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Singapore-US Feasibility Study on Regional Connectivity: Interim Report

December 2023

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U.S. DEPARTMENT of ENERGY

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There is strong potential amongst the Association of Southeast Asian Nations (ASEAN) to adopt subsea interconnectors and benefit from increased energy trade and decarbonization benefits. As part of the Net Zero World Initiative, co-sponsored by the U.S. Department of Energy and the Energy Market Authority of Singapore, the technical and economic potential for such connectivity was investigated. This interim report provides a summary of the economic and technical feasibility analysis conducted related to increasing regional connectivity in Southeast Asia via subsea cables. This report includes four sections:

1. Technical feasibility and estimated costs of a long-distance subsea interconnection in Southeast Asia
2. Renewable energy supply-demand landscape of ASEAN countries
3. Study of grid infrastructure of ASEAN countries
4. Socioeconomic impacts of regional connectivity.

The focus of the analysis to date has been on item 1. Analysis on items 2, 3, and 4 is ongoing, and results will be shared in a final report.

Contents

1. Technical Feasibility and Estimated Cost of Long-Distance Subsea Interconnections in the SE Asia Region

The Net Zero World team evaluated the technical feasibility and estimated costs for connecting Singapore to other ASEAN nations with a long-distance subsea interconnector. This section covers:

1. Regional context
2. High-voltage direct current (HVDC) projects to date
3. Potential routes from Singapore to Vietnam
4. Risks, mitigation best practices, and potential impacts
5. Conceptual cable system
6. Cost estimates.

1.1 Regional Context

Southeast Asia is a region characterized by a rich diversity of nations and renewable energy resources. Several of these resources have already been harnessed and will continue to be further developed. Solar irradiance is plentiful throughout the region, land-based winds are economically viable in the northern countries, and robust offshore winds are found in the South China Sea, particularly near Vietnam and the Philippines (RE Data Explorer 2023). Major river systems have enabled development of a robust hydropower fleet, and Myanmar and Indonesia hold untapped development potential (International Renewable Energy Agency and ASEAN Centre for Energy 2022).

The distribution of these resources throughout the region provides an opportunity for load balancing and power trading between nations, which could be unlocked by subsea and overland interconnectors. The benefits of interconnectors are multi-faceted. They can enable production cost savings; greenhouse gas and local pollutant emissions reductions; generation capital cost savings; mitigation of risks associated with fossil fuel price volatility, load growth, renewable energy development, and thermal plant retirements; resource adequacy contributions; power supply resilience; and jobs associated with renewable energy development and integration (Energy Systems Integration Group 2022). Given these opportunities, a technical feasibility study of long-distance interconnections in Southeast Asia was initiated under the Singapore-US collaboration under the Net Zero World initiative.

1.2 Projects to Date

Interconnector technology has already been proven in shallow waters, such as those near Singapore. In 2015, Ardelean and Minnebo (2015) summarized 28 commissioned subsea HVDC interconnectors worldwide, reproduced in Figure 1. Relevant projects in the region are the Leyte-Luzon interconnector in the Philippines, which links geothermal resources to the load center in Manilla, and the Basslink interconnector between the Australian mainland and Tasmania. Until October 2022, this interconnector was owned by the Singapore-listed Keppel Infrastructure Trust (Packham 2022). In the seven decades of subsea HVDC installations worldwide, the power transfer capability and route length of interconnectors have increased as cable manufacturing and

installation technology has matured. Three projects have been commissioned since 2015, including the Norway-UK interconnector or "North Sea Link." The North Sea Link is the longest subsea interconnector in operation today at 720 km with a total power capacity of 1.4 GW (Figure 2). Due to high-capacity power transfer, interconnector length, and similar bathymetric conditions, the North Sea Link project (Figure 2) serves as an excellent proxy for an interconnector in the South China Sea.

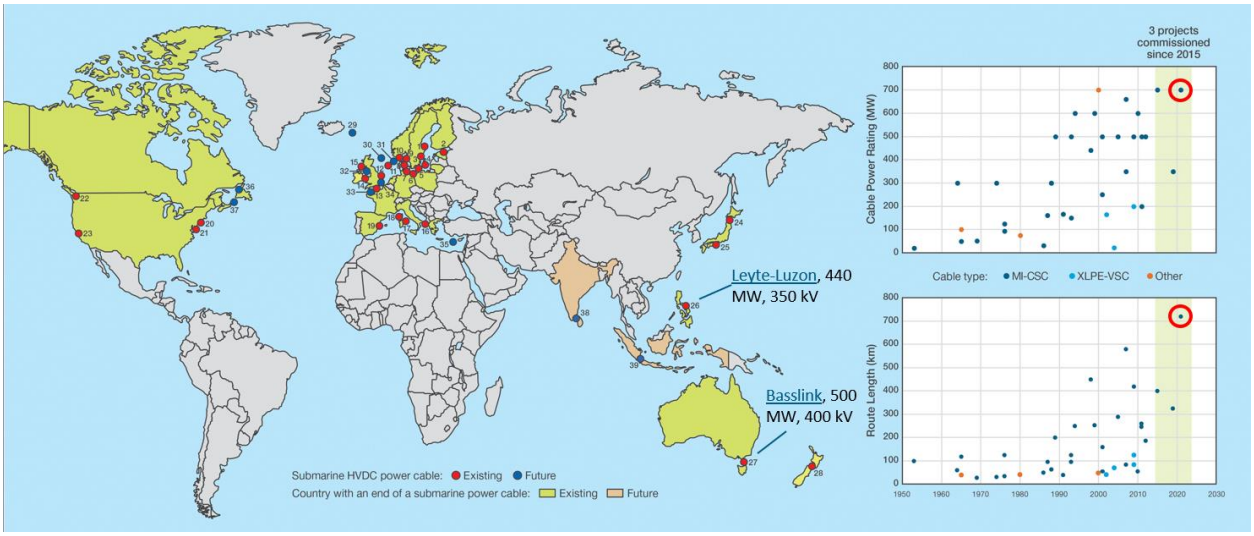

Figure 1. Commissioned (red dots) and planned (blue dots) HVDC subsea transmission projects around the world (Ardelean and Minnebo 2015). Power rating and route lengths have increased over time. The vast majority of cables incorporate mass impregnated-current source converter technology. North Sea Link project circled on inset plots at right.

The North Sea Link uses an HVDC "bipole" converter station configuration, with two 700 MW HVDC subsea cables installed alongside each other in separate burial trenches. The bipolar configuration will be the center of discussion in this section of the report. Other electrical configurations of subsea interconnectors are discussed in the Annex. A bipole system transmits power through two high-voltage cables of opposite polarity (e.g., +550 kV and –550 kV) (National Grid 2014). A bipolar HVDC link is composed of two separate monopoles. When a fault occurs on one of the poles, or to facilitate maintenance work, one pole can carry half the capacity of the entire bipole system. Because of a single return conductor, the losses in an HVDC bipole are also lower when compared to two separate monopoles for achieving the same power transmission capacity.

Spacing of the conductors in a long-distance interconnector is a key consideration in an interconnector design. Due to the requirement for two separate conductors in an HVDC bipole, the North Sea Link cables were installed in separate trenches. To minimize the potential for damage to both conductors due to the same external threat, the trenches were separated by approximately 50 meters. Within 200 meters from shore, the trenches begin to converge to the landing point and are separated by approximately 20 meters.

Figure 2. UK-Norway North Sea Interconnector (North Sea Link 2023).

The specific cable design used is a key component of the interconnector. Most of the commissioned projects to date, including the North Sea Link project and the very first HVDC transmission project in Sweden in 1951, have relied upon mass impregnated-voltage source converter (MI-VSC) technology (Figure 1). For the UK-Norway North Sea Link, two cables nearly 15 cm in diameter are used, weighing 50 kg/m. The cables have a copper core, are insulated by MI paper, and are protected by steel cable armoring. For high-capacity subsea links (more than 1 GW HVDC) and long distances (upwards of 50 km), these are the only types of cables used. MI type cable is a proven technology and has been widely used on similar HVDC cable projects (e.g., the UK-France interconnector, the BritNed interconnector between UK and the Netherlands, and the SwePol link between Sweden and Poland). The MI cable is a stranded-type single copper core cable that has paper insulation impregnated with high-viscosity mineral oil. It is not pressurized like a fluid filled cable and has no free oil that can leak out in the event of a cable sheath rupture. Supply chains for such cables are well established, though lead times for orders are significant, and there may be opportunities for supply chain expansion in SE Asia.

As an alternative to conventional HVDC design, VSC-HVDC has recently grown in popularity as a means of improving the stability of AC grids. Voltage and frequency instabilities, power swings, and transients are the main potential sources of instabilities in AC grids. To prevent these system disruptions from happening or to attenuate them altogether, a variety of methods are used, such as imposing operating constraints on transmission capacity or installing phase-modifying equipment. Locations suitable for large clean energy projects are often prone to poor reliability due to

vulnerabilities in existing local grids and a lack of short-circuit capacity. Increased renewable penetration frequently requires additional measures to address these problems. Installing VSC-HVDC at such places can facilitate in stabilizing the local grid as well as offer a mechanism to transport clean energy to regions of high demand. More information on VSC-HVDC and its alternatives is provided in the Annex.

