Assessment of Regional Interconnections to Meet Southeast Asia's Renewable Energy Targets

Phase I of the Singapore – U.S. Collaboration

PNNL: Travis Douville, Sohom Datta, Jay Barlow, Saptarshi Bhattacharya, Patrick Maloney, Syed Naqvi, Shahnawaz Siddiqui, Daniel Gaspar

NREL: Prateek Joshi, Howard Marano, Erin Johnson, Derina Man

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NET ZERO WORLD INITIATIVE
Accelerating Global Energy System Decarbonization

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Acknowledgments

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List of Acronyms

AC	alternating current
ADS	accelerated development scenario
AIMS	ASEAN Interconnection Masterplan Study
AIS	automatic identification system
ASEAN	Association of Southeast Asian Nations
ATB	annual technology baseline
CBRA	cable burial risk assessment
CEM	capacity expansion model
CRS	coordinate reference system
CSC	current source converter
DC	direct current
DEM	digital elevation model
ESCAP	United Nations Economic and Social Commission for Asia and the Pacific
FTE	full-time equivalent
GDP	gross domestic product
GEBCO	General Bathymetric Chart of the Ocean
GHG	greenhouse gas
GW	gigawatts
HVAC	high voltage alternating current
HVDC	high voltage direct current
ICPC	International Cable Protection Committee
IEX	Indian Exchange Market
kV	kilovolt
LCC	line communicated converter
LDS	low speed development scenario
LTMS-PIP	The Laos-Thailand-Malaysia-Singapore power interconnection project
MI-VSC	mass impregnated-voltage source converter
MPAs	marine protected areas
MW	megawatts
NREL	The National Renewable Energy Laboratory
PDS	progressive development scenario
PM&E	protection, mitigation, and enhancement
PNNL	Pacific Northwest National Laboratory
PV	photovoltaic
RE	renewable energy
REE	Red Eléctrica de España
RTE	Réseau de Transport d'Électricité
SARI/EI	South Asia Regional Initiative for Energy Integration
TW	terawatt
UHVDC	ultra high voltage direct current
VSC	voltage source converter
VSC-HVDC	voltage-source converter-high-voltage direct current
WEA	Wind Energy Area

Executive Summary

This report summarizes the results of a study of long-distance subsea electrical interconnections in Southeast Asia, conducted under the first phase of the Singapore-U.S. collaboration under the Net Zero World Initiative. In Phase 1, the Net Zero World team evaluated the current state of the renewable energy landscape in Southeast Asia; developed an open-source capacity expansion model using GridPath and evaluated several future scenarios including changes in interregional transmission; explored the technical feasibility of regional subsea interconnectors; and estimated socio-economic benefits of expanded regional transmission.

Southeast Asia is a region characterized by a rich diversity of nations and renewable energy resources, including strong solar irradiance throughout, onshore wind in the northern highlands, hydroelectricity along the major river systems, and offshore wind near Vietnam and the Philippines. However, transmission between the Association of Southeast Asian Nations (ASEAN) members is limited primarily to overland lines. Adding subsea electricity interconnection cables could enable an integrated ASEAN power grid, with benefits including: 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.

The report describes the Net Zero World analysis of the current state of interregional transmission and renewable energy supply and demand, demonstrating the need for significant additional transmission of renewable electricity among ASEAN nations in a future characterized by high renewable energy deployment. The report then describes the development and use of the GridPath capacity expansion model. The analysis indicates potential cost savings of $715 million USD for the region from the deployment of additional transmission interconnections.

The technical feasibility of subsea interconnectors in the region is demonstrated through a detailed analysis of regional hazards and mitigations. A parametric cost model indicates a project of 500 km would cost approximately $1.22 billion USD and a project spanning 2,000 km would cost approximately $4.86 billion USD. These costs include surveying the route, cable supply and installation, installation of high voltage, direct current (HVDC) converters, project management and engineering, and insurance.

