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California North Coast Offshore Wind Studies

Subsea Transmission Cable Conceptual Assessment



This report was prepared by Aaron Porter and Shane Phillips of The Mott MacDonald Group. It is part of the *California North Coast Offshore Wind Studies* collection, edited by Mark Severy, Zachary Alva, Gregory Chapman, Maia Cheli, Tanya Garcia, Christina Ortega, Nicole Salas, Amin Younes, James Zoellick, & Arne Jacobson, and published by the Schatz Energy Research Center in September 2020.

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Technical Memorandum

Transmission Cable

Project:	Humboldt Offshore Wind		
Our reference:	507100657	Subject:	Humboldt-SF Bay Subsea Transmission Cable
Prepared by:	Aaron Porter, PE	Date:	8/28/20
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Executive Summary

A concept-level assessment was conducted to develop options and document hazards and constraints for routing a high voltage direct current (HVDC) cable from the Humboldt Bay area to the San Francisco Bay (SF Bay) area. The transmission cable would be intended to deliver power generated from an offshore wind farm(s) in the Humboldt area to load centers in the SF Bay area. The subsea transmission cable was assessed in parallel to upland grid upgrade options. The subsea distance between SF Bay and Humboldt Bay (~250 miles) necessitates the use of an HVDC electrical system to minimize electrical losses. The HVDC cable system would consist of the cable system itself and an HVDC converter station at each end of the transmission cable (Humboldt Area and SF Bay Area) to convert the power to/from the standard alternating current (AC) grid system.

The subsea study area between Humboldt Bay and SF Bay includes both natural and anthropogenic constraints and hazards with variable levels of risk. These hazards and constraints will require a combination of avoidance and mitigation measures to install a transmission cable between the two areas. In summary, the project risks due to hazards and constraints are the following:

- Hazards
 - Deep subsea canyons extending from the nearshore area to depths below the continental shelf, where subsea landslides strong enough to rupture cables are common.
 - Seismic fault line surface displacements which may be too large to mitigate for. Cable repairs may be required with a major seismic event.
 - Some of the largest subsea sandwaves in the world are present outside the Golden Gate, which may preclude subsea transmission cable routing through the Golden Gate.
- Constraints
 - Areas of exposed bedrock and other hard substrate are located within marine habitat areas where cable protection methods may be either expensive or not permitted by agencies.
 - Potential interferences with or damage from fishing activities if the cable is not able to be buried or otherwise protected
 - No power cables have been installed to the depths required to route offshore of the subsea canyons (over 9,000 feet deep), and proven cable technology has not yet been developed for installation at these depths.
 - The offshore route will likely require crossing telecommunication cables in very deep water (5,000 feet or greater), which will require permissions from the existing operators. Though telecommunication cables

crossings at these depths are common, power/telecommunication cable crossings at this depth do not appear to have previously been attempted.

Based on the location and mitigation possibilities for the hazards and constraints, two potential cable corridors have been developed: a “Nearshore” corridor, an “Offshore” corridor. Both corridors have significant challenges that would need to be overcome to install and operate an HVDC link, though the challenges may not be insurmountable. Further analysis may be conducted to refine the severity of these risks and to develop possible mitigation strategies.

The construction cost of the system is estimated to be approximately \$2.1 – 3.1 billion, depending on whether one or two cables are installed. It is likely that a single pole pair (one cable bundle) would be able to meet the rating requirements of 1,800 megawatts (MW). Installing two cables along different routes would provide redundancy for the transmission system in the case one cable incurs a fault or is damaged but would come at an additional cost of approximately \$1 billion. Should multiple transmission cables be required to support transmission of multiple offshore windfarms (greater than 1800 megawatts), separation of cable routes should be considered to reduce risk of cable damage due to the hazards identified.

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1 Introduction and Criteria

A pre-feasibility level assessment was conducted to evaluate hazards and constraints, potential cable design parameters (route and type), and costs of a potential subsea power link between the Humboldt Bay area and the San Francisco Bay area. The subsea transmission cable was assessed in parallel to upland grid upgrade options to transmit excess power generated in the region to the load centers in the San Francisco Bay area.

The distance between Humboldt and San Francisco Bay (SF Bay) is approximately 250 miles, and this length necessitates the use of a high-voltage direct current (HVDC) electrical system to minimize electrical losses. A HVDC cable system would consist of the cable itself, and an HVDC converter station at each end of the cable (Humboldt Area and SF Bay Area) required to convert power to/from the standard alternating current (AC) grid system. There are not technical limits to the length of an HVDC system, but at present levels of technology, HVDC cables can only be deployed as links, rather than a network of HVDC cables. HVDC link systems have been deployed world-wide for long-distance transmission requirements for solar energy, subsea cables, and transmitting hydropower energy, with examples on the US West Coast. On the US West Coast the Pacific Direct Current Intertie was initially constructed by Bonneville Power Administration over a length of 846 miles to provide lower-cost hydropower energy to the Southern CA region.

The subsea routing assessment was conducted by compiling publicly available data to map potential hazards and constraints to cable installation and operation in the subsea study area. Within this document, hazards are defined as an event, process or phenomena which results in a risk of damage to the cable system (such as fault line displacement). Constraints are defined as established mapped conditions or environmental conditions, such as marine habitat areas, which need to be addressed as part of the routing assessment. The mapped hazards and constraints are the basis for the routing assessment. Associated requirements for upland infrastructure (converter stations) were developed and assessed at a pre-conceptual level.

The project team included experienced submarine cable installers, coastal engineers, and power export cable design engineers. This memorandum provides study criteria, existing conditions, cable design considerations, converter station considerations, installation considerations, mapping of mitigation levels required, and two potential cable route options with a summary of risks and benefits of each.

1.1 Study Criteria

Level of Assessment

This assessment is intended to be conceptual in nature and is based only on review of publicly available data. No electrical modeling or system studies have been conducted as part of this work. Work conducted was based on desktop level review only. Findings are intended to be used at a planning-level only and are not intended to be used for design or other engineering purposes without additional analysis. High-risk areas have been identified, but detailed investigation of the potential high-risk areas was not conducted.

Electrical Rating requirement

It is assumed that the HVDC link aims to have a rating of approximately 1800MW, but the final rating may be less, if required based upon results of the assessment.

Routing Assessment Approach

Hazards and constraints should be considered in determination of potential submarine cable routing corridors. Hazards are not necessarily an obstacle to feasibility, as hazards (such as anchor strike) impose different ranges of risk, and those hazards can be mitigated to result in a lower risk level, which may be acceptable in some cases. Similarly, a constraint is not necessarily an obstacle to feasibility, but different constraints (such

as existing telecommunication cables), require different levels of mitigation. This assessment estimated the likelihood of feasible mitigation measures for the different hazards and constraints. The following classifications will be utilized to categorize the different hazards and constraints as they relate to mapping:

- **No-go area**; mitigation of high-risk elements likely not possible.
- **Major mitigation**; cable installation possible with major mitigation. Major mitigation is intended to include solutions that require further analysis to develop, necessitate additional coordination and permissions, are associated with a very high cost, or technology needed is not yet proven.
- **Minor mitigation**; cable installation possible with minor mitigation. Minor mitigation is intended to include proven technologies and engineered mitigation measures that are widely applied in industry.
- **No mitigation required**

Cable routing hazards and constraints in the study region between Humboldt Bay and SF Bay are summarized in Section 2 and assessed in Section 3.

2 Existing Conditions

Existing conditions were evaluated to develop the hazards and constraints which may affect concept level routing¹, assessment of installation risks, and design of the cable transmission system. Information was collected from the public domain, and hazard information was also provided by Humboldt State University (HSU). The potential hazards and constraints are listed in Tables 1 and 2.