1.3 Potential Routes from Vietnam to Singapore

Two viable cable routes from Singapore to a strong location of renewable energy resources in the Bin Thuan province of Vietnam have been analyzed. This section presents these two options (Figure 3) for routing an HVDC cable between Singapore and Vietnam and includes estimates of the characteristics of the two cable routes. Additional information and considerations for routing can be found in the Annex at the end of this document.

The Singapore landing location, Pulau Ular Labrador A (Figure 4), is an approximately 9-hectare area of reclaimed land between Pulau Ular and Pulau Busing. It was designed to provide an expansion area for nearby refineries (Connolly and Muzaini 2021) but is currently unused.

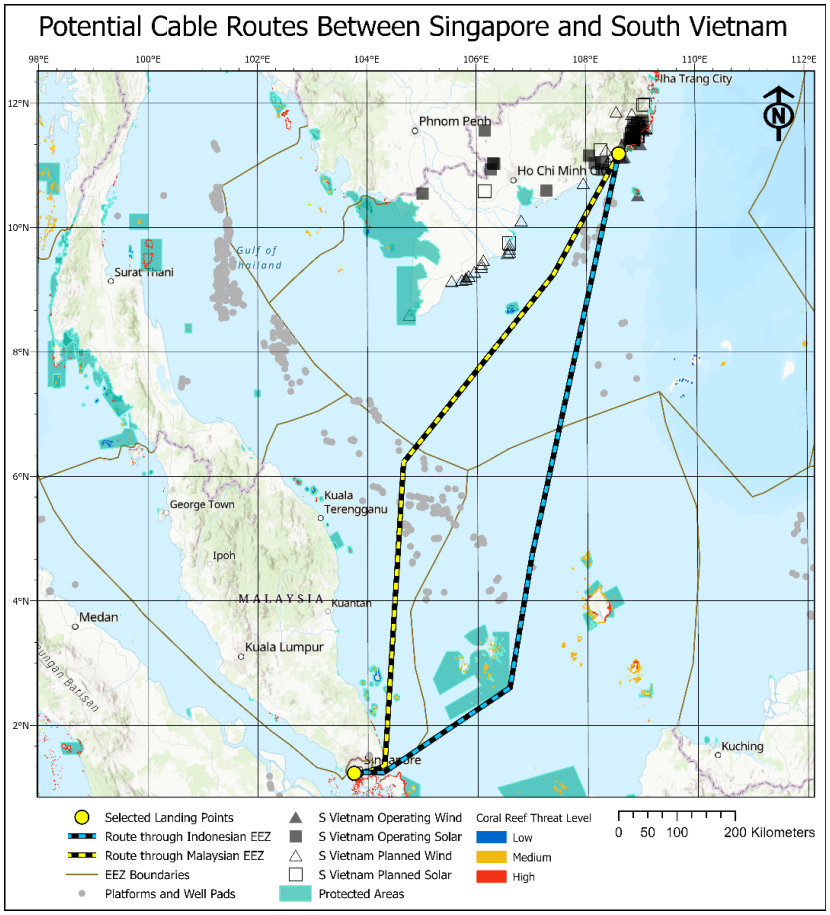

Figure 3. An overview of potential cable routes between Singapore Landing Location G, Palau Ular Labrador A, and Binh Thuan, Vietnam. Overlays include environmental and infrastructural data that were important for modeling the routes.

The Vietnam landing location in the Bin Thuan province was chosen from among several coastal sites due to its proximity to current and planned renewable energy sources. Its location to the northeast of the Mekong Delta reduces the impacts of scour from the emptying Mekong River on the cables.

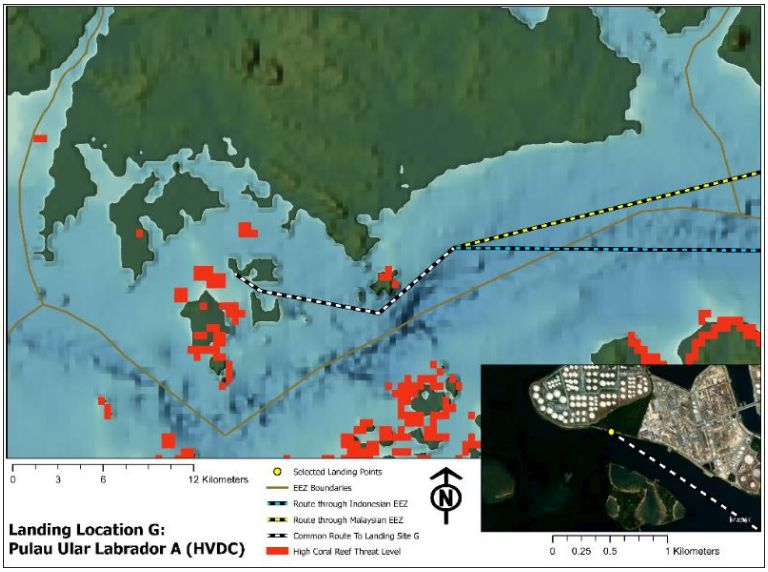

Figure 4. Detail of Landing Location G with an inset showing recent satellite imagery of the site.

The cable routes between the landing locations were determined using a combination of infrastructure, environmental, and boundary data (see Table A.1 in the Annex for more information). Potential routes were created with the goals of reducing cable and pipeline crossings, reducing the environmental impact on marine protected areas (MPAs) and critical habitats, and reducing the number of crossings between exclusive economic zones.

The total estimated length of the two routes is similar, with the Malaysian route slightly shorter at 1,225 km compared to 1,249 km for the Indonesian route. Similarly, the maximum estimated depth for the Malaysian route is slightly less than that of the Indonesian route at 78 m and 100 m, respectively (as seen in the Annex, Figure A.1). The Malaysian route includes 52 telecom cable crossings and 11 pipeline crossings. The Indonesian route includes 48 telecom crossings and 9 pipeline crossings (as seen in the Annex, Figure A.2). Both routes are fewer than 2 km from the nearest MPA. Depending on distance requirements from MPA boundaries, adjustments to the route will increase overall cable length for the Indonesian route by approximately 3.5 km for every 5 km increase in distance from the nearest MPA (as seen in the Annex, Figure A.3).

1.4 Risks, Mitigation Best Practices, and Potential Impacts

This section summarizes findings from a literature review of the risks—which can lead to faults—facing subsea cables, actions that can mitigate these risks, and impacts when faults occur.

Risks

Subsea cables face numerous risks and can fail due to both external and internal causes. The following external risks could affect the project under consideration:

1. Turbidity flows and scouring currents. Subsea currents carrying sediments (turbidity flows) can place damaging mechanical stresses on cables (Carter, Gavey et al. 2014). Scouring currents can cause local de-burial—the exposed free-spanning segments of cables can fatigue from strumming vibrations (The Crown Estate 2015, Li, Hao et al. 2023). These risks are expected to be greatest near the northern landfall of the cable in routes closer to the Mekong Delta (Liu, DeMaster et al. 2017).
2. Anchor strikes. Anchor strikes from shipping activity are a potential threat across the entire cable length but are especially pertinent in shipping channels and designated anchorages. The greatest anchor penetration depth found in the literature was 9.2 m, a modeled impact corresponding to a 20–30 tonne anchor in soft clay seabed (Sharples 2011).
3. Fishing. The greatest fishing gear penetration depth found in the literature was 0.45 m, corresponding to a hydraulic clam dredge in loose gravel (Pitcher, Hiddink et al. 2022).
4. Crossings with pipelines and other cables. Crossing considerations are expected to vary case by case. In general, there is a risk of chronic abrasion damage or acute damage from the installation or repair of the other piece of infrastructure involved in a crossing, processes that may involve de-burial (Reda, Rawlinson et al. 2020). In some cases, cables must depart their burial trenches to cross over cables or pipelines on the surface. Though point protections such as rock piles or concrete mattresses help mitigate this risk, cables may be relatively exposed in proximity to the points of crossing, which increases other external risks.

In addition to external risks, cables can also fail from internal causes like manufacturing defects. An expanded discussion of fault statistics is provided in the Annex.

Mitigations

Mitigation of external threats can be decomposed into a hierarchy. First, routes can be planned to minimize exposure where avoidable. Cable burial is expected to be the primary means of protection and could likely mitigate items 1–3 above. Finally, point protections can be applied to specific situations like crossings and landfalls. Interconnector route design or installation mitigations of internal threats, like manufacturing defects, were not readily identified in the literature.

Cables are commonly buried to a depth of 0.5–3.0 m below the seabed for protection (International Cable Protection Committee (ICPC) 2023). Cables located under actively dredged shipping channels have been buried up to 4.5 m below the seabed (Champlain Hudson Power Express Inc. 2013, Carbon Trust 2015). The deepest burial found in the literature was 14 m below the seabed, to accommodate the construction of a future port (Ardelean and Minnebo 2015).

