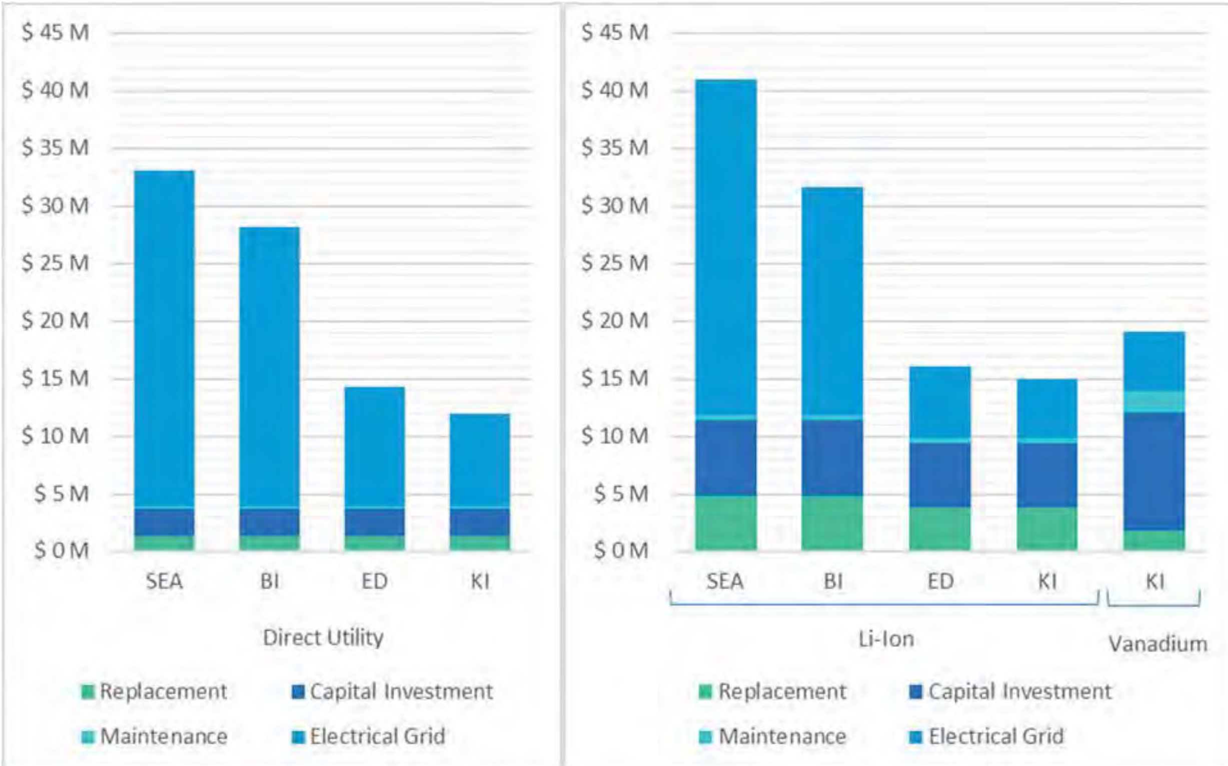


Figure 29 Left: Direct Utility Transfer Lifecycle Cost; Right: Battery Buffered Transfer Lifecycle Cost

As seen in Figure 29, the direct utility transfer provides the lowest lifecycle cost option for all terminals. It is important to note, however, that the most significant contibutions to lifecycle cost are the annual electrical grid charges. These charges are calculated based on rate schedules described in Section 6.1.2. These rate schedules, particularly PSE's rate schedules, vary significantly based on type of service. For this application, it was assumed that high voltage interruptable service was appropriate, based on direction from WSF.

6.2 Ship-to-shore Interface Lifecycle Cost

Ship-to-shore interface lifecycle cost analysis includes the ship-to-shore interface technology, civil infrastructure upgrades, engineering associated with foundation and mounting arrangement design and commissioning, and additional electrical components required

6.2.1 Capital Investment

6.2.1.1 Ship-to-shore Interface

Capital investment costs for each ship-to-shore interface were determined through discussions with each vendor. These costs include one terminal unit. Cost for vessel hardware were provided to Elliot Bay Design Group for inclusion in the project lifecycle cost analysis.

6.2.1.2 Capacity Factor

The capacity factor is a multiplier added to the ship-to-shore interface capital costs for options where a market rate cost was supplied for each vendor's "off-the-shelf" technology. Since this application will require additional customization, a multiplier was applied to these options to accommodate increases in power and voltage capacity over "off-the-shelf" products. This capacity scaling scheme only applies to conductive charging technologies. For inductive charging technology, a custom cost was provided by the vendor.