These hazards and constraints were mapped to provide a guide to determine which could be avoided or may require mitigation solutions. To provide a basis for development of concept routes, the applicable hazards and constraints were mapped in a graphical information system (GIS), as shown in Figure 1. Details, risks and potential mitigation levels required for the hazards and constraints are addressed in Section 3.3.

Table 1 – Subsea Study Area Hazards

Hazard	Details
BOEM Offshore Wind Call Areas	Offshore wind farm areas are assumed to contain subsea cables and anchors which likely have embedment requirements.
Seismic Surface Fault Rupture and Deformation	Three high risk fault lines within the project area were identified in coordination with HSU: San Andreas Fault, the Cascadia Megathrust, and the Mendocino Fault line. Further investigation is needed to quantify the probability of an extreme seismic event and to estimate the amount of displacement at these fault lines. Displacement may be on the order of 10m vertical and 50m horizontal with probabilities ranging from 1/700-1/300 years (HSU, 2019)
Seismic Shaking	There is a high concentration of historical earthquakes offshore of Cape Mendocino (historically, 1M6 event or greater per decade). The shaking could include long duration of large accelerations and strong motion effects (HSU, 2019). Seismic activity appears to be reduced near the existing telecommunication cables, off further offshore.
Submarine Canyons	Several submarine canyons fed by high-discharge rivers are found off California's coast at the outer edge of the continental shelf. Many of these canyons are characterized by high sediment transport rates, submarine landslides, and rapid turbidity currents. The canyons shown in Figure 1 span a depth range upwards of 3280ft (1000m) and are incised at least 328ft (100m) into the continental slope (Harris, 2014).
Sand Waves	Sand waves up to 33ft (10m) in height and 700ft (220m) in length propagate in water depths between 100-300ft seawards of the Golden Gate Bridge.
Shipping Vessel Traffic	Cargo and tanker ships navigate throughout the project area and in emergencies may need to drop anchor. Vessel tracking data suggests that ships sailing north-south parallel to the west coast are concentrated within a corridor located 50 miles offshore. The water depth in which vessels operate is likely beyond the depth at which vessels drop anchor.
Bottom Trawl Fishing	Trawling fishing activity occurs throughout the project area; it is primarily concentrated within 30 miles of the shoreline. Bottom trawl fishing is prohibited in waters between the Essential Fish Habitat Conservation Area between the 1280m and 3500m depth contours.
Tsunami	Tsunami impact to the seabed is minimal in deep water. Tsunami inundation may result in erosion and strong currents near shore (HSU, 2019)
Gas Hydrates	Gas hydrates are one of contributing factors to landslides on the continental margin offshore of Cape Mendocino. Gas hydrates have been documented offshore of Eureka between the state/federal boundary and the Humboldt Call Area (HSU, 2019).
Ocean Disposal Sites	Offshore dredged material disposal dumping may interfere with the cable.

¹ Shipwrecks and other smaller nearshore obstructions and interferences are not assessed at this scale but will need investigation in a later phase.

Table 2 - Subsea Study Area Constraints

Constraint	Details
BOEM Offshore Wind Call Areas	Wind farm call areas may require site permissions.
Existing Submarine Telecommunications cables	Four subsea transmission cables make landfall at Manchester, CA (approx. 125mi south of Humboldt). Additionally, a series of subsea cables are routed parallel to the shoreline, approx. 100 miles offshore, and were installed between 1997-2002. Parallel cables should be installed horizontally apart by at least 2x water depth to conduct repairs without affecting nearby features (such as existing cables), but 3-4x water depth is the preferred spacing in industry.
Steep Slopes	Very steep slopes (exceeding 30°) are found within the submarine canyons and along the submerged Mendocino Ridge, which is a feature extending seawards from Cape Mendocino. Further south, steep slopes are observed are 10-30 miles offshore.
Hard Substrate	Hard substrate is documented along Mendocino Ridge, in isolated nearshore areas between Eureka and Manchester, and along the coastline north of San Francisco Bay. Burial in hard substrate is typically more challenging, and if not possible can require post-lay protection mats.
Ocean Disposal Sites	There are several federal ocean disposal sites offshore of Humboldt Bay and San Francisco Bay which may require permissions.
Installation Depth	Water offshore of the continental shelf is very deep. The deepest water which power cables have previously been installed in is approximately 6560 ft (2,000m). Depth in the study area exceeds 9,840 ft (3,000m).
Sea-State	Large wave heights and long wave period swell along the California coastline
Cable Installation Vessel Operational Limitations and Capacity	Because the cable installation would be primarily parallel to shoreline, the vessels will be in a beam sea condition, which decreases the sea state in which the vessels can operate. At present the approximate vessel cable length capacity is ~62 miles/vessel (100km/vessel) due to current tonnage capacity. Because multiple vessel campaigns are needed to install the cable, joints are likely required. Cable recovery and operation & maintenance activity is limited by sea state, and it is possible that such activities will not be able to occur for significant wave heights exceeding 10 feet
Marine Habitat Areas	Marine Habitat Areas are defined as those areas mapped by NOAA in the Marine Protected Area Inventory (2017). These areas cover nearshore area (within ~40 miles of shoreline) between Manchester and San Francisco Bay; Mendocino Ridge; Eel Canyon area further north.

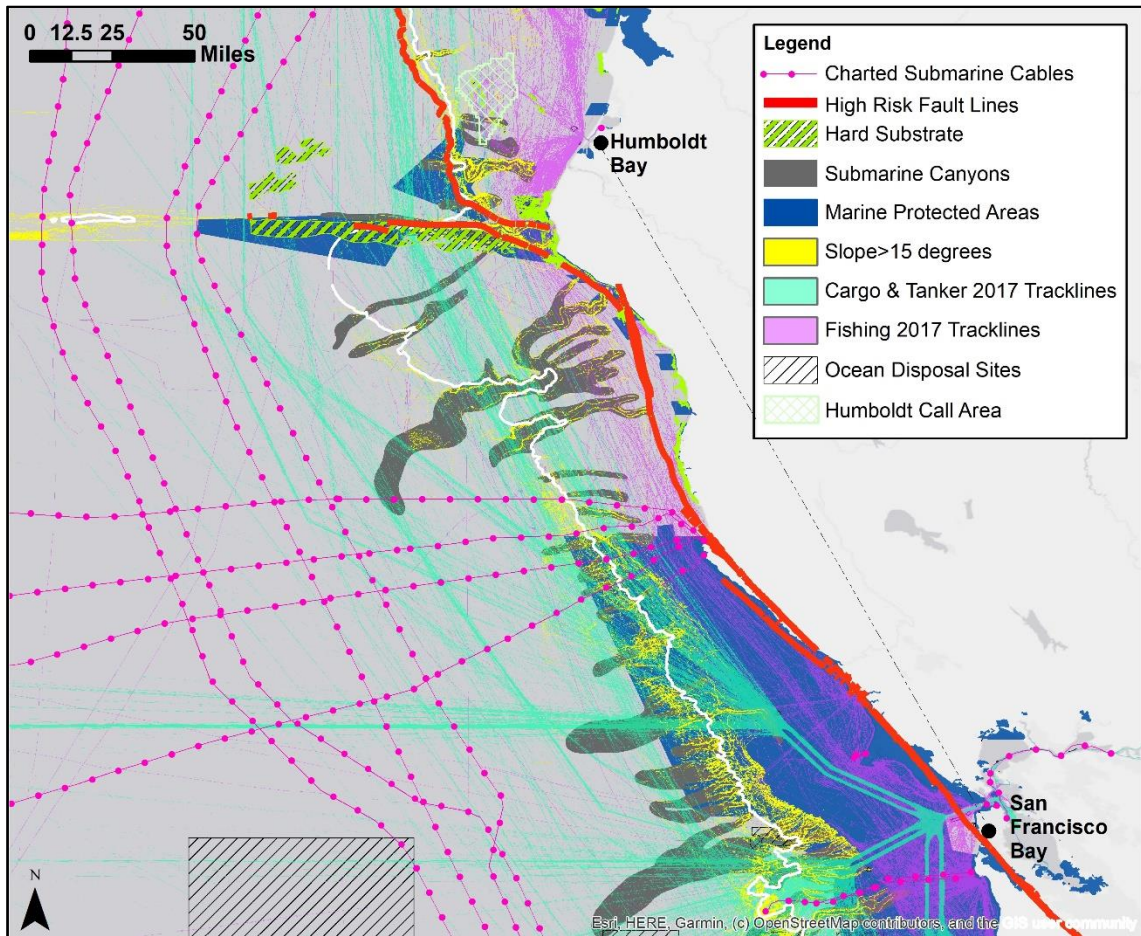


Figure 1 - Existing Subsea Conditions Between Humboldt and San Francisco Bays. White line shows the 6,560ft (2,000m) contour