Cable burial depth comes with tradeoffs. Deeper burial generally provides greater protection from penetrating threats but comes with greater cost and installation time. Deeper burial may also impede future maintenance or repair operations and reduce cable power capacity due to thermal limits and the greater thermal insulation provided by seabed sediment.

A notable best practice is a robust cable burial risk assessment (CBRA) for the entire interconnector route. A CBRA is a comprehensive method for identifying risks and determining the optimal depth of burial relative to the seabed (Figure 5). Specific CBRA methodology has been

developed to optimize tradeoffs between the cost of burial and the reduction of risk (Carbon Trust 2015). In general, a CBRA is carried out by:

1. Discretizing the cable route into smaller, e.g., 1-kilometer, analysis segments.
2. Characterizing the shipping data (corresponding to anchor strike risk), fishing activity (corresponding to fishing gear risk), seafloor sediment hardness (which affects penetration depth by anchors and fishing gear), and other factors for each segment.
3. Applying a statistical analysis to arrive at an optimal burial depth for each segment.

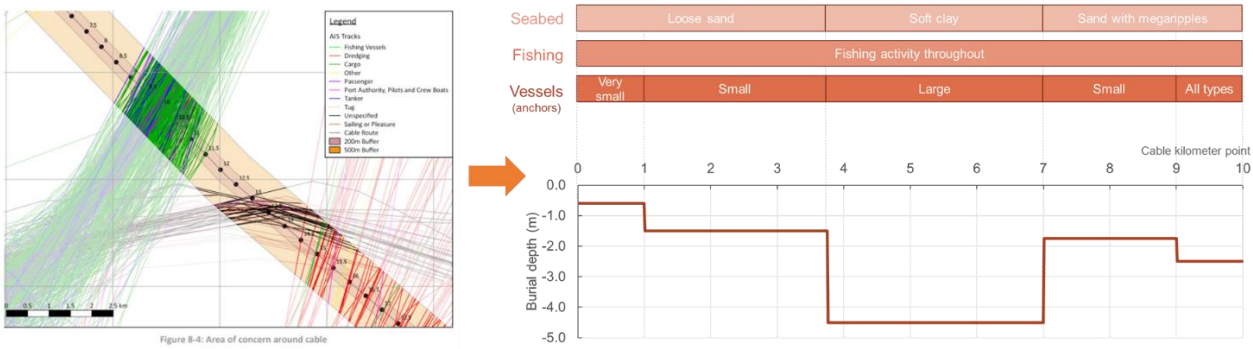

Figure 5. An illustration of a CBRA method. Left: example analysis of shipping data across a cable route (Carbon Trust 2015). Right: an example of determining optimal burial depth corresponding to conditions at each segment, based on a worked example in Carbon Trust (2015).

An important outcome of the CBRA is that the optimal burial depth may vary by segment for the same cable, reflecting varying conditions and risk. Another important outcome is that this risk is rarely zero. Multiple CBRA scenarios can be run with varying levels of risk, with lower risk corresponding to greater burial depth. By including the cost of burial as a function of depth, these CBRAs may yield the evaluation of multiple designs and the down-selection of desirable cost-risk design points.

Stakeholders typically help determine the acceptable level of risk, which is commonly *as low as reasonably practicable* (American Clean Power 2022). There is no widely defined acceptable level of risk, though the DNV Standard F101 (a technical standard for submarine pipelines, not cables) presents a range of risk return intervals based on the expected severity of consequences. Doan et al. (2017) suggest that a return interval of 1000 years (annual probability of 0.001, or 0.1%) may be an acceptable overall risk level for a subsea power cable fault.

Cable crossings and other unique situations like shore landings may require point mitigations like rock burial, protection sleeves, horizontal directional drilling, or concrete mattresses. There are numerous other technical and legal mitigations and best practices, including the use of crossing agreements to govern these situations (International Cable Protection Committee (ICPC) 2014, Askheim 2020, Reda, Rawlinson et al. 2020). Additional discussion of crossings is provided in the Annex.

Impacts

Repairing subsea power cables can be a lengthy and expensive process. Individual repair times found in the literature ranged from 29 days (NKT 2020) to 102 days (New Civil Engineer 2017,

Offshore Energy 2017). Generalized repair times drawn from experience were found to be 65–90 days (GHD 2016). Multiple factors contribute to repair time, including identification of the fault, availability of replacement equipment, and weather conditions. These factors vary seasonally and geographically, resulting in a wide range of potential repair times.

Repairs are associated with two main cost factors: the direct cost of the repair (including the mobilization and staffing of the vessel for the duration of the repair campaign) and the revenue lost while the cable is unable to transmit power (Gulski, Anders et al. 2021). Repair cost estimates are discussed below under cost estimates.

Costs of downtime over these durations are significant. Energy resilience planning will need to account for repair time, and economic projections of the value of lost load may justify more expensive installations with deeper burial or other mitigations, as well as spare part and repair vessel investments. However, as regional connectivity increases, the ability to feed power through alternate routes will inherently reduce the costs of temporary failure of any one interconnector.

1.5 Conceptual Cable System

A comprehensive system design for interconnectors is required to ensure accurate costs, risks, and benefit accounting. This section reviews the full list of major components of the interconnector system.

Interconnector systems are typically composed of two or more laterally separated subsea cables buried beneath the sea floor to minimize the risk of a cable failure due to external impact from a vessel anchor or other ocean co-use equipment. Figure 6 indicates potential separation buffers and burial depths, as extracted from the North Sea Link project. A multi-cable approach is chosen to increase power transfer capacity and limit the risk of a loss of infeed power to the entire interconnector from a single external fault. Naturally, the burial trenches come together near a common landing point and are spaced further apart for the majority of the route.

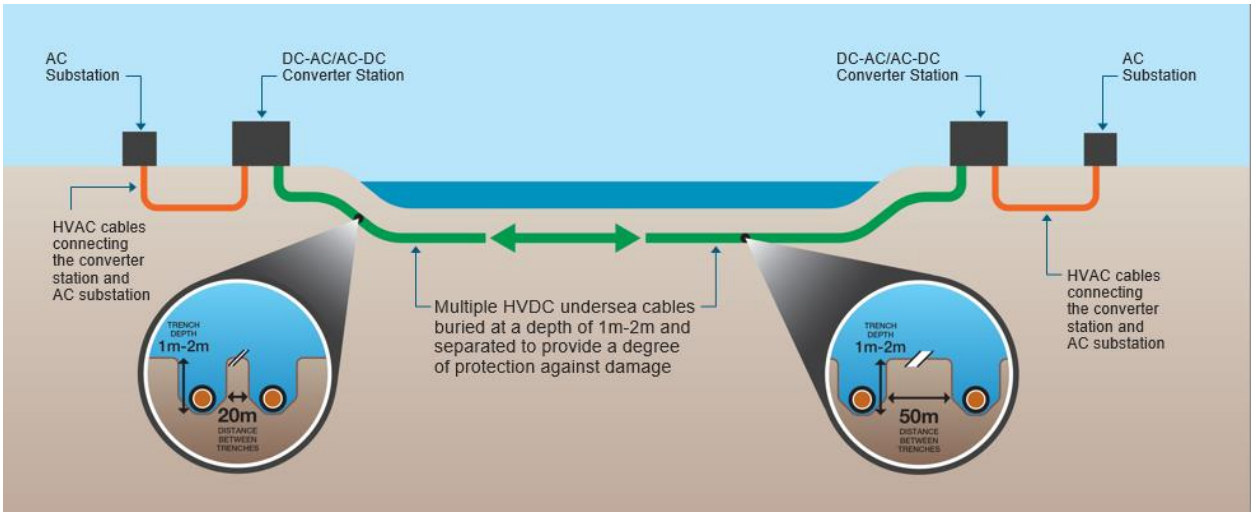

Figure 6. Components of an interconnector system, adapted from National Grid and North Sea Link (2014).

In addition, interconnector systems incorporate substations at the endpoints. These substations are required to convert the interconnector cable voltage and current type to be compatible with the onshore grids. These substations may be in the water or on land. For long distances, such as those considered in this feasibility study, HVDC technology is required to limit power losses along the interconnector length and avoid the costly reactive power compensation equipment required for high-voltage alternating current (HVAC) designs. Because onshore grids run on AC power, expensive converters are required to translate the power from the DC feed of the interconnector cables to the AC grid onshore. Finally, underground high-voltage cables are needed onshore from the HVDC converter stations to HVAC substations. The stations and cables will include protection equipment as well as transformers to step down the AC voltage to meet the needs of the onshore system.