Finally, the Net Zero World team evaluated potential benefits of a single approximately 2,000 km project using models adapted from literature reports. Highlights include the creation of 2,000-9,000 regional jobs; $2 billion USD in regional annual research and development investment; $1.4 trillion USD in cumulative power generation investment; real gross domestic product increases ranging from 0.8% to 4.6% for ASEAN nations; improved power supply reliability and resilience to extreme weather events; and 50% average decrease in particulate matter 2.5 (PM2.5) impacting 99% of the population and leading to 15,000 fewer deaths annually. Together, these results point to the feasibility and specific potential benefits of expanded interregional renewable electricity transmission.

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1 Introduction

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 wind is already 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 led to 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 energy balancing and power trading between nations, which could be unlocked by subsea and overland interconnectors. The benefits of interconnectors are multi-faceted (Energy Systems Integration Group 2022). 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.

Given these opportunities, the feasibility of long-distance interconnections in Southeast Asia was explored under Phase 1 of the Singapore-U.S. collaboration under the Net Zero World Initiative. This report documents the findings of the exploration and is organized in four main sections. In Section 2, existing Association of Southeast Asian Nations (ASEAN) energy and transmission systems are described. In Section 3, the energy supply and demand landscape is characterized through the use of an open-source capacity expansion model, constructed under this work and utilized to represent planning scenarios for the region. Section 4 summarizes the technical feasibility and estimated costs of long-distance ASEAN interconnectors. Finally, Section 5 describes the socio-economic impacts associated with regional connectivity.

2 ASEAN Energy and Transmission Landscape

This analysis explores the distribution of renewable resources and electricity demand in ASEAN, as well as current and anticipated interregional transmission, to inform future interconnection plans.

2.1 Transmission Interconnections in ASEAN

As of 2022, the largest total cross-regional interconnection in ASEAN is Thailand-Laos (700 megawatts [MW]), followed by Laos-Vietnam (570 MW) and Malysia (Peninsula)-Singapore (525 MW). Other interconnections exist between Thailand-Malaysia (Peninsula) (300 MW), Malaysia (Sarawak)-Indonesia (Kalimantan) (230 MW), Malaysia (Sabah)-Malaysia (Sarawak) (50 MW), Vietnam-Cambodia (200 MW), Laos-Cambodia (200 MW), and Thailand-Cambodia (230 MW). The data is from the ASEAN Interconnection Masterplan Study (AIMS III) Phase 1 and 2 Update (ASEAN Centre for Energy 2023). The AIMS III study models three main scenarios for capacity and transmission expansion: Updated Power Plans, ASEAN Renewable Energy (RE) Target, and High RE Target. The interregional transmission capacity for the Updated Power Plans scenario, along with transmission line utilization, is shown in Figure 1 for 2025 and 2040.

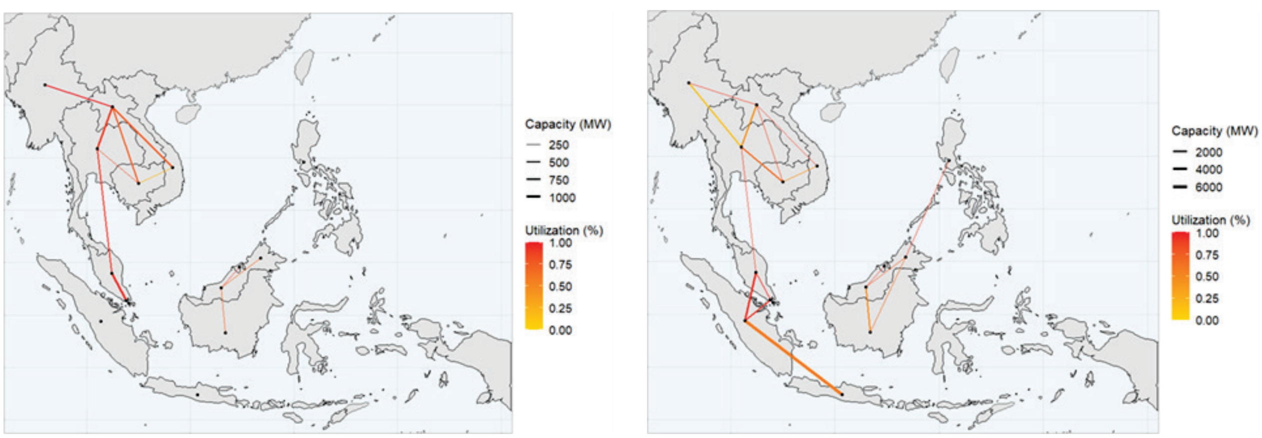

Figure 1. Interregional Transmission in Southeast Asia – Updated Power Plans (2025 – left & 2040 – right). Note: the transmission routes shown in the figure are representative lines connecting regions in Southeast Asia and are not exact routes.