3 Assessment

An assessment has been conducted to identify potential transmission cable system requirements and to document the constraints and hazards relative to potential cable routes. This section first includes an assessment of the cable and converter station components (Section 3.1), key constraints (Section 3.2), and key hazards (Section 3.3). Based on these inputs a routing risk assessment was conducted (Section 3.4) for potential nearshore and offshore cable corridors. Potential landfall in the SF Bay area is described in Section 3.4, and an overview of a probable construction cost for the system is provided in Section 3.5.

3.1 Electrical Technical Assessment

3.1.1 Cable Design

Cable design includes consideration of the rating requirements, types, and number of cables/

3.1.1.1 Cable Rating

- Assessment
 - Assume 500kV cable. The industry is moving towards this option for multiple cable types and should be considered within the project timeframe.

3.1.1.2 Cable Types:

The type of cable affects how many cables are required for the potential cable rating.

- MIND
 - The highest capacity type of cable is mass-impregnated non-draining (MIND) with Polypropylene Paper Laminate (PPL) insulation (to +/- 800kV), though the highest present service rating of this type of cable is +/- 600 kv. With a 4000A converter station, it would be able to be rated up to ~2.4GW for a single pole pair (cable bundle). The cost of MIND cable is about \$800,000 per km of cable supplied
- XLPE
 - Extruded cross-linked polyethylene (XLPE) cables are designed for use up to +/- 320kV, though service experience has shown them up to 400 kV (cable rating of approximately 1.3-1.6 GW per cable). For this project it is assumed that the cable may be up to 500 kV given the project timeline, which would likely be able to meet the project rating requirements, depending on landfall details. The cost of XLPE cable is about \$650,000 per km of cable supplied.
- Assessment
 - The cable may be XLPE or MIND, but for both cable types there is not a proven technology at 9,840ft+ (3,000m+) water depth.

3.1.1.3 Number of cables

- The number of cables is dependent on water temperature & landfall details.
- Based on a 500kV cable technology being available, 1 pole pair may be possible to meet the rating requirements but requires further analysis.
- If multiple cable routes are required offshore, further assessment of spacing requirements relative to the proposed cable alignments and existing constraints needs to be investigated further. Industry standard offset distance for repair and maintenance is approximately 2-4x water depth, which is needed to safely

bring the cable to the surface, repair the cable, and lay back down on the seabed in accordance with industry practice. Horizontal offset distances need further investigation at pinch points (such as between existing subsea cables) to evaluate if two cables can feasibly be installed.

- Details at the SF Bay area interconnection could result in a need to have two 1GW solutions, rather than a single 1.8GW solution.

- **Assessment**

- A single pole pair (single installation) is likely possible, as shown in Figure 2 for an example XPLE pole pair. A two-cable bundle solution (splitting transmission into two cable routes) would provide additional resiliency but would result in significantly higher cost, and further analysis is needed to confirm spacing availability and offshore route feasibility.

3.1.1.4 Cable Design Summary

A single pole pair is likely possible (single installation). XPLE or MIND cable is likely possible to meet rating requirements, but there is not presently a solution for safe installation at 3,000m water depth. Technology developments would be required to allow installations at 3,000m and are not yet proven to be feasible.

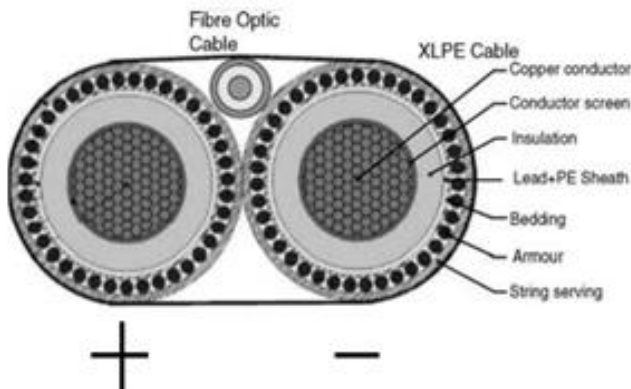


Figure 2 - Cable Cross-Section Concepts - Bundled XPLE Pole Pair example

3.1.2 Converter Stations

3.1.2.1 Background and Type

- Converter stations are needed to convert AC current to DC, and vice-versa. An HVDC transmission system requires converter stations at both terminals of the DC link. Converter stations include specialty electrical equipment such as valves, converter transformers, and filters.
- There are two types of technology available for converter station: Line Commutated Converters (LCC) and Voltage Sourced Converters (VSC). Both converter station types require multiple acres of land, but there are some key differences between converter types that are considered for this study, as described in Table 3.

- **Assessment:**

- VSC is more likely for this project due to likely space requirements in the SF Bay Area and potential AC strength issues with any rolling blackouts/brownouts in CA region for LCC converter stations.

Table 3 – Converter Station Type Summary

LCC	VSC
<ul style="list-style-type: none"> Compatible with only one type of cable (MIND) If AC strength is too low; could lead to instability in the system. Cannot do a “black-start” requires external power. Likely requires space equivalent on the order of 10-20 acres. Mature technology 	<ul style="list-style-type: none"> Compatible with either MIND, or cheaper XPLE cable. More expensive, but smaller footprint likely on the order of 5-12 acres Does not require external power support Newer technology, emerging in the 1980s and 1990s At the time of this study there are no active VSC converter stations operating at the design rating of approximately 1800MW (though there are others in planning stage).

**Figure 3 - Example LCC Converter Station (Western Link, 2200MW)****3.1.2.2 Location**

This section provides commentary on siting of an HVDC converter station, whether offshore or onshore.

Onshore

- The converter stations should be designed for seismic considerations and should be sited with regard to tsunami inundation risk.
- Assessment:
 - If in the inundation zone, the converter station may need to include mitigative measures such as a flood wall or construction on fill.

Offshore

- In general, offshore converter stations are more expensive and complex than converter stations on land.
- At the time of this study there are no existing floating HVDC converter stations, the only offshore converter stations are affixed to the seabed. However, floating HVDC converter stations may be

developed in the future. The Carbon Trust (2018) undertook a concept assessment for floating offshore substations, which included California, and found that floating substations in this wave climate are likely feasible when considering likely floating structure accelerations. However, HVDC converter stations were not specifically addressed.

- If developed, a floating HVDC converter station will need to accommodate potentially large motions at Humboldt due to the energetic wave climate.
- If a fixed offshore platform HVDC converter option were installed it would need to be close to the coast in water depth less than approximately 150 feet, which may not be preferred by stakeholders or permitting agencies. Two platforms may be required, which would require two cables
- Similar to floating offshore wind, the floating structures would necessitate dynamic cables, designed to be able to move within the water. At present, there is no HVDC solution for dynamic cables. The cost for dynamic HVDC cables is likely to be higher as they will likely require copper sheathing.

- Assessment:

- For this study it has been assumed the HVDC converter stations are on land since floating offshore HVDC converter stations and the associated dynamic HVDC cables have not yet been proven technology. Secondly, there are limited locations for a shallow-water fixed foundation HVDC converter station offshore.