1.6 Cost Estimates

The costs of long-distance interconnectors are significant, requiring long-duration financial instruments and well-funded investors. As a first step, infrastructure cost estimates have been made, and further cost analyses including the potential allocation of those costs to ratepayers will be required in the future. Noting the potential routes, hazards, mitigations, and repair costs of the interconnector system, a simple cost model of the cable route was constructed based on the work of Gordonnat and Hunt (2020). The costs of HVDC converters, HVAC substations, and underground cabling are not included in the model, though the cost of two HVDC converters is approximately $500M USD. Designers must consider any other projects that may be connected on the interconnector and any existing plans for AC-DC conversion near landing points to yield a site-specific, accurate, and comprehensive system cost estimate. Cable supply dominates the capital outlay, followed by installation and protection, mitigation, and enhancement (PM&E), as indicated in Figure 7.

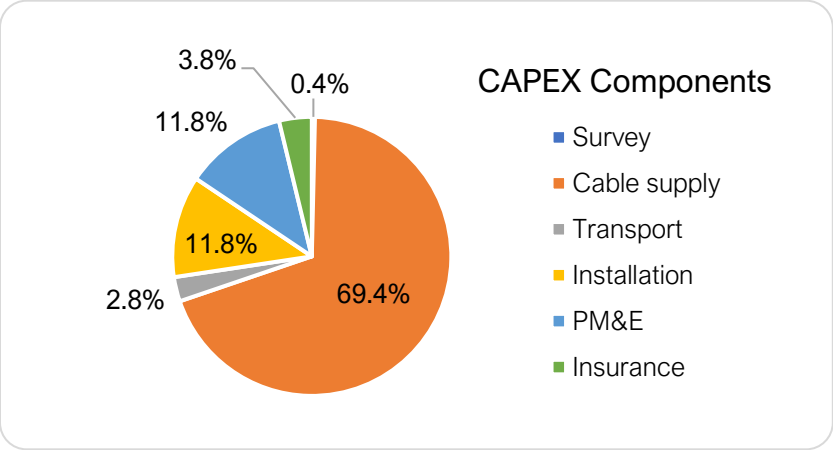

Figure 7. Capital outlay sources for a long-distance ASEAN interconnector.

The overall capital costs of interconnectors with routes spanning Singapore, Malaysia, and Vietnam exclusive economic zones fall between 2 and 3 billion USD ($2023), depending on the Vietnamese landing point (Figure 8). These costs do not assume cable failures during the 25-year project lifespan.

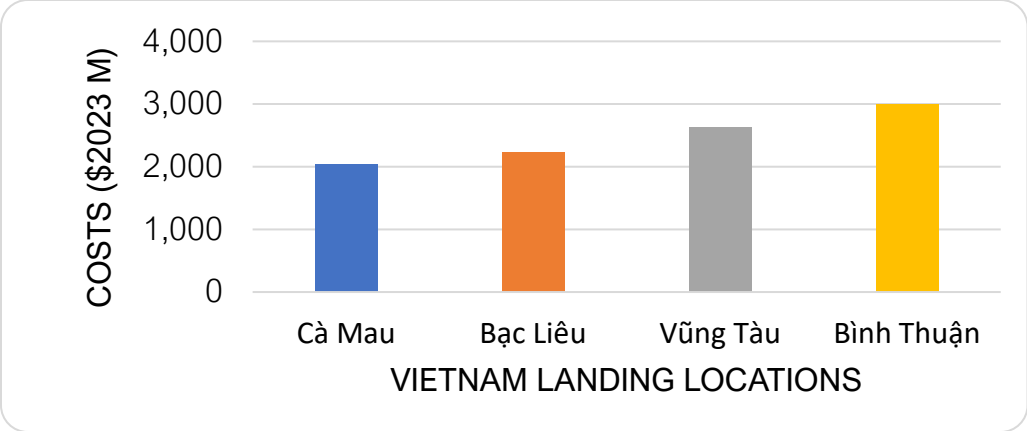

Figure 8. Total capital costs of potential interconnector cable routes between Singapore and Vietnam for various landing points. Costs of HVDC converters, onshore HVAC substations, and transmission links are not considered.

Finally, a sensitivity analysis was run with the cost model to consider the impact to the overall capital costs, in 2023 present value, of repair procedures that may be required during the project lifetime. A repair cost estimate of $16M was used, approximated from reported subsea power cable repairs in the UK (Offshore Wind Programme Board 2017). Repair cost data in the public literature are generally disparate and scarce, and repair costs are expected to vary significantly case by case. These costs are relatively small compared to the capital outlays shown in Figure 8. However, as the frequencies of these repairs are increased, the overall project costs may grow by 6 to 9% for the longest and shortest routes, respectively (Figure 9).

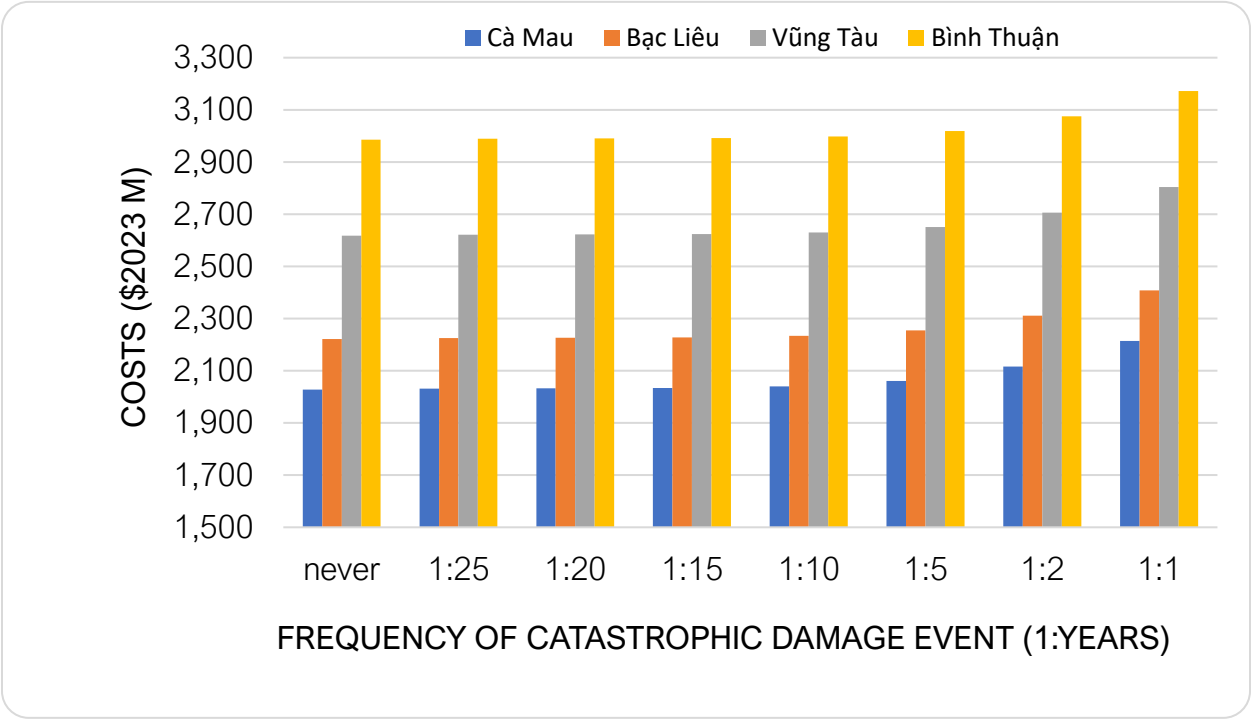

Figure 9. Total project costs for four different interconnector routes between Singapore and Vietnam with varying frequencies of cable failures incurring repair costs.

These costs do not account for the value of lost load, which could be much higher depending on the duration of the outage, and the assumed value of lost load, which some studies have estimated ranges from $5,000 to $50,000 per MWh (Energy Systems Integration Group 2022). In addition, project downtime would be costly due to the opportunity costs associated with the lack of resource adequacy, production savings, and other benefits previously described. An analysis of these factors is recommended to support discussions of risk mitigation in the conceptual design of the interconnector system.

2. Renewable Energy Supply-Demand Landscape of ASEAN Countries

The renewable energy supply-demand landscape of the ASEAN region will be conducted in two steps. First, the best sites for utility-scale energy integration will be reviewed through a power transport model. This will be accomplished by modeling energy supply and demand throughout the region, but at coarse resolution. The fundamental power transport model will be informed by publicly available studies, models, and datasets like renewable energy targets and (subsea) transmission candidates. The Net Zero World team is also coordinating with the Energy Market Authority, Ministry of Trade and Industry, and the ASEAN Center for Energy to obtain the necessary dataset inputs for the region. The power transport analysis will build off the AIMS III analysis, which identified interconnections to meet a regional goal of 23% renewable energy (Suryadi et al., 2022). The AIMS III study focused on the integration of onshore wind and solar and land-based interconnections only; the Net Zero World initiative will expand on AIMS III to consider subsea interconnections, updated renewable energy goals, and opportunities for offshore wind development. The Net Zero World team is also coordinating with other stakeholders in the region analyzing interconnection opportunities, namely the USAID Smart Power Program, Delphos, and the U.S. Trade and Development Agency. Information from the subsea interconnection feasibility studies already underway in the region (i.e., Sumatra-Malaysia and Kalimantan-Surabaya) will inform this work.