The interregional transmission capacity for the High RE Target scenario, along with transmission line utilization, is shown in Figure 2 for 2025 and 2040.

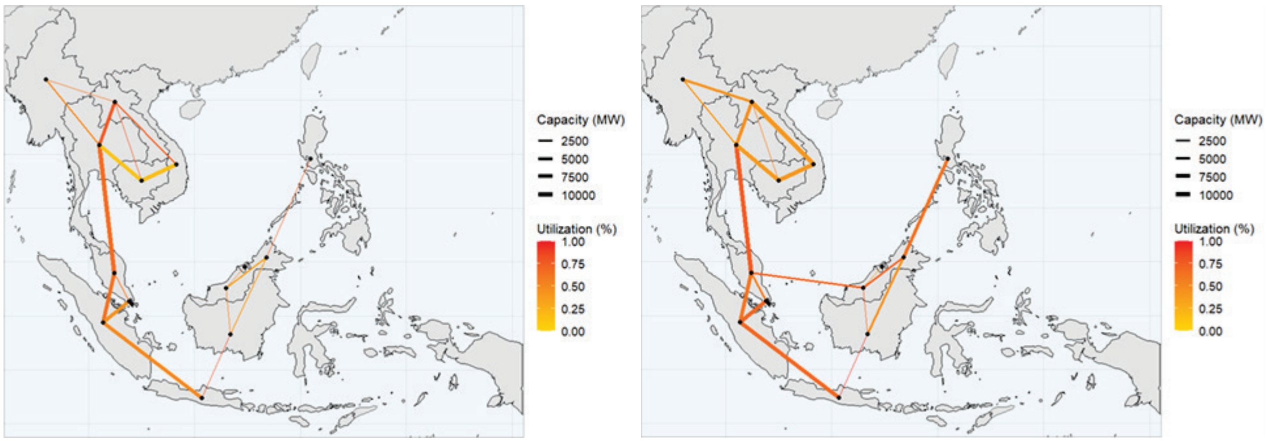

Figure 2. Interregional Transmission in Southeast Asia – High RE Target (2025 – left & 2040 – right). Note: the transmission routes shown in the figure are representative lines connecting regions in Southeast Asia and are not exact routes.

Interregional transfer capability versus peak demand for ASEAN countries in the different AIMS III scenarios is plotted in Figure 3 for 2040. In 2040, Indonesia (Java), the Philippines, and Vietnam are below the 20% threshold across all scenarios. In 2040, Brunei, Indonesia (Java), Indonesia (Kalimantan), Myanmar, the Philippines, Singapore, Thailand, and Vietnam are below the 20% threshold in the Updated Power Plans and ASEAN RE Target scenarios. Increasing interregional transfer capacity as a percentage of annual peak electricity demand could help reduce the risks of supply shortfalls and thus bolster domestic and regional energy security. Other regions such as Cambodia, Laos, and Malaysia (Sabah) have interregional transfer capacities that are well over 100% of their annual peak electricity demand in the AIMS III High RE scenario. This is due to their relatively low electricity demand and their geographic positions at the nexus of several different ASEAN regions; therefore, most of their transmission capacity is used to transmit power to other regions and not to serve local demand. The 20% threshold is based on Deyoe et al. (2024), where it was used as a rough estimate to gauge whether regions in the United States had sufficient interregional transfer capability.