3.1.2.3 Converter Station Summary

VSC is more likely for this project due to space requirements and potential issues with blackouts/brownouts in the CA region for LCC converter stations. A floating HVDC converter station may potentially be developed in the future, but no existing technology currently exists for the converter station, or the required dynamic HVDC cables required for interconnection. On-shore converter stations of this magnitude are currently in the planning stage elsewhere in the world.

3.1.3 Potential Spurs to Coastal Towns

At the request of HSU, the possibility of developing spurs to coastal towns from an offshore HVDC backbone has been considered. A brief summary of the challenges and opportunities are described below.

- Converter Stations.
 - A converter station is required to tap off power to smaller communities along route; ongoing maintenance of offshore converter station required (expensive), unless routed to shore.
- Cables
 - More joints offshore means higher risk for potential damage
- Routing
 - If cables are routed onshore, this might provide opportunity for upland routing to avoid canyons/faults.
- Assessment:
 - A spur off the main subsea HVDC link would be very expensive solution to deliver a relatively small amount of power to these communities. This alternative is unlikely to be pursued with existing technology but may potentially be pursued if the DC link is routed upland for a portion of the route.

3.2 Hazard and Constraints Assessment

An assessment of the hazards and constraints affecting the cable system has been developed relative to the mitigation and risk criteria listed in Section 1. Results of this assessment are provided in Tables 4 and 5 for

hazards and constraints, respectively. Details for key constraints and hazards affecting the cable routing are provided in Appendix B.

Table 4 - Hazard Assessment Summary

Potential Hazard	Potential Risk to Transmission Cable System	Potential Mitigation	Assessment
BOEM Offshore Wind Call Areas	Cable may conflict with anchoring and mooring plans.	Coordination with developer or avoidance	Major Mitigation Required
Surface Fault Rupture and Deformation	Displacement of transmission line within upper plate of Cascadia subduction zone.	Align cable along fault lines; Provide excess slack in the cable; Cable armoring with improved tensile strengths and deformation capabilities; Install additional cable for redundancy. Mitigation techniques are applicable for small events; for significant earthquakes cable damage can be inevitable.	Major Mitigation Required. Repairs may need to be planned for. Cable should cross faults in area where repairs are feasible.
Seismic Shaking	Strong motion effects to transmission line	Cable armoring with improved tensile strengths and deformation capabilities; Converter station design considerations.	Major Mitigation Required. Area limits not specified.
Submarine Canyons	Displacement of transmission cables from possible lateral motion during landslide event (HSU, 2019). Steep slopes of canyon walls create spanning and vibration issues.	Complex remedial leveling work would be needed to mitigate for cable spanning. No known mitigation for landslide/turbidity currents.	No-go Area. High risk of damage likely not possible with mitigation. Cable repairs within submarine canyons may not be possible. Submarine canyon details may be assessed further to identify favorable areas.
Shipping Vessel Traffic	Anchors dropped from shipping vessels penetrate and are dragged along seabed, potentially damaging cable.	A cable burial risk assessment (CBRA) utilizing automatic information system (AIS) vessel tracking data should be conducted to aid in acceptable burial depth recommendations.	Minor Mitigation Required
Bottom Trawl Fishing	Bottom Trawl fishing gear is dragged along the seabed. If not buried to sufficient depth, fishing gear can damage cable.	A cable burial risk assessment (CBRA) should be conducted to determine the acceptable burial depth based on acceptable risk.	Minor Mitigation Required
Tsunami	Erosion and strong currents near shore could cause displacement of transmission cable. Inundation and damage to converter station	Sufficient cable burial depth to protect against scour during tsunami event; Seabed in deeper water will be less impacted by a tsunami wave; Placement of converter stations outside design tsunami inundation area.	Minor Mitigation Required
Sand waves	Height and geometry of sand waves can prevent plow from achieving uniform burial depth.	Mitigation typically limited to sand waves of 2-3m. Dredge away sand waves to create flat surface prior to burial; Provide additional burial depth to prevent cable exposure; Stabilize with rock.	Major Mitigation Required. See Section 3.4
Gas Hydrates	Destabilization of subsurface sediment resulting in displacement of transmission cable.	Alternative engineering solutions may be possible, but not within the scope of this assessment. Avoidance if possible.	Minor Mitigation Required.

Table 5 - Constraint Assessment

Potential Constraint	Potential Risk to Transmission Cable System	Potential Mitigation	Assessment
BOEM Offshore Wind Call Areas	Site use permissions may not be possible.	Coordination with developer or avoidance	Major Mitigation Required
Existing submarine cables in deep water	Agreements likely need to be obtained. In many cases, protection must be installed at vertical crossing of existing submarine telecommunication cables. May be challenging to install cable protection infrastructure at these depths. Cable protection more common in shallower water.	Shallow water (<6,560ft or <2,000m). Cable protection measures may need to be installed, such as concrete mattresses. Typical crossing between 65-90 degrees Deep water (>6,560ft or >2,000m): installation of mitigative measures in very deep water are rare or do not exist.	Shallow water (<6,560ft or <2,000m): Minor Mitigation Required Deep water (>6,560ft or >2,000m): Major Mitigation Required
Steep Slopes	Risk of runaway of the plough or ROV and consequential damage to the cable. Fiber optic cables appear to be laid on California shelf on slopes up to 30 degrees.	Avoidance if possible. Specification or development of appropriate cable installation and/or cable burial equipment.	Minor Mitigation Required
Hard Substrate	Required depth of burial may not be achieved in areas with hard substrate.	Alternative cable protection measures such as concrete mattress or rock cutting.	Major Mitigation Required
Ocean Disposal Sites	Site use permissions may not be possible.	Coordination with United States Army Corps of Engineers, provide adequate cable burial or protection or avoidance.	Major Mitigation Required
Installation Depth	HVDC transmission cables at 9,840ft (3,000m) water depth are not yet proven to be feasible	Technology developments would be required to allow installations.	Major Mitigation Required
Sea State	Installation and maintenance activity downtime due to sea state may increase costs.	Further analysis required.	Minor Mitigation Required
Cable Installation Vessel Operational Limitations and Capacity	Multiple joints may result in higher risk of cable fault. Multiple installation campaigns may result in a multi-season or multi-year installation process. .	Industry may develop vessels with larger capacities to meet global demand; may be able to install with 1 or 2 campaigns by 2030s.	Minor Mitigation Required
Marine Habitat Areas	Cable installation can impact/disturb the seabed and it is possible may not be permitted. Prototype review indicates these could be major issue, but mitigation may be possible. Each MPA in California has different regulations. E.g. some restrict fishing, type of vessel traffic, etc., Further refinement needed as part of next steps.	Coordination, avoidance or other mitigation techniques/requirements TBD.	Major Mitigation Required

3.3 Routing Assessment

Results of the hazard and constraint assessment have been applied to the available data layers for each hazard and constraint. The hazards and constraints which geographic data was available for are summarized in Table 6². Based on the assessment in Section 3.2 a suitability map was generated by assigning the classifications for the compiled GIS data layers (Figure 4). Converter stations were not assessed as part of the routing assessment since they are assumed to be located on land. As part of this study, Mott MacDonald was scoped with developing offshore and onshore corridors for assessment. Potential cable corridors were developed based on hazard and constraints mapping, and in coordination with technical experts during a multi-disciplinary team workshop (shown in Figure 4). Two potential cable corridors were developed based on concept-level avoidance of the mapped constraints and are summarized in Table 7.