The power transport model will be used in approximate expansion planning analyses to identify the best sites for utility-scale renewable energy integration in ASEAN countries in support of regional and national decarbonization targets and Net Zero World initiative metrics. The study will encompass the ASEAN region and specifically emphasize Singapore and Vietnam.

A preliminary benefit-cost analysis, informed by the power transport and interconnector system cost models, will be conducted to provide an initial set of recommendations for the planning process. Costs of meeting renewable energy targets with and without subsea interconnectors will be quantified, and overland interconnectors will remain out of scope.

3. Study of Grid Infrastructure of ASEAN Countries

Fundamental to the prospects of regional interconnectors are the existing transmission systems in ASEAN countries. Review of the existing transmission lines, generator locations, and planned generation and transmission fleet expansion will reveal the upgrades necessary to supply renewable energy resources to loads. In Singapore, of eight potential locations, a landing point of Pulau Ular Labrador A has been chosen due to its location in Singapore's harbor and proximity to

electrical infrastructure, 38 meters of seafront for cable landfall, and 4.5 hectares of land to accommodate an HVDC converter station. A detailed view of this location may be seen in Figure 4.

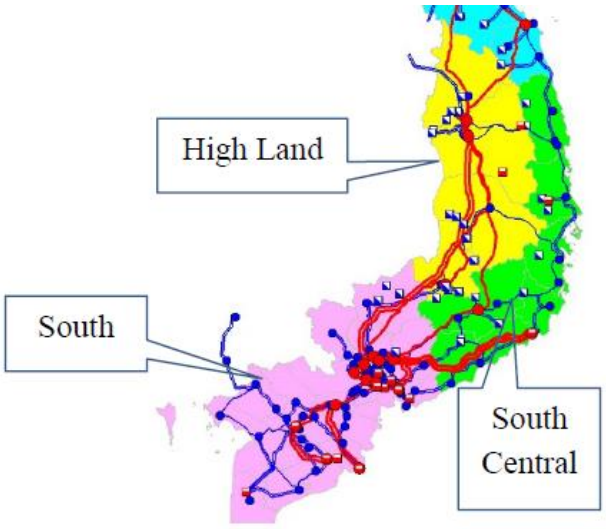

Figure 10. Vietnam's Southern Transmission Grid. The blue and red lines correspond to 220 kV and 500 kV, respectively. Three of six transmission regions are shown (EREA & DEA, 2019).

Analysis of existing onshore electrical and civil infrastructure, landfall potential, and land availability are also required on the other end of the interconnector. To date, this work has only considered Vietnam. The presence of high-capacity transmission lines, shown in Figure 10, and numerous generators in the vicinity of Ho Chi Minh City and near the coast to its northeast, may provide the potential for a robust electrical interconnection to the onshore Vietnamese system with limited system upgrades.

Future work will consider in greater detail the potential for Points of Interconnection in the South and South Central regions of the Vietnamese transmission grid. Collaboration with Vietnamese experts will be necessary. Land access and landfall considerations will also be reviewed in these regions. The electrical topology of Singapore and other ASEAN nations will be similarly reviewed.

4. Socioeconomic Impacts of Regional Connectivity

Clean energy transitions will be accompanied by economic change and socioeconomic impacts, which may include employment, human health, social equity, and technological advancement. A literature review is underway to understand the potential societal impacts of increasing regional connectivity to provide a more holistic approach to energy planning. This literature review will target the benefits that can accrue with increased grid interconnectivity based on findings from other studies or assessments, including improved grid flexibility, lower costs of operations, and lowered emissions. The Net Zero World team is also evaluating the job creation potential from renewable energy deployments enabled by subsea interconnection-based studies conducted on offshore wind projects in other parts of the world. Additional socioeconomic benefits will be evaluated upon completion of the power transport modeling activities.

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Annex A – Interconnector Feasibility

This annex includes additional technical information relevant to the interconnector feasibility assessments to date.

A.1. Additional Cable Routing Considerations

This section includes additional information related to the potential cable routes presented in the main report and information for consideration before finalization of routes. Overlay and proximity analysis was completed in ArcGIS Pro 3.2 (ESRI, 2023). All analyses were completed and referenced to the World Robinson coordinate reference system (CRS) because this was deemed appropriate for the estimation. Final calculations of routes should be referenced to a local CRS for improved accuracy. Data sources considered are listed in Table A.1.

Table A.1. Data layers used for route determination.

Data Layer	Source	Year	Coordinate Reference System	Source Link
Exclusive Economic Zones	ArcGIS Hub	2020	WGS84	https://services1.arcgis.com/VwarAUbcaX64Jhub/arcgis/rest/services/World_Exclusive_Economic_Zones_Boundaries/FeatureServer
Bathymetry Digital Elevation Model	GEBCO	2023	WGS84	https://download.gebco.net/
Bathymetric Contours	GEBCO	2022	WGS 1984 Web Mercator (auxiliary sphere)	https://tiles.arcgis.com/tiles/C8EMgrsFcRFL6LrL/arcgis/rest/services/GEBCO_contours/MapServer
Subsea Telecom Cables	ArcGIS Online	2018	WGS 1984 Web Mercator (auxiliary sphere)	https://services.arcgis.com/nzS0F0zdNLvs7nc8/arcgis/rest/services/UnderseaTelecomCables_2018/FeatureServer
Pipelines and Platforms	ArcGIS Online	2022	WGS 1984 Web Mercator (auxiliary sphere)	https://services6.arcgis.com/62zavqsrcK71xG8O/arcgis/rest/services/Global_Oil_and_Gas_Features/FeatureServer
Protected Areas	World Database on Protected Areas (WDPA)	2020	WGS 1984 Web Mercator (auxiliary sphere)	https://data-gis.unep-wcmc.org/server/rest/services/ProtectedSites/The_World_Database_of_Protected_Areas/FeatureServer
Coral Threat Areas	World Resources Institute	2011	WGS 1984 Web Mercator (auxiliary sphere)	https://databasin.org/datasets/cc89c7fba5a84a638db4ef8631d4641b/

The depth profile used to determine maximum estimated depth (Figure A.1) was created by extraction of bathymetric data from a General Bathymetric Chart of the Ocean (GEBCO) Digital Elevation Model (Table A.1) using points created at 5 km spacing along the route lines. The Indonesian route is deeper than the Malaysian route, but both routes are relatively shallow compared to nearby areas or areas outlined in other studies (Gordonnat and Hunt 2020).

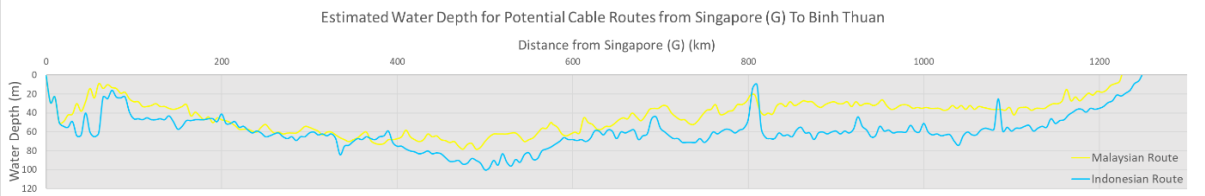

Figure A.1. Depth profiles for both routes presented in this report.

The overlay of the telecommunications networks in Figure A.2 shows the numerous cables that cross through the region, many of which land in Singapore. As a regional communications hub, there are nearly 30 cables that land in Singapore or pass through the Singapore Strait. This makes the incidence of cable crossing high for a new deployment. Cable crossings by the potential routes were determined through spatial intersection of the lines. Cables and pipelines cannot be avoided. Note that some of the data from these layers are misleading because they are potentially generalizations of the actual locations (overland routes) and could also be incorrect representations of some landing locations.