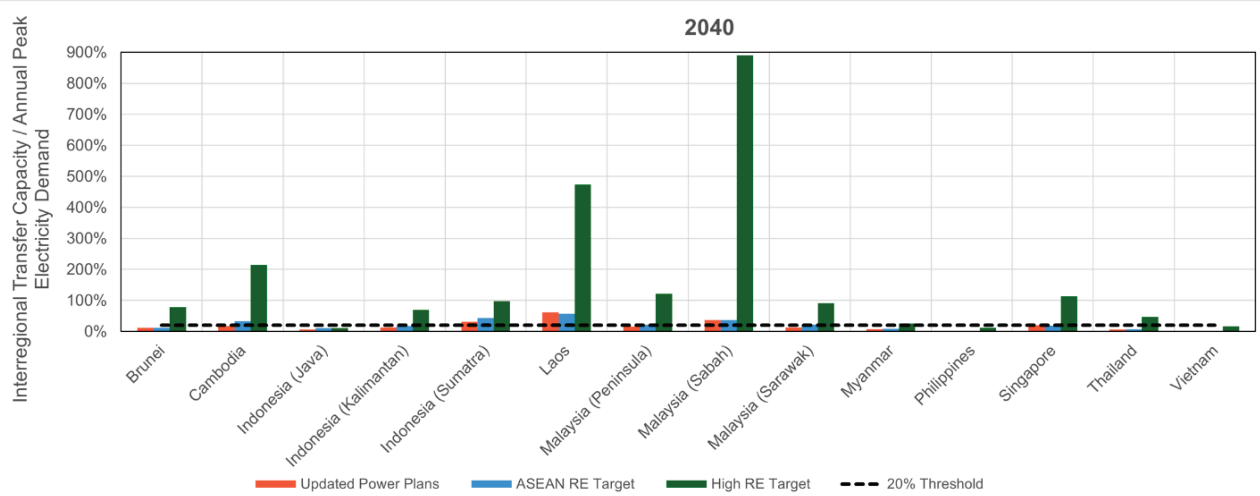

Figure 3. Interregional Transfer Capacity as a Percentage of Annual Peak Electricity Demand for ASEAN Countries in 2040 Across Different Future Scenarios.

2.2 Conclusions

2.2.1 Key Takeaways: Geographic Diversity of Resources and Demand

ASEAN has a geographic diversity of renewable energy resources that can be leveraged via interregional transmission. There are strong solar resources throughout all regions, and strong wind and hydropower resources in the North subregion. ASEAN countries will experience growing electricity demand, but at different rates. For instance, the combined anticipated electricity consumption in the South and East regions in 2030 is approximately equal to that of the North region. Overall, there is an opportunity to transport renewable electricity from the North to the South and East regions. The only existing or proposed connection between the North region and the other two regions is between Thailand and Malaysia (Peninsula).

2.2.2 Key Takeaways: Interregional Transmission Capacity

ASEAN interregional transmission capacity is expected to grow significantly through 2040 to meet renewable energy targets. For instance, there are 19 total transmission corridors modeled, including 12 new interregional connections that are proposed. Several regions in ASEAN could have insufficient transfer capacity in 2040. Finally, several transmission corridors could have high utilization in 2040, which could lead to congestion.

3 Regional Interconnections in the ASEAN Region

The purpose of this analysis is to examine the role of regional interconnections to meet the ASEAN renewable energy targets.

3.1 Modeling Framework

3.1.1 Methodology and Modeled Scenarios

This study used a capacity expansion model developed for Southeast Asia in GridPath, which is an open-source tool with the underlying code base available on GitHub. The model provides insights on investments in new generation capacity, transmission, and storage infrastructure to meet ASEAN's targets from 2025-2050 and maximize system net present value, considering load growth, reliability requirements, and other constraints. The study examined two primary scenarios:

1. **Baseline**: The Baseline scenario assumes that each country in ASEAN will reach their announced renewable energy targets. Beyond the year of the ASEAN RE targets, this scenario assumes a reasonable growth rate of renewable energy capacity for ASEAN countries within certain pre-determined limits.
2. **Baseline, Restricted Transmission**: The sensitivity applied to this scenario (i.e., Restricted Transmission) restricts interregional transmission capacity in ASEAN.

For both scenarios, certain interconnection routes between ASEAN countries are assumed, and the model determines the optimal amount of transmission capacity for each route. Each country in ASEAN is represented in the model, except for the Philippines and Brunei, which could be included in future work. For the included countries, each is represented by a single node, except for Malaysia and Indonesia, which are represented by three nodes each corresponding to different regions of those countries. Data and assumptions on generation, load, transmission, and reserve margin are aggregated to each node. Note that the GridPath capacity expansion model is robust enough to analyze different RE targets and scenarios and is not restricted to the scenarios discussed in this study. In future work, the GridPath model can be utilized to answer specific what-if scenarios and sensitivity studies based on planning requirements.