Table 6 - Potential subsea cable hazards and criteria for constraint mapping

Potential Hazard/ Constraint	Mapping Classification	Mapped Data
Submarine Canyons	No-Go	Large submarine canyons, extending over a depth range of at least 3,280ft (1,000m) and being incised at least 320ft (100m) into the slope at some point along the thalweg (Harris, 2014).
Existing submarine cables in deep water	Major Mitigation Required	NOAA charted submarine cables on the ocean floor at depths greater than 6,560ft (2,000m) contour.
BOEM Offshore Wind Call Areas	Major Mitigation Required	BOEM offshore wind call area data layer (Marine Cadastre).
Surface Fault Rupture and Deformation	Major Mitigation Required	Three highest-risk fault lines (as coordinated with HSU: San Andreas Fault, Mendocino Fault, and Cascadia Megathrust. Mapped according to USGS QFaults layer.
Existing submarine cables (depth<6560ft (2000m))	Major Mitigation Required	NOAA charted submarine cables on the ocean floor at depths shallower than the 6,560ft (2,000m) contour.
Marine Habitat Areas	Major Mitigation Required	MPA's (excluding the 700fm – 1094fm Essential Fish Habitat Conservation Area).
Hard Substrate	Major Mitigation Required	Hard substrate layer provided by HSU.
Ocean Disposal Sites	Major Mitigation Required	Ocean disposal sites layer (Marine Cadastre)
Shipping Vessel Traffic	Minor Mitigation Required	Combined cargo and tanker vessel transit counts for 2017 were mapped based on AIS data from Marine Cadastre.
Fishing	Minor Mitigation Required	Fishing vessel transit counts for 2017 were mapped based on AIS data from Marine Cadastre.
Steep Slopes	Minor Mitigation Required	Areas steeper than 15° degrees were categorized as minor constraints.

² Not all hazards and constraints are mapped due either to the nature of the hazard/constraint, or the available data.

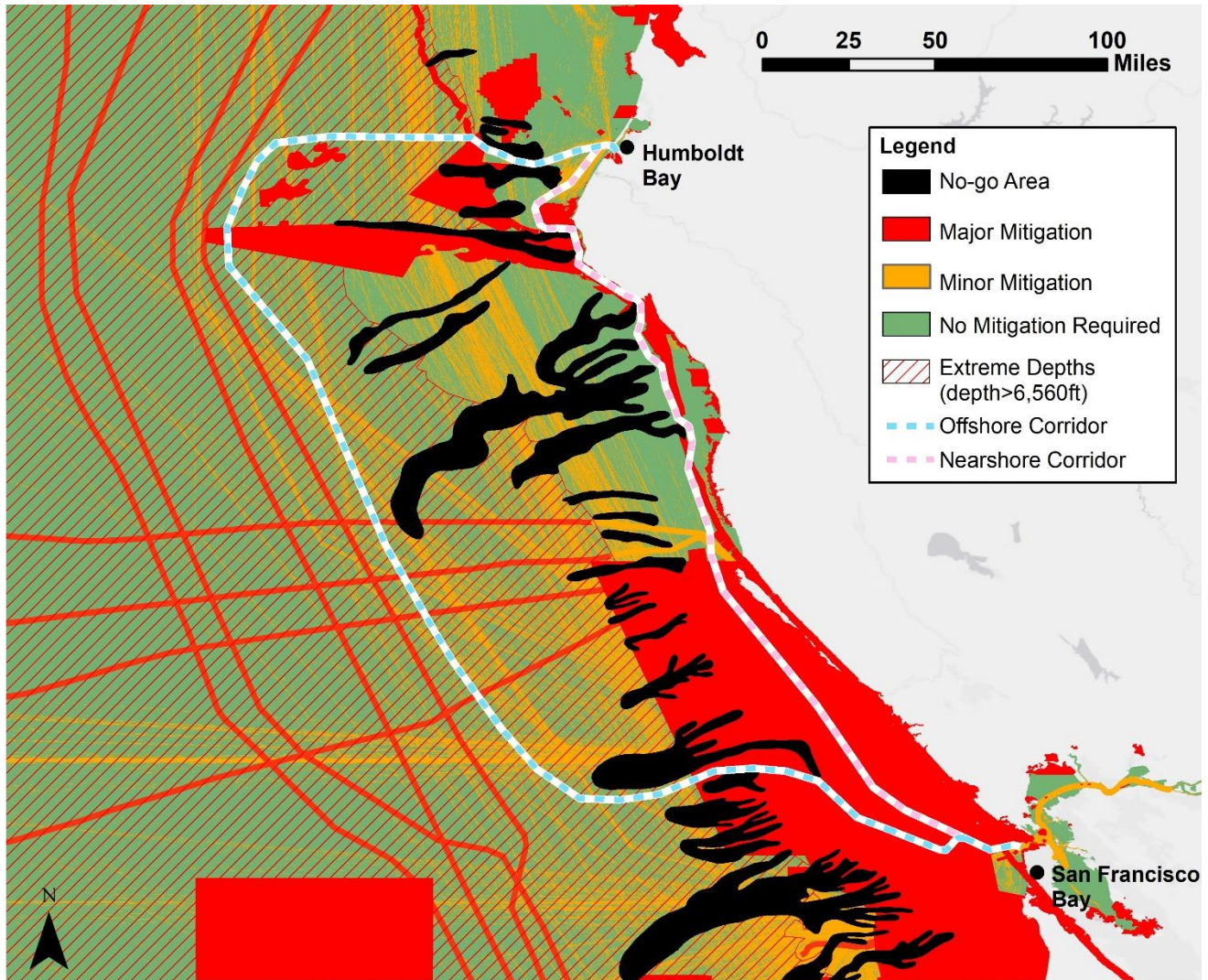


Figure 4. Suitability Map for the Study Area relative to the Offshore and Nearshore Corridors.

Table 7 - Cable Corridor Summary

Cable Corridor	Nearshore	Offshore
Approximate Length	~260 miles	~410 miles
Maximum Distance From Shore	~25 miles	~100 miles
Maximum Depth	~600 feet	~13,000 feet
Primary Constraints	Submarine canyons, hard substrate, marine habitat areas, metocean conditions	Water depth, proximity to, and crossings of telecommunication cable crossings in deep water, continental shelf, metocean conditions
Primary Hazards	Submarine landslides, seismic shaking and displacement, fishing vessels	Seismic shaking and displacement

3.4 Landfall

Potential landfall at the Humboldt Bay and SF Bay termini of the HVDC cable were assessed at a pre-conceptual level, and results of the assessment are provided below.

3.4.1 Humboldt Bay

Landfall at Humboldt is anticipated to be similar to the landfall methodologies outlined in the Humboldt Cable Landfall Memorandum (MM, 2020), with the cable making landfall on a sandy beach.

- Assessment: The likely methodology for landfall is horizontal directional drill (HDD) on the South or North Spit, with a secondary HDD to cross the bay and be routed to the selected converter station site, depending on landfall location. HDD feasibility is dependent on geotechnical investigations, and size of the cable bundle, and requires further analysis.

3.4.2 San Francisco Bay

HSU requested MM to investigate the possibility of routing the HVDC cable to a location within SF Bay. Landfall and nearshore routing in this area are more complex than landfall in the Humboldt Area. No cables presently are routed through the Golden Gate. A number of different challenges were identified:

- Presence of large sandwaves in the Golden Gate (e.g., Figure 5)
- A majority of the shoreline north and south of the Golden Gate consists of steep bluffs and cliffs
- Marine Sanctuary
- High volume of vessel traffic
- Multiple cable crossings appear to be required.

A number of the complexities may be able to be mitigated with appropriate engineering operational permissions, but there are a number of complexities which may preclude routing through the Golden Gate. The presence of sandwaves is typically mitigated by dredging and flattening the area in which the cable will be buried to the same level of the trough of the sandwave. However, CSA Ocean Sciences Inc. (2019) reports this may not be an economical solution for sandwaves with a height of 7-22 feet (2-3 meters). The sandwave height in the Golden Gate are some of the largest in the world (Barnard et al, 2006), reported to be on the order of 30ft (9m). Additionally, in order to conduct repairs in this area, dredging would be required to retrieve the cable for repair, or a new cable would be required.