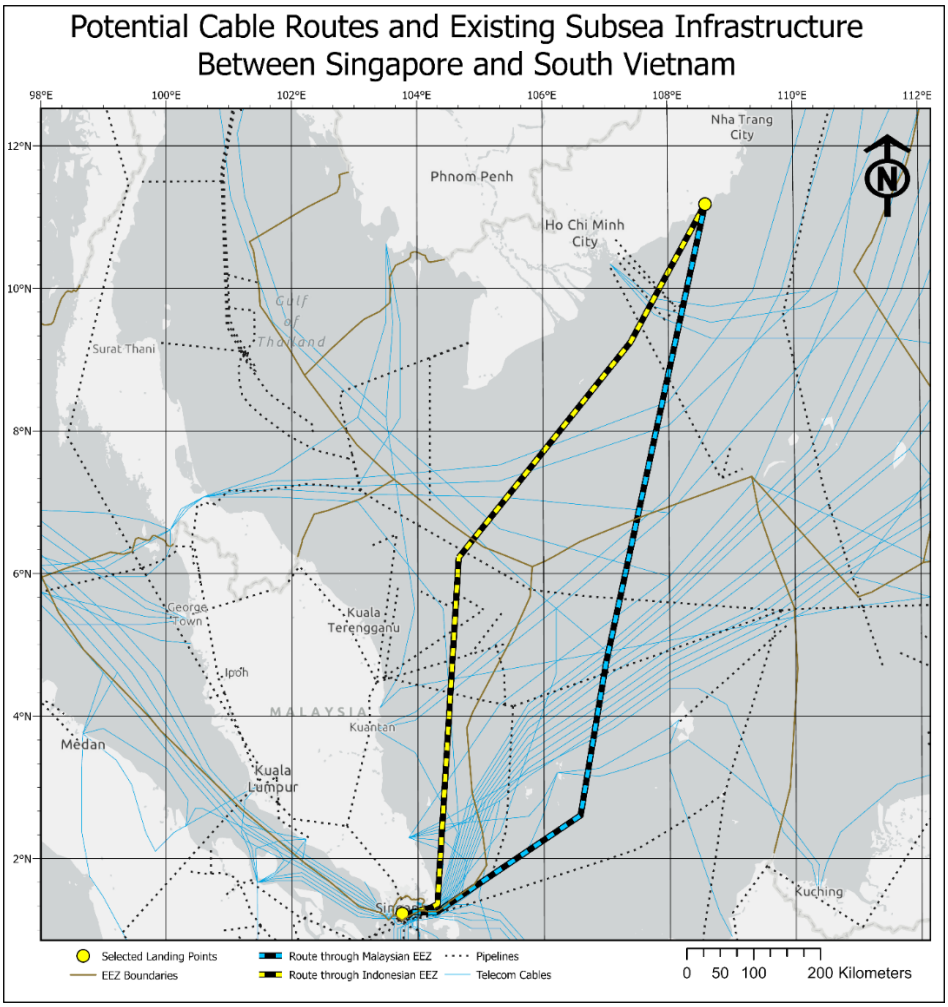

Figure A.2. Potential cable routes overlayed on telecommunications cable and pipeline data for the region.

Both routes pass by designated protected areas. The routes presented in this document could be modified based on any regulations or recommendations related to the conservation of these protected areas, such as increased distance from protected area boundaries due to mechanical or acoustic construction disturbance. Alternate distance routing for the Indonesian route near KKPN[1] Kepulauan Anambas Dan Laut Sekitarnya is shown in Figure A.3. A summary of the change in route length relative to the distance shift from the protected area boundary is included in Table A.2.

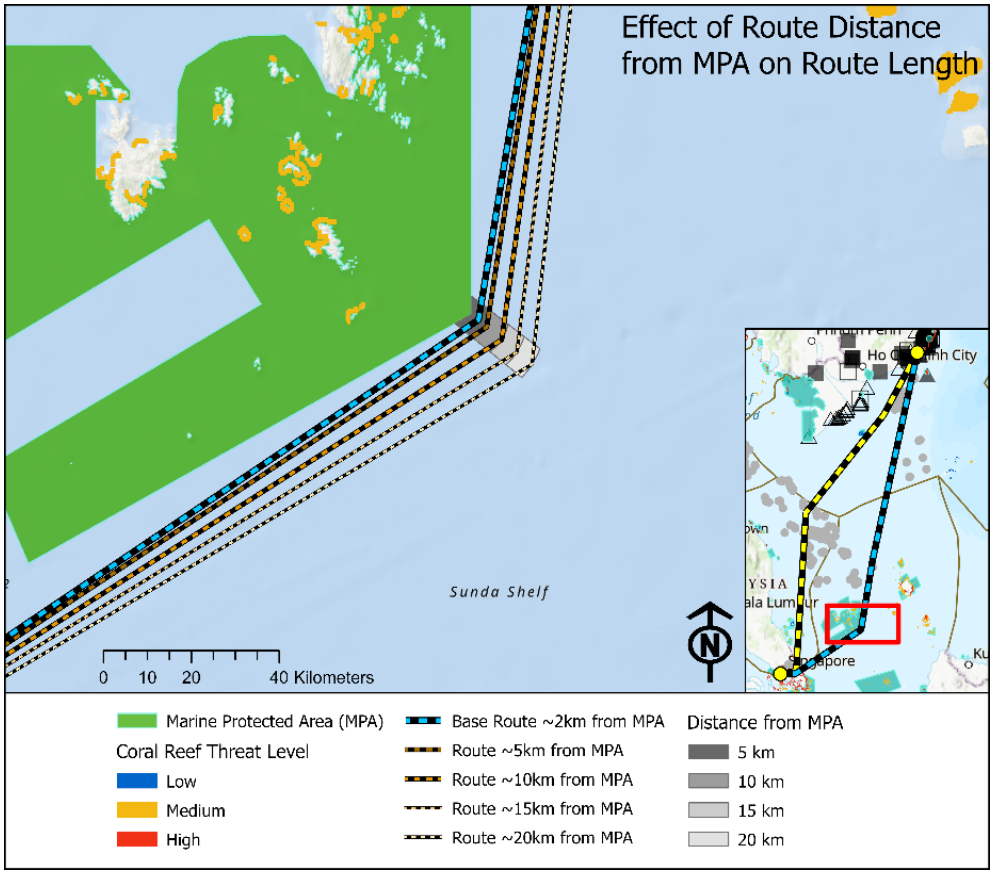

Figure A.3. Detail of the cable route through Indonesian waters showing the location where the cable route passes around the nearest marine protected area and changes to the route as a result of moving the route line further away in 5 km increments.

Table A.2. Route length change relative to the shift away from the protected area near the Indonesian route.

Route Variation	Distance from Protected Area (km)	Calculated Route Distance (km)
Potential Route	< 2	1,249
5 km shift	5	1,251
10 km shift	10	1,254
15 km shift	15	1,258
20 km shift	20	1,262

[1] KKPN is the acronym for a National Marine Protected Area in Indonesian.

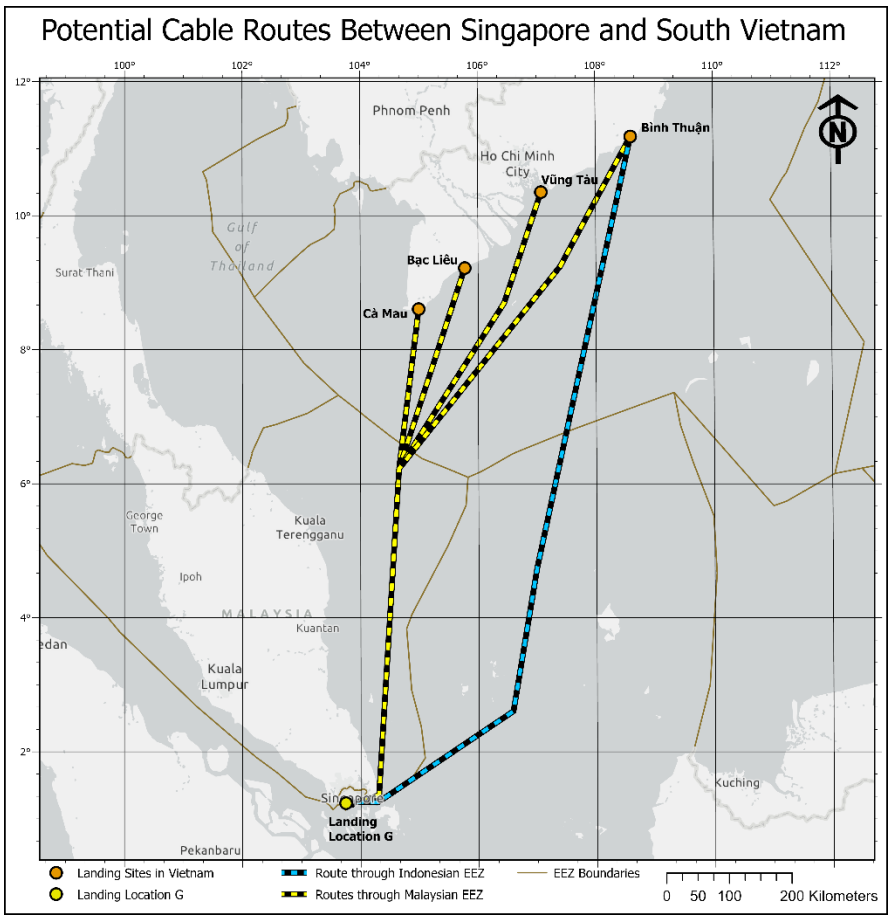

Figure A.4. Considered routes for all potential Vietnamese landing locations.

A.2. Review of Cable Fault Statistics

This section summarizes a Pacific Northwest National Laboratory (PNNL) literature review of subsea cable fault statistics. Publicly available data are generally limited. In general, surveys of older cables have a higher proportion of external faults (Figure A.5). This may be because newer cables are increasingly buried as a means of protection against external threats.