3.2 Results

3.2.1 Results: Interregional Transmission

In the Baseline scenario, the transmission capacity as a fraction of the limit set in the model is fully or near-fully utilized for most of the interregional corridors (Figure 4). Thus, it may be cost effective to increase the maximum transmission capacity further along certain corridors to meet ASEAN RE targets.

Overall, interregional transmission capacity decreases when going from the Baseline scenario to the Baseline (Restricted Transmission) scenario. New transmission capacity decreases along the following corridors because of an imposed restriction on maximum interconnections: Singapore – Malaysia (Peninsula), Singapore – Malaysia (Sarawak), and Singapore – Vietnam. As a result of this decrease along certain corridors, new transmission capacity increases along the following routes: Indonesia (Kalimantan) – Malaysia (Sarawak) and Singapore – Cambodia.

Compared to the Baseline Scenario, the Restricted Transmission Sensitivity results in transmission capacity as a fraction of the model limit increasing for the Singapore – Cambodia, Singapore – Malaysia (Sarawak), and Singapore – Vietnam corridors (Figure 5). This reduced interconnection capacity is offset by increased generation of fossil fuel power plants.

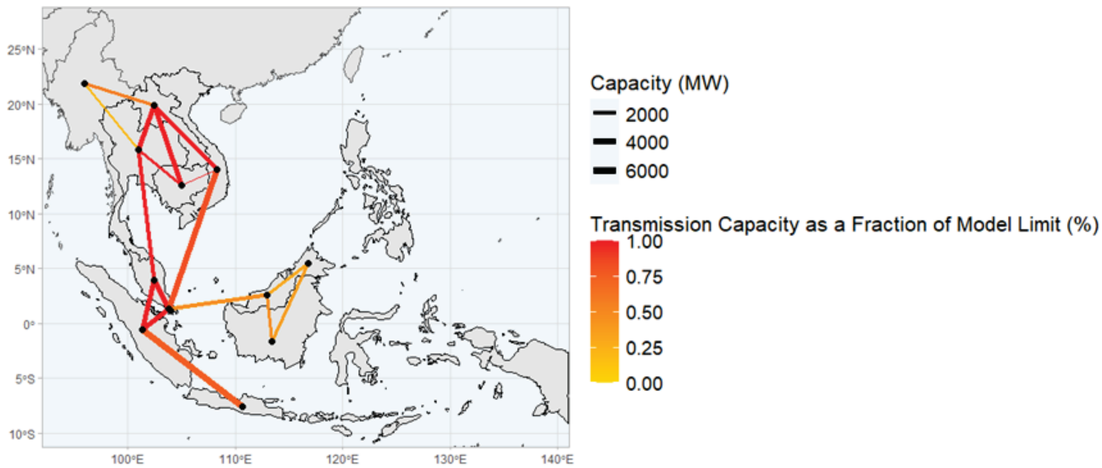

Figure 4. Baseline Scenario: Interregional Transmission Capacity in 2050 (Note: the transmission routes shown in the figure are representative lines connecting regions and are not exact routes)