- Assessment: Further analysis required to assess feasibility of routing subsea cable through the Golden Gate, whether around or through the sandwave areas, but at this level of assessment the option appears unfavorable.

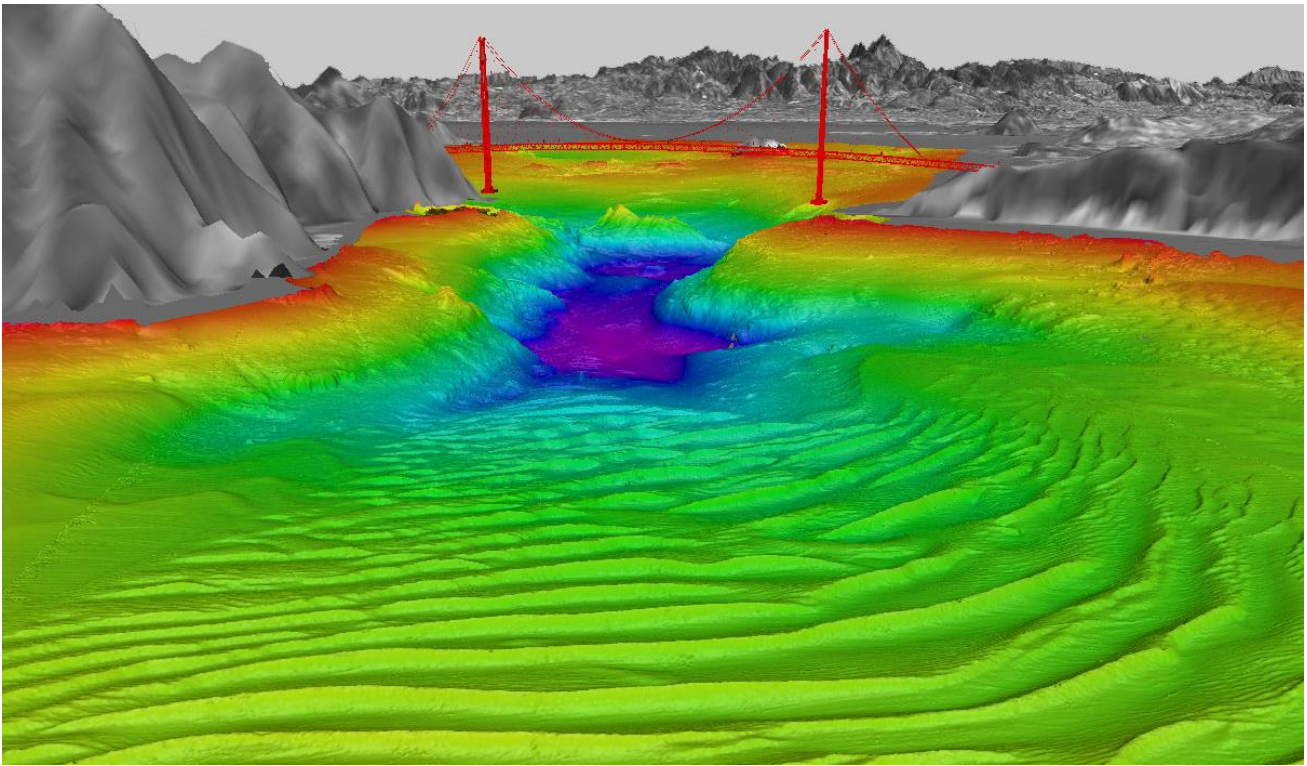


Figure 5 - Golden Gate Sandwaves (note 3x vertical exaggeration) (USGS, 2006)

3.5 Cost

A conceptual-level assessment of potential construction cost was developed to aid in infrastructure planning. Construction costs were based on prior project experience only, and no engineering was conducted. It is important to note that in the subsea cable industry, construction cost is heavily dependent on market at time of bidding. Considering this, a high-level cost estimate was developed. Costs developed do not include land acquisition, re-grading, permitting, engineering, or taxes. Converter station cost is assumed to be for an on-shore station.

- ~\$300m per converter station → \$600million (supply only). Additional cost for land, earthworks, upland routing (depending on location of converter station) should be incorporated into planning, but were not scoped for Mott MacDonald
- ~\$2.5m per km of HVDC link for supply and install (400km) → \$1 billion.
- 30% contingency for market fluctuations and complexity of install.
- Planning-level cost estimate: \$2.1 billion (for 1 cable bundle), \$3.1 billion if two cables required.

4 Summary

A concept-level assessment was conducted to develop options and documents risks and challenges for a high voltage direct current (HVDC) cable from the Humboldt Bay area to the San Francisco Bay (SF Bay) area for the 1,836 MW scenario. The HVDC cable system would consist of the cable system itself and an HVDC converter station at each end of the cable (Humboldt Area and SF Bay Area).

The construction cost of the system is estimated to be approximately \$2.1 – 3.1 billion (based on the nearshore route length), depending on whether one or two cables are installed. It is likely that a single pole pair would be able to meet the rating requirements of 1800 megawatts (MW). Installing two cables along different routes would provide redundancy for the system in case one cable incurs a fault, but would come at an additional cost of approximately \$1 billion.

The subsea study area between Humboldt Bay and San Francisco Bay includes both natural and anthropogenic constraints and hazards with variable levels of risk. These hazards and constraints will require a combination of avoidance and mitigation measures in order to install a transmission cable between the two areas. The primary risks include:

- Hazards
 - Deep subsea canyons extending from the nearshore area to depths below the continental shelf, where subsea landslides strong enough to rupture cables are common.
 - Seismic fault line surface displacements which may be too large to mitigate for. Cable repairs may need to be expected to be conducted with a major seismic event.
 - Some of the largest subsea sandwaves in the world are present outside the Golden Gate, which may preclude subsea transmission cable routing through the Golden Gate.
- Constraints
 - Areas of exposed bedrock and other hard substrate are located within marine habitat areas where cable protection methods may be either expensive or not permitted by agencies.
 - Potential interferences with fishing activities if the cable is not able to be buried or otherwise protected
 - No power cables have been installed to the depths required to route offshore of the subsea canyons (over 9,000 feet deep), and proven cable technology has not yet been developed for installation at these depths.
 - The offshore route will likely require crossing telecommunication cables in very deep water (5,000 feet or greater), which will require permissions from the existing operators. Though telecommunication cables crossings at these depths are common, power/telecommunication cable crossings at this depth do not appear to have previously been attempted.

Due to the location and severity of the constraints and hazards, two potential cable corridors have been developed, a “Nearshore” corridor, an “Offshore” corridor (Figure 6). Both corridors have significant challenges that would need to be overcome to install and operate an HVDC link, though the challenges may not be infeasible. A risk/benefit table has been developed for these corridors based on the results of the hazards and constraints assessment in Table 8.