6.2.1.3 Additional Equipment

Additional equipment costs were only included if the technology could not transfer power at the design voltage. This cost accounts for the initial cost of additional components, including transformers. This cost does not include the impact that these additional components will have on space.

6.2.1.4 Gross Positioning

As discussed in previous sections, the off-the-shelf technologies investigated for this study are not capable of accommodating the full range of motion required to reach the vessel under all static conditions. They *are* all capable of some degree of motion, but require further development meet the 'gross positioning' requirements of these terminals. The cost of a gross positioning mechanism for each technology were determined based on a base value for designing and fabricating a custom positioning tool to compensate for the static displacement design requirements. The base value was set at $500,000, based on Glosten's experience with costs of equipment with the required range of motion. Increases and/or reductions were applied to this base value based on the vertical and horizontal displacement compatibility of each technology.

6.2.1.5 Civil Infrastructure

Civil infrastructure costs were determined based on a base value for a dolphin mounted solution, since this was the most versatile mounting option. These costs were assumed to be independent of the selected technology.

6.2.1.6 Engineering

Costs for engineering were estimated from a base value. The base value was determined to be 10% of the average the hardware cost of each technology. Increases and/or reductions to that value were determined based on how much additional design work would be required to accommodate the vertical and horizontal displacements (i.e. gross positioning).

6.2.2 Operational Costs

6.2.2.1 Maintenance

Maintenance costs were determined from information provided by vendors. Because of disparate availability of maintenance cost information from vendors, an average maintenance cost was assumed for all technologies. Additional maintenance costs were added to technologies that would require additional switchgear to cover maintenance of those parts.

6.2.2.2 Replacement

Replacement costs for each ship-to-shore interface option were assumed to occur once at year 20 at 75% of the initial investment cost. No significant cost savings were applied to the replacement of the technology, under the assumption that new and updated versions of this technology will require some additional engineering and infrastructure modifications. Equipment obsolescence and its associated costs were not accounted for in this study.

6.2.3 Ship-to-shore Interface Lifecycle Cost

The results of the ship-to-shore interface lifecycle cost analysis identified three technology options with very similar lifecycle costs. These technologies are, the Cavotec APS Horizontal, Cavotec APS Vertical, and Stemmann Technik FerryCHARGER. Although there are some slight variations in cost, the level of detail of this estimate indicates that these three options have the lowest cost. The higher lifecycle cost of the other technologies is driven primarily by their, higher capital cost. Lifecycle costs and hardware costs for one vessel are shown graphically in Figure 30. Hardware costs for one vessel were included to illustrate the differences in vessel side cost for each technology.