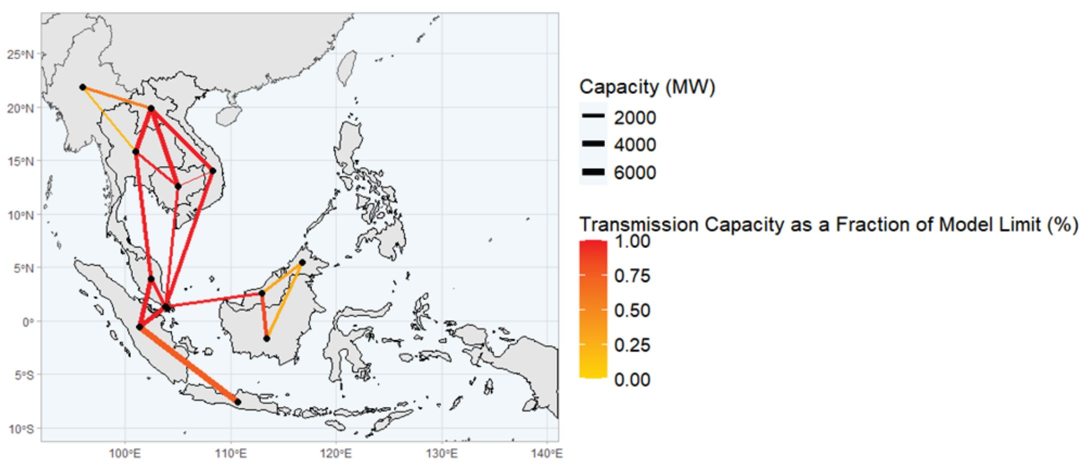

Figure 5. Baseline Scenario (Restricted Transmission): Interregional Transmission Capacity in 2050 (Note: the transmission routes shown in the figure are representative lines connecting regions and are not exact routes)

3.2.2 Results: Total Costs

For all of the ASEAN countries modeled, when transmission is restricted in the Baseline scenario, generation capacity costs decrease by approximately $216 million USD (0.7% decrease), transmission capacity costs decrease by approximately $371 million USD (18.6% decrease), fuel costs increase by approximately $1.2 billion USD (1.5% increase), and operations and maintenance costs increase by approximately $60 million USD (2.1% increase) for all of

ASEAN in 2050, resulting in a net increase in costs of approximately $715 million USD (0.6% increase) for all of ASEAN by 2050 (Figure 6).

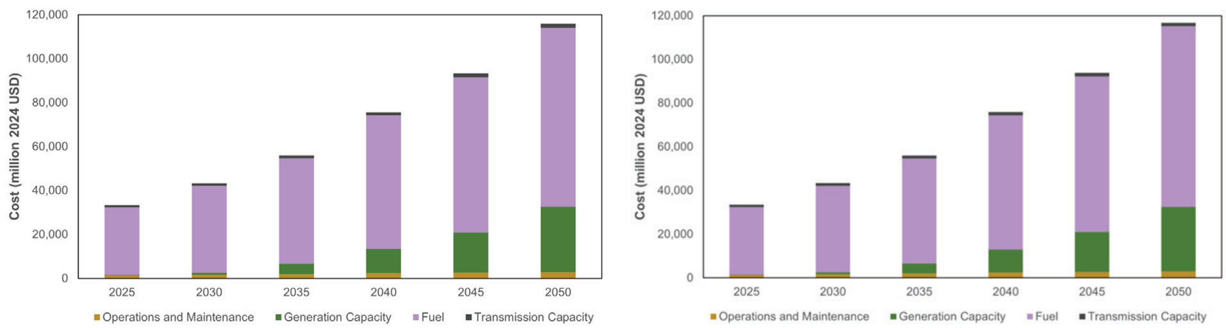

Figure 6. Baseline (left) Baseline (Restricted Transmission) (right) Scenarios: Total Costs (ASEAN)

When transitioning from the Baseline (Restricted) to the Baseline scenario, the modeled countries save approximately $1.2 billion USD in fuel costs and operations and maintenance cost savings of approximately $60 million USD in 2050. Transmission costs increase by approximately $371 million USD and generation capacity cost increases by approximately $216 million USD in 2050 for modeled ASEAN countries. The net cost savings for modeled ASEAN countries in 2050 in the Baseline scenario with expanded transmission is approximately $715 million USD. Therefore, the benefit ($1.3 billion USD) to cost ($587 million USD) ratio for ASEAN is 2.2.

3.3 Conclusion

An open-source capacity expansion model of most of ASEAN has been developed by the Net Zero World team, leveraging prior work in the region, national power sector planning, technology costs, and renewable energy resource potential.

3.3.1 Key Takeaways

The key takeaway for generation is:

- When transmission is restricted in the Baseline scenario, the reduction in electricity trade is offset by increased fossil fuel generation.

The key takeaway for transmission is:

- The regional transmission capacity generally reaches the limits set by the model, showing the value of interconnectors in a least-cost power sector future for Southeast Asia.