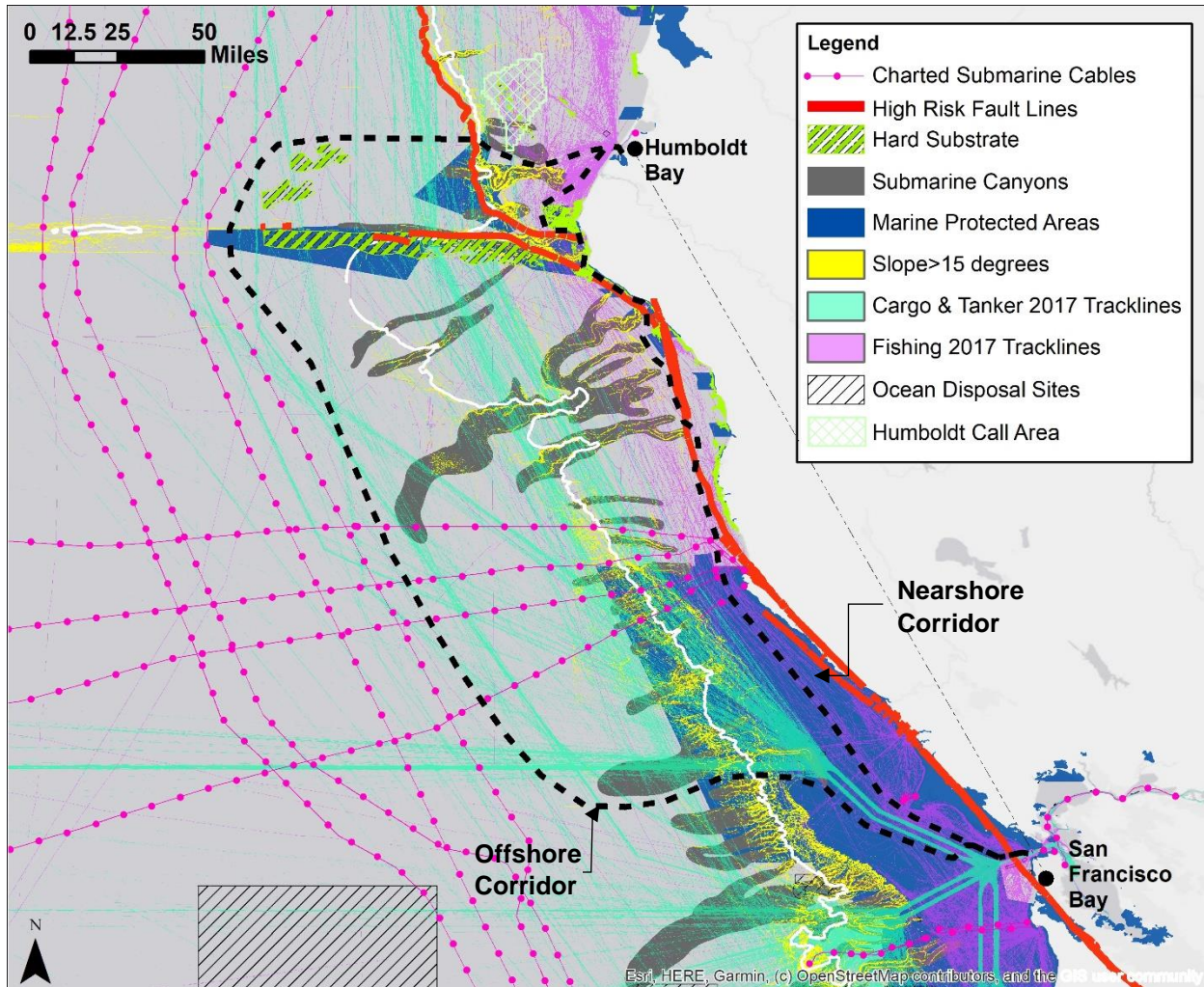


Figure 6 - Offshore and Nearshore Corridors relative to hazard and constraint map.

Further analysis may be conducted to refine the severity of the risks, develop mitigation strategies, and further assess feasibility of the nearshore and offshore routes. The next steps may include:

- Broader data compilation effort and more detailed assessment of trenchability along the seabed
- Outreach to manufacturers to determine likelihood of cable armoring design that can accommodate 9,840+ feet (3,000+ meters) of water depth.
- Conducting a cable burial risk assessment for the nearshore route. This would include detailed assessment of the pinch-points near the heads of Eel and Delgada Canyon, and the Golden Gate.
- Assessment of a combination of subsea and overland routing along the coastline to avoid canyons and potentially avoid the Golden Gate.
- Siting analysis for the required converter stations
- Landfall conceptual engineering to confirm two cables are not required.
- Overland routing engineering analysis in combination with refinement of the subsea and landfall assessments. Overland, subsea, and landfall constraints should be considered together.

Table 8 - Risks/Benefits

	Nearshore	Offshore
Benefits	<ul style="list-style-type: none"> ● Shallower water: Potentially fewer constraints on cable design and ability to bury and protect cable. ● Vessel Anchor Strike: Fewer vessel traffic zone crossings ● Cost: Shorter distance → less material, shorter schedule. ● Steep slopes: Does not require crossing the shelf, but does require crossing Mendocino Ridge 	<ul style="list-style-type: none"> ● Submarine Canyons: Does not cross submarine canyons or turbidites. ● Fishing: Fewer interferences with fishing vessels or trawling if cable is not buried. ● Marine Habitat Areas: Minimizes installation length in marine habitat areas. ● Shipping Vessels: Requires crossing high vessel traffic zone but is at water depth where anchor use is very unlikely.
Risks	<ul style="list-style-type: none"> ● Submarine Canyons: Approaches multiple submarine canyons – high risk of either damage to cable during installation or during operation. ● Hard Substrate: Nearshore bedrock may preclude burial, require expensive burial of the cable, or require other protection methods such as concrete mattresses. ● Seismic: Crossing of multiple large faults, crossing Mendocino Ridge in seismically active zone. ● Fishing: Interferences with fishing vessels or trawling if cable is not buried. ● Marine Habitat Areas: May require installation for significant length of Marine Habitat Areas. ● Alignment: May require a higher number of turns to avoid nearshore interferences and to cross fault lines at oblique angles.. ● Downtime: May result in additional construction downtime 	<ul style="list-style-type: none"> ● Cost: Approximately 30% longer distance → more material, longer installation schedule. ● Continental Shelf: Requires crossing the shelf ● Seismic: Crossing of Megathrust large faults (Cascadia Subduction), crossing Mendocino Ridge in less seismically active zone. ● Depth: may exceed 9,480ft (3,000m), and is much deeper than any existing installed transmission cable. Will likely require special considerations during design of cable, considering strain from installation at this depth. ● Cable Crossings: Power/Telecommunication cable crossings appear to have never been previously attempted at this depth. Risk is that permission to cross cable is not received. Limited area between North/South Cables and the “toe” of the submarine canyons, which should be avoided if possible due to sediment flows.

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Appendix A

Geographic layers utilized for the mapping assessment

<u>Dataset</u>	<u>Source</u>
NOAA Central California DEM	NOAA
NOAA Northern California DEM	NOAA
NOAA Central Pacific Coastal Relief Model	NOAA
NOAA California Ocean Uses	CA Offshore Wind Energy Gateway
Vessel Tracklines (2017)	Marine Cadastre
Marine Protected Area Inventory (2017)	Marine Cadastre Original Source: NOAA Marine Protected Areas Center
Lithological Seafloor	Humboldt State University (HSU)
Fault Lines (QFault)	USGS
California State Waters Map Series Data Catalog	USGS
Geology side-scan sonar	Marine Cadastre
Wrecks + Obstructions	Marine Cadastre
Ocean Disposal Sites	Marine Cadastre
NOAA Charted Submarine Cables	Marine Cadastre
Mean Ocean Surface Current	Marine Cadastre
Mean Tidal Current	Marine Cadastre
2017 Vessel Transit Counts (Fishing, Cargo, Tanker)	Marine Cadastre
Geomorphology of the oceans “canyons” layer	Harris et al, 2014