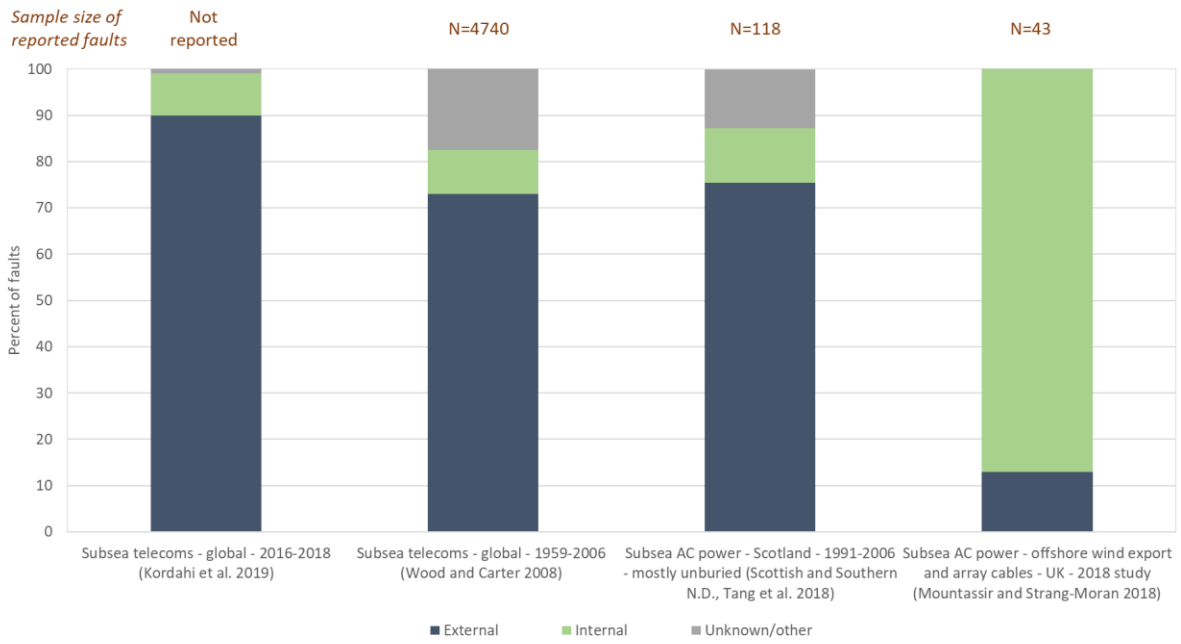

Figure A.5. Share of subsea cable faults by cause category (external, internal, or unknown/other).

Table A.3. Data corresponding to the summary figure above.

Description	Fault cause						Total sample number
	External		Internal		Unknown/other		
	Share (%)	Number	Share (%)	Number	Share (%)	Number	
Subsea telecoms - global - 2016-2018 (Kordahi, Rapp et al. 2019)	90	Not reported	9	Not reported	1	Not reported	Not reported
Subsea telecoms - global - 1959-2006 (Wood and Carter 2008)	73	3460	9.5	450	17.5	829	4740
Subsea AC power - Scotland - 1991-2006 - mostly unburied (Tang, Brown et al. 2018, Scottish and Southern Electricity Networks N.D.)	75	89	11.8	14	12.7	15	118
Subsea AC power - offshore wind export and array cables - UK - 2018 study (Mountassir and Strang-Moran 2018)	13	6	87	37	0	0	43

Some data on subsea high-voltage direct current (HVDC) cables, specifically, are available from CIGRE Technical Brochure 815. The brochure contains information surveyed from global industry experience with subsea high-voltage cables from 2006 to 2015. However, the sample size of reported subsea HVDC faults is very small.

Methodological Notes for Review of Cable Fault Statistics

All studies reviewed above clearly identified the portion of faults from external causes. Faults reported as “unknown” or “other” were attributed to the “unknown/other” cause category. The remaining faults were attributed to the “internal” cause category. PNNL applied some discretion in aggregating sub-categories of faults, where reported. Not all original details are shown in the summary figure. Some absolute numbers were inferred from information about sample size and share of faults. Some results in the table have been rounded.

Faults Relative to Cable Age

Faults were also examined relative to cable age. The most relevant findings are from CIGRE Technical Brochure 815, which contains statistics surveyed from global industry experience with subsea high-voltage cables for 2006–2015. However, the sample sizes of reported faults are very small, and the sample population of cables is dominated by those less than 10 years old, thereby limiting observations of faults over longer periods.

In a survey of high-voltage alternating current offshore wind export cables in the United Kingdom, several sites experienced internally caused faults during the commissioning phase or shortly thereafter (Warnock, McMillan et al. 2019).

A.3. Crossings

The cable routes under consideration cross numerous incumbent telecommunications cables and pipelines. The proposed cable may itself also be crossed by future infrastructure. These situations raise technical and legal considerations.

Technical Considerations

Point protections can be deployed at crossings to mitigate external threats. These include concrete mattresses, protective sleeves, rock burial, grout bags, and specialized structures like crossing bridges. Figure A.6 illustrates a combination of these measures for a subsea cable crossing a pipeline.

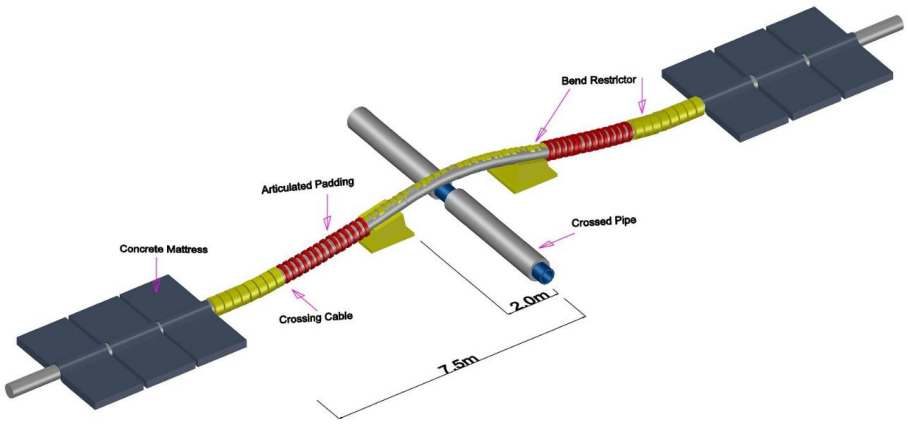

Figure A.6. A combination of point protections for a subsea cable crossing a pipeline (Reda, Rawlinson et al. 2020).

Legal Considerations

This material summarizes considerations identified in the literature and does not provide advice.

The International Cable Protection Committee (ICPC) identifies in its Recommendation 3 (2014) that it is in the interest of parties to establish crossing agreements. A crossing agreement is generally between the owner of the incumbent infrastructure (affected party) and the owner of the incoming infrastructure (crossing party), where the infrastructure can be pipelines, telecommunications cables, or power cables (Askheim 2020). Insurers, lenders, and contractors are typically interested third parties to crossing agreements.

In Askheim's (2020) experience, construction by the crossing party will be covered by construction all risks insurance. This regularly includes liability cover toward affected parties in crossings. Therefore, the insurer(s) will have a strong interest in crossing agreements. Crossing agreements can establish liability caps. Related insurance requirements can be addressed but are not always included. Crossing agreements commonly also address future repair and maintenance procedures (Askheim 2020, section 4.1).

Industry has experience with managing crossings involving subsea HVDC power cables. The NordLink power cable has approximately 20 crossings, and the North Sea Link power cable has approximately 30 crossings (Askheim 2020).

A sample crossing agreement can be obtained from the ICPC Secretariat by request of a member.

A.4. Shipping Data

Shipping data would be a key input for a cable burial risk assessment. Figure A.7 shows vessel traffic density for the region of interest from a 2015 dataset (Halpern, Frazier et al. 2015).

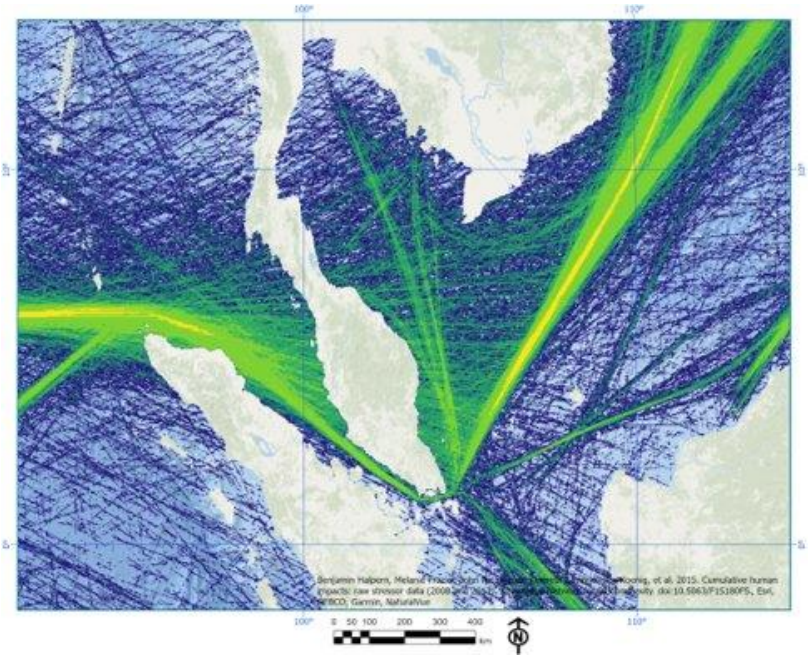

Figure A.7. Illustrative vessel traffic density for the region of interest (data from Halpern, Frazier et al. 2015).