The key takeaways for costs are:

- When transmission is restricted, overall costs increase because higher fuel and operations and maintenance costs outweigh lower generation capacity costs for the modeled ASEAN countries.
- The Benefit-to-Cost ratio of expanding interregional transmission in the Baseline scenario is approximately 2.2 (approximately $2.20 USD is saved in fuel and operations and maintenance costs for every dollar spent on expanded interregional transmission and associated generation capacity).

3.3.2 Potential Next Steps

The GridPath capacity expansion model for Southeast Asia can be further enhanced as a part of future efforts. For instance, the model could compare the costs for the Baseline scenario with a future Net-Zero scenario, both with and without additional regional interconnections. This could allow stakeholders to better understand the cost-savings associated with reaching renewable energy and net-zero targets with expanded regional transmission lines. In the future modeling efforts, some of the key countries can be split into multiple regions to better estimate the intra-regional transmission and power flows. The model can be expanded to other ASEAN countries, sources of generation, and/or loads, the model can be linked to zonal models for resource adequacy or disaggregated to provide production cost estimates by country, and is highly adjustable to simulate additional scenarios or case studies. Efficient modeling of key power system tradeoffs using this model can inform national policies across the region.

4 Technical Feasibility and Estimated Cost of Long-Distance Subsea Interconnections in Southeast Asia

This section summarizes a technical feasibility study of long-distance interconnectors in the region and is organized into four main subsections. The first reviews subsea high voltage direct current (HVDC) projects to date, including a recent relevant case study from the North Sea. The second subsection reviews high-level risks, their potential impacts, and mitigation best practices. The third subsection presents a conceptual interconnector system. Finally, the fourth subsection presents a cable cost model and its initial estimates for a conceptual long-distance ASEAN interconnector.

4.1 Projects to Date

Interconnector technology has already been proven in shallow waters, such as those near many ASEAN countries. In 2015, Ardelean and Minnebo summarized 28 commissioned subsea high voltage, direct current (HVDC) interconnectors worldwide, reproduced in Figure 7 (Ardelean and Minnebo 2015). 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 kilometers (km) with a total power capacity of 1.4 gigawatts (GW) (North Sea Link 2023). Due to high-capacity power transfer, interconnector length, and similar bathymetric conditions, the North Sea Link project (North Sea Link 2023) serves as an excellent proxy for an ASEAN interconnector.