Appendix B – Hazard and Constraints Assessment Details

Hazard Assessment

Submarine Canyons

- The most common faults in deep water are submarine landslides and associated turbidity currents. Where possible, cable route planners avoid zones of active landslides and turbidity currents such as submarine canyons and channels, but this is not always possible (Source: International Cable Protection Committee)
- CSA Ocean Sciences Inc. (2019) has mapped subsea canyons in the study area. Of the major canyons, Eel Canyon and Delgada Canyon are both mapped within 1-3km of the shoreline. Harris (2014) has mapped additional canyons, which have been included in this analysis.
- Puig et al (2004) has identified periodic storm-induced sediment gravity flows at head of Eel Canyon.
- The continental margin off Cape Mendocino contains more submarine landslides than any other region along west coast of US. One of more prominent slides is Humboldt slide zone, west of Eureka 250-500m water depths. (Field, 1990).
- Submarine Cables and Pipelines (2017) has identified landslides and turbidity currents caused by seismic activity in Taiwan. The events identified travelled over 300 kilometers and caused 19 breaks in 7 different cable systems. The cable repairs works required 11 different vessels which disrupted internet connections for China, Japan, The Philippines, Singapore, and Vietnam.
- CSA Ocean Sciences Inc. (2019) notes the following with regards to the Taiwan event: “Each of submarine cable failures to date: less robust telecom failures, not buried, in deep water, or had been laid in mudslide area down slope of continental shelf”.
- Carter et al (2014) summaries the following w/regards to submarine canyons
 - 2006 Taiwan earthquake triggered instantaneous breakage of cables due to sediment density flows
 - Key lesson: avoid, where possible, submarine canyons, especially those fed by high discharge rivers.
 - Frequency of sediment density flows is a consideration – crossing a system with a probability of 1x/century may be acceptable.

Seismic Activity

- The HVDC cable will need to cross multiple fault lines, with varying risk of a seismic event and surface displacement. For this study, the focus was on the major fault lines.
- Seismic risk is a significant consideration for cable maintenance risk. For example half of all trans-pacific cables were damaged due to 2011 Japan Earthquake.
- BOEM recommends to avoid direct fault areas where large displacements occur.
- Some mitigation techniques exist, but its unlikely that all risk from seismic activity can be mitigated.
- Both CSA Ocean Sciences Inc. (CSA Ocean Sciences Inc., 2019) and the California Public Utility Commission (CPUS, 2014) have issued reports recommending that additional cable slack be incorporated in fault areas where displacements could occur. Additionally, crossing the fault line at an oblique angle and improved cable tensile strength may provide some resilience. However, there is likely no reasonable mitigations available, and some level of repairs should be expected due to displacement.
- The need for planning for seismic risk will likely be a function of the likelihood of occurrence relative to the design life of the cable.

- Fault lines will need to be crossed, and depending on the severity of the vent, no mitigation may be able to preclude damage. Therefore, the cable should be routed through areas where maintenance activities can be safely carried out. Additionally, avoiding the downslope area of a subsea canyon may reduce risk. Fault crossings and cable route requires further geologic investigation to quantify risk. A secondary cable, crossing different fault lines, could provide resilience against a major seismic event.

Constraints Assessment

Installation Depth

- Given the current status of existing HVDC cable technology, it is installation of the HVDC cable in water deeper than 1600m would likely incur significant risk due to the levels of lay strain and water pressures at such depths.
- High-risk to plan for HVDC cable installation in very deep (1600m+ water depth), but should not be precluded from possibility.

Installation Vessels

- At present the approximate vessel cable length capacity is ~100km/vessel (current tonnage capacity). Therefore, multiple vessel campaigns would likely be required with the existing vessel fleet.
- Industry may develop vessels with larger capacities to meet global demand; may be able to install with 1 or 2 campaigns by 2030s.
- To reduce installation timeline, it may be possible to have multiple vessels installing in parallel.

Open Ocean Operations and Wave Climate

- Because joints are likely required between the multiple vessel campaigns needed to install the cable, further assessment needed to assess downtime during this process.
- The jointing process is similar in deep/shallow water, but additional time and complexity is present in deep-water locations to bring up the cable from large depths.
- During jointing operations the vessel needs to be stable (e.g. requiring calm seas) for long period of time (3-5 days), which may be difficult in the Pacific.
- Because the cable installation would be primarily parallel to shoreline, the vessels will be dealing with beam seas, which decreases the sea state in which the vessels can operate (more downtime).
- Barge installations in shallower water are typically more weather dependent due to the type of equipment used.
- There is likely to be downtime for cable installation vessels/barges in the study area more so for near-shore areas. Additional assessment may be required to confirm weather window availability for jointing operations.

Maintenance

- According to the International Cable Protection Committee:
 - Worldwide there are approximately 150-200 subsea cable faults per year, due to a number of different causes.
 - 60-70% of faults are due to fishing and shipping occurring in shallow (<600 feet) water.
 - Less than 10% of faults are caused by natural hazards, but do occur in deep water.

- Cable recovery and operation & maintenance activity is limited by sea state. It is possible that such activities will not be able to occur for significant wave heights exceeding 10 feet (3m). During these operations the vessel needs to be stable for long period of time (3-5 days), which may be difficult in this area of the Pacific in winter conditions. Repairs may be limited to summer seasons.
- Requires cable installation spacing of typically at least 2x water depth to conduct repairs without affecting nearby features (such as existing cables). 3-4x water depth is preferred spacing.
- Maintenance takes longer offshore than in nearshore due to deeper water and complexity of operations.
- Certified, trained jointers need to be available to maintain the cable warranty.
- Maintenance planning should be conducted. There may be significant downtime should a cable fault occur, between the time of the fault, and repairs being conducted. Appropriate vessels will need to be mobilized with trained crew, and repairs to power cables have never before been conducted for the depths along portions of the study area.

Telecommunication Cable Crossings

- Permissions will likely be needed to cross existing telecommunications cables. In shallow-water applications the risks of export cables crossing telecommunication cables are mitigated by engineering appropriate protection measures, such as a concrete marine mattress or other. Telecommunication cables also cross one another in deep water, but the permission risk for a high-voltage cable crossing an existing telecommunications cable may be more challenging.
- Concrete mattress protection may be deployed from vessels or remote operated vessels (ROVs) to protect cables which are crossed (CSA Ocean Sciences Inc., 2019), as shown in . However, installation of this technology at extreme depths where a number of the telecommunication cables are present, is likely to be very be challenging. Installation of concrete mattresses at extreme depths (3,000m+) is not known to have occurred globally (note that a detailed investigation was not conducted, and examples may exist).
- Feasibility of cable crossing in very deep water requires additional investigation.

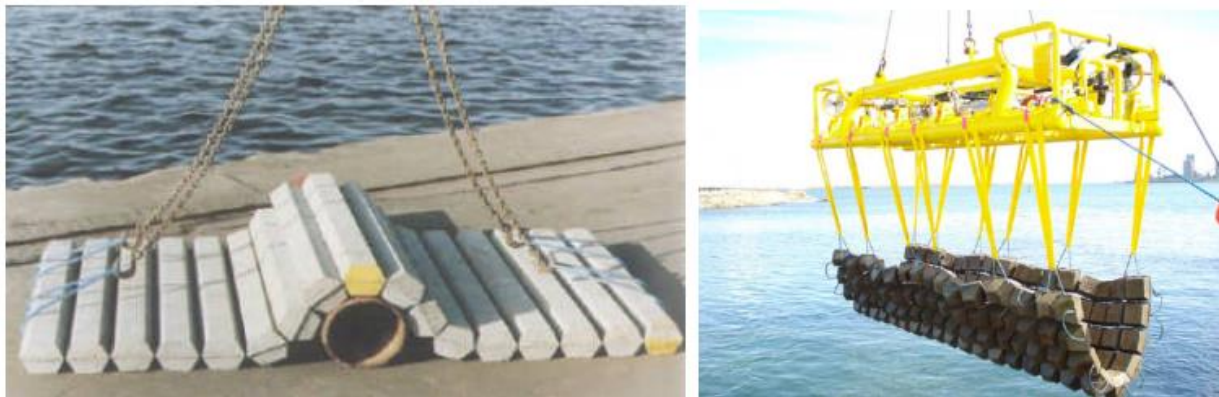


Figure 7 - Cable Crossing Protection Example Applications