Updated and more specific vessel data, from automatic identification system (AIS) transponders for example, could provide a more detailed representation. AIS data can indicate the vessel speed, size, and type. These factors serve as inputs to anchor strike risk calculations. Figure A.8 shows example AIS data as part of a cable burial risk assessment (Carbon Trust, 2015).

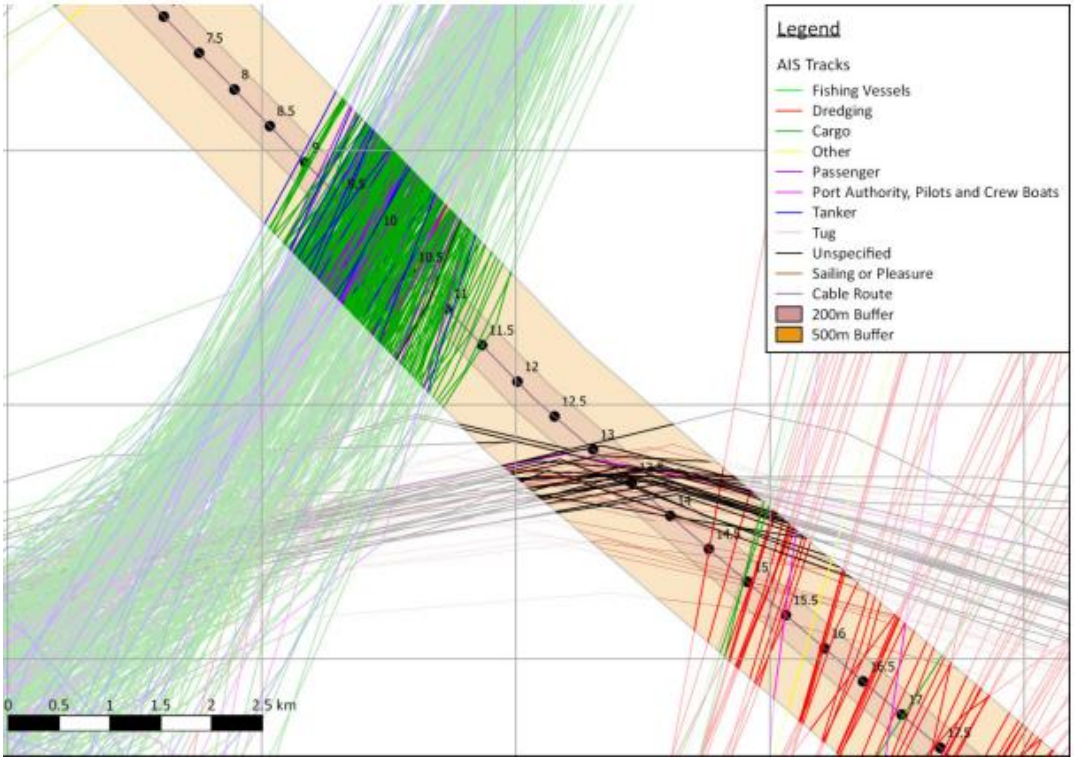

Figure A.8. Example AIS shipping data as an input to a cable burial risk assessment. Black dots indicate cable kilometer posts. Image from Carbon Trust (2015).

A.5. Cable Technologies

Mass impregnated-voltage source converter (MI-VSC) cable technology, as used in the North Sea Link project, could be used for an ASEAN interconnector. Detailed composition of a MI-VSC cable is shown in Figure A.9.

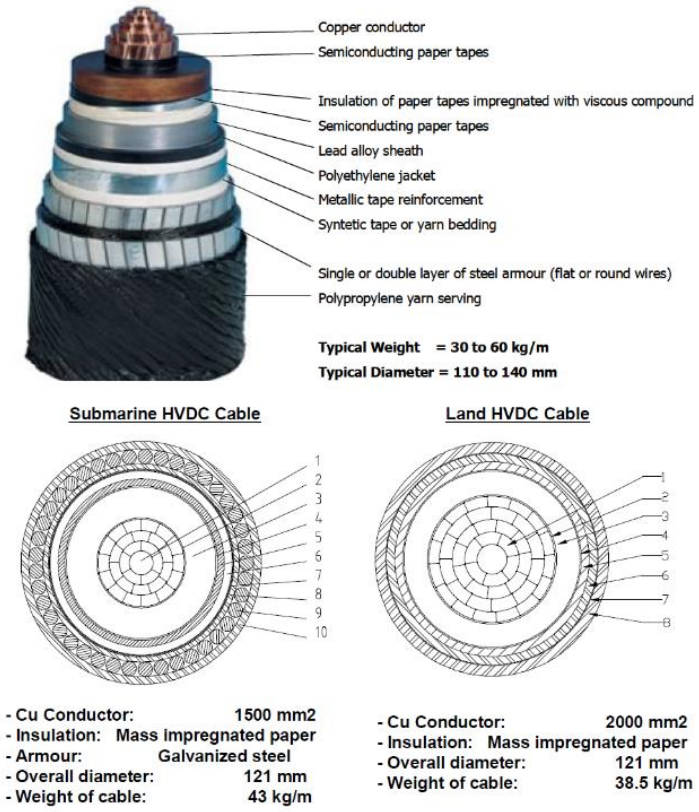

Figure A.9. Mass impregnated HVDC cable cross section (ENTSO-E 2023).

A.6. HVDC Configurations and Technologies

Bipolar HVDC configurations were discussed above. Additional detail is provided in this section concerning HVDC bipoles and their alternatives, as summarized in Figure A.10. Monopolar links are best suited for transmitting power over a long distance, even in the case of long submarine cables. An HVDC monopolar link with a ground return conductor is the most cost-effective solution. In cases where there are restrictions on ground return due to infrastructure or environmental concerns, a separate metallic return conductor is necessary, although it comes at an added cost. The most important aspect of bipolar normal operation is that, through the return conductor, the imbalance current is as small as possible. This type of configuration applies in cases where the transfer capacity of a monopolar connection is insufficient, as well as in cases where it is desired to increase power supply security (Stan, Costinaş et al. 2022).

With a growing need for interconnected power systems and offshore wind plants, a multi-terminal HVDC system presents an elegant solution over a traditional two terminal HVDC connection. Such a system provides the ability to operate all converter ends either as an inverter or a rectifier and provides multi-directional power flow control within the network.

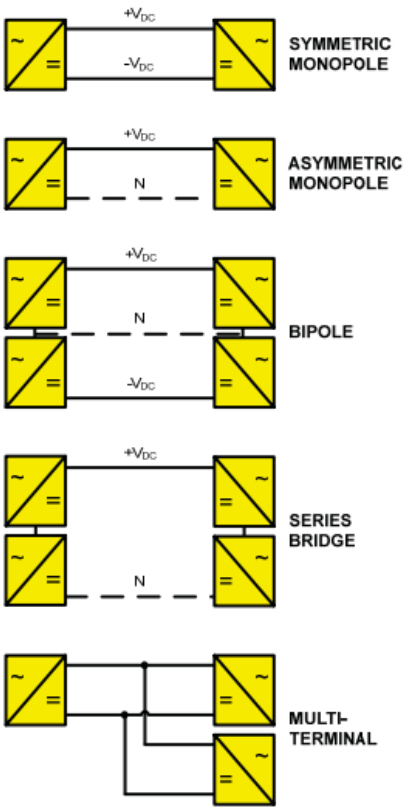

Figure A.10. Common system topologies (Sellick and Åkerberg 2012).

A.7. HVDC Control Strategies

HVDC technology allows operators to control the magnitude and direction of active and reactive power. Based on the power electronics switching and control method, there are currently two available technologies: a line commutated converter (LCC) and a voltage source converter (VSC).

LCC technology, also known as a current source converter (CSC), uses a thyristors base technology for its converter (Oni, Davidson et al. 2016). It provides only active power control, with no black start capability. In an LCC/CSC HVDC connection, the converter substation operating as an inverter controls the DC voltage, keeping it at a constant value, and the converter substation acting as a rectifier regulates the DC voltage so that the current flowing through the DC link corresponds to the active power. The direction of the active power transferred by the HVDC connection can be reversed by changing the polarity of the terminal's voltages.

VSCs use insulated gate bipolar transistor technology and provide control for both active and reactive power, along with a black start capability. The main control methods used in VSC-HVDC systems are the "power angle" control strategy and "vector current" control strategy. In power angle control, active power is controlled by changing the phase angle of the voltage, while the reactive power is controlled by changing the magnitude of the voltage of the HVDC connection. The vector current control strategy controls the current associated with the HVDC connection.

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