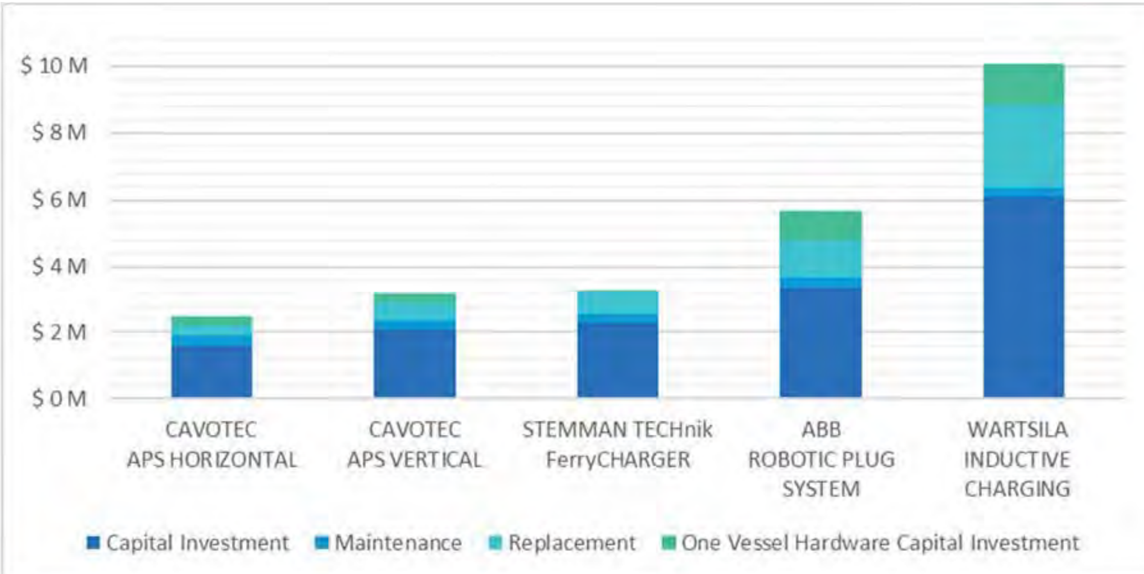


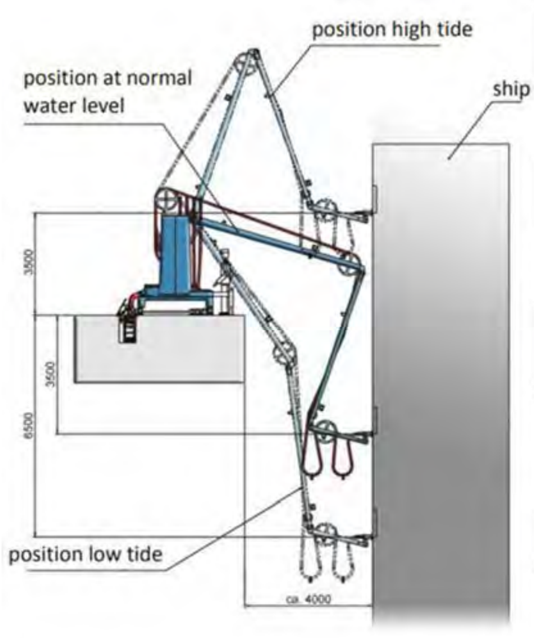
Figure 30 Lifecycle costs for automated shore power connection technology

Section 7 Bridging the Gap

All commercially available technologies studied require some level of modification to meet the unique and challenging design criteria for this application. The most demanding of these criteria is the horizontal reach requirement driven by the vessel docking arrangement. Although this range of motion accommodation does not currently exist for automated shore power installations, it does exist for other applications. Leveraging existing positioning equipment designs with the new automated shore power technology could provide an effective solution for WSF.

A gross positioning mechanism would be required to move the automated shore power plug to a location within the receptacle's automated operating range. The mechanism would have to rotate parallel to the vessel, reach towards the vessel, and travel along the length of the vessel. Ideally, the mechanism would have pre-programmed positions that would correspond to vessel docking positions. Final gross alignment of the mechanism would then be operated by a remote-control device and a single operator, similar to the current operation of the passenger apron. Final connection could happen automatically once the connection device was in range.

Several technologies currently exist to accommodate similar ranges of motion in both the shore power industry and other industries. In the shore power industry, cruise ships and containerships frequently operate in terminals with significant tidal ranges and large reach distances. One terminal in Hamburg, Germany recently installed a SAMPS (Stemmann Alternative Maritime Power System) ShoreCONNECT device to accommodate significant static displacement. The system is controlled by a radio remote control unit guided by a single operator. Horizontal reach, angular rotation and tidal ranges are accommodated by an arm that rotates on a base. The tidal compensation and reach (travel between the ship and quay wall), as shown in Figure 31, exceed what is required for WSF's application.



High tide, height difference hatch/quay: **3.5 m**	(~12 ft)
Low tide, height difference hatch/quay: **6.5 m**	(~21 ft)
Travel distance parallel to quay wall: **300 m**	(~984 ft)
Distance between ship and quay wall: **4 m**	(~13 ft)
Distance between SAMP-System and quay wall: **approx. 2.5 m**	(~8 ft)
Distance between hatch and socket: **approx. 3.5 m**	(~12 ft)
Hatch dimensions (h x w): **1.2 x 0.8 m**	(~4ft x3 ft)
Transmittable voltage: **12 MVA**	

Figure 31 Particulars to SAMPS installation in Hamburg, Germany (adapted from Reference 32)

Figure 32 SAMPS installation in Hamburg

This system does not currently accommodate an automated shore power connection plug, but it seems reasonable to expect that it could be adapted to accommodate one.

Allied Systems Company, based in Oregon, specializes in custom design of marine overboard handling equipment. Allied has a series of commercially available products, but specializes in design and fabrication of custom equipment that can adjust for long reach and angular and vertical displacement. Allied is a large provider of crane and scientific offshore research handling solutions in the marine market, and is familiar with the ranges of motion and ruggedness of the marine environment. An example of a scientific payload handling system is shown in Figure 33.

Figure 33 Allied scientific payload system (source: Google images)

Allied has developed a preliminary concept design for this application, shown in Figure 34, which can support the plug end of the shore power connection device and is programmable. Fine adjustment would be done by a single operator using a remote control. Following the issue of specific design requirements, at least one year would be required to design and fabricate the first unit of a custom solution of this kind. Subsequent units would follow much more quickly, provided they do not require significant design changes.

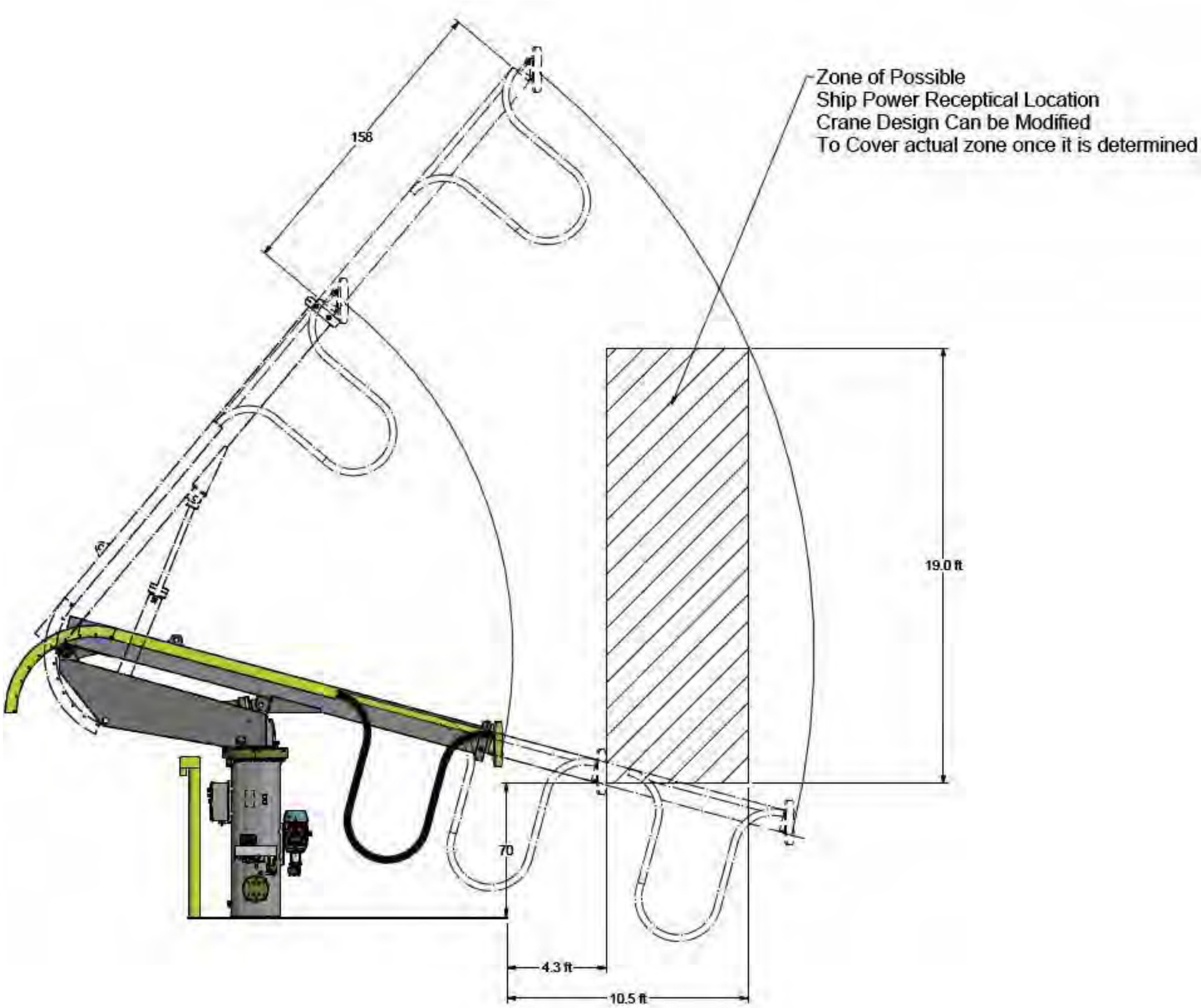


Figure 34 Allied concept design for gross positioning mechanism

Technologies like those described above significantly improve the feasibility of developing automated shore power solutions for WSF. However, they do not come without cost and additional design and fabrication time. This timeline is longer than the expected vessel design and construction timeline.