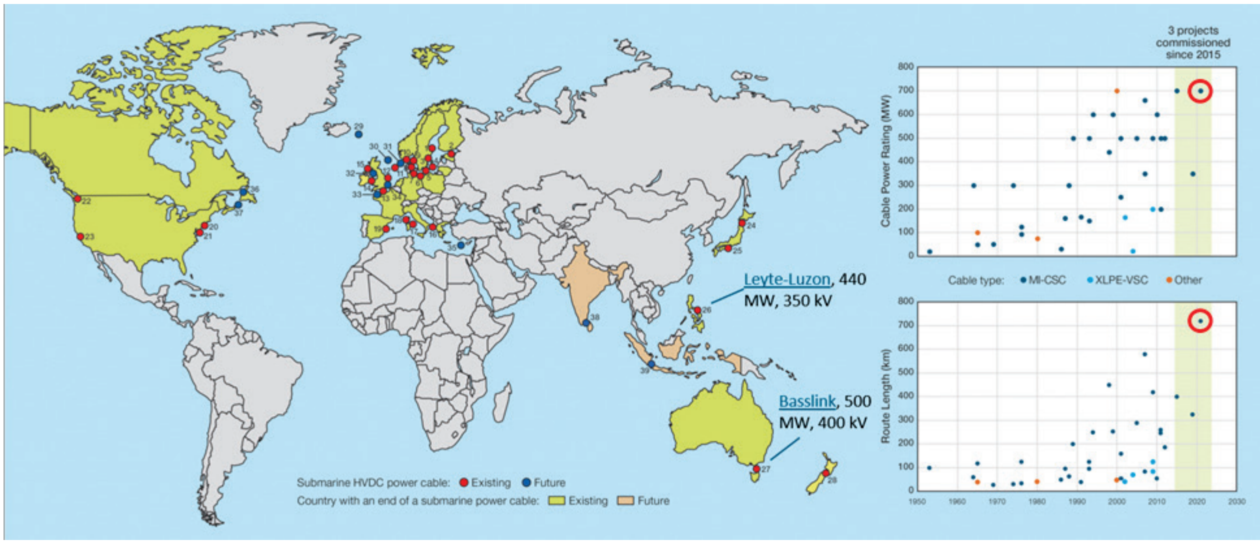

Figure 7. Commissioned (red dots) and planned (blue dots) HVDC subsea transmission projects around the world (Ardelean and Minnebo 2015). Power rating and route lengths have increased over time. The vast majority of cables incorporate mass impregnated-current source converter technology.

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 appendix. 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 comprised 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 (North Sea Link 2023). More details on the North Sea Link are provided in Appendix B. To minimize the potential for damage to both conductors due to the same external threat, the trenches were separated by approximately 50 meters (m). Within 200 m from shore, the trenches begin to converge to the landing point and are separated by approximately 20 m.

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 8). For the Norway-UK North Sea Link, two cables nearly 15 centimeters (cm) in diameter are used, weighing 50 kilograms/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.

As an alternative to conventional HVDC design, voltage-source converter-high-voltage direct current (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 all together, 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 appendix.

4.2 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.

4.2.1 Risks

Subsea cables face numerous risks and can fail due to both external and internal causes. The following external risks were identified relevant to a conceptual ASEAN interconnector project:

1. **Turbidity flows and scouring currents**. Subsea currents carrying sediments (turbidity flows) can place damaging mechanical stresses on cables (Carter 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 et al. 2023). These risks may be present in the Mekong Delta area, in particular (Liu 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 metric ton 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 et al. 2022).
4. **Crossings with pipelines and other cables.** Crossings considerations are expected to vary on a case-by-case basis. 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 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.

Other external risks have been identified in the literature, though they are generally less representative of reported faults. 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 technical appendix.

4.2.2 Mitigations

Mitigation of external threats can be decomposed into a hierarchy. First, routes can be planned to minimize exposure where avoidable. Second, cables can be protected by various means – cable burial is expected to be the primary means of protection and is likely an applicable mitigation strategy for risks 1-3 identified 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 at a 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 8). 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., one-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.

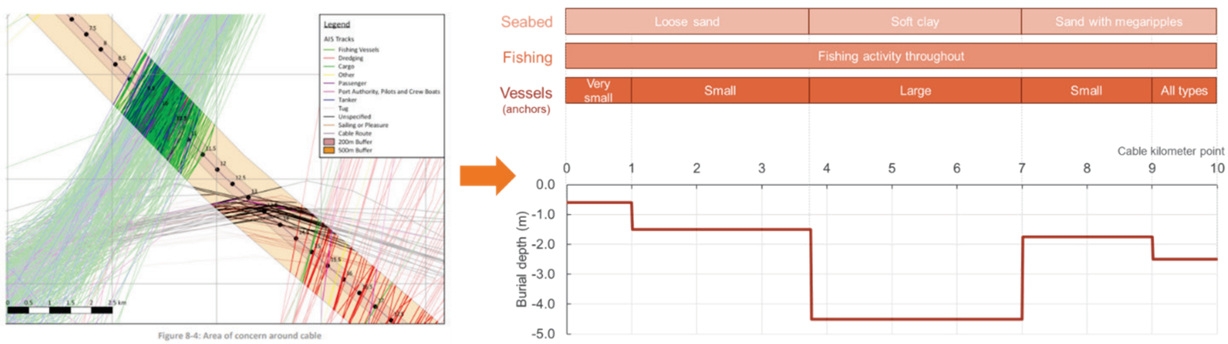

Figure 8. An illustration of a CBRA method. Left: example analysis of shipping data across a cable route (Carbon Trust 2015). Right: an example of determining optimal burial depth corresponding to conditions at each segment, based on a worked example in Carbon Trust (2015).

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.

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 et al. 2020). Additional discussion of crossings is provided in the appendix.

4.2.3 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 et al. 2021). Repair cost estimates are discussed below under cost estimates.

4.3 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 an 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 9 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 landing points and are spaced further apart for the majority of the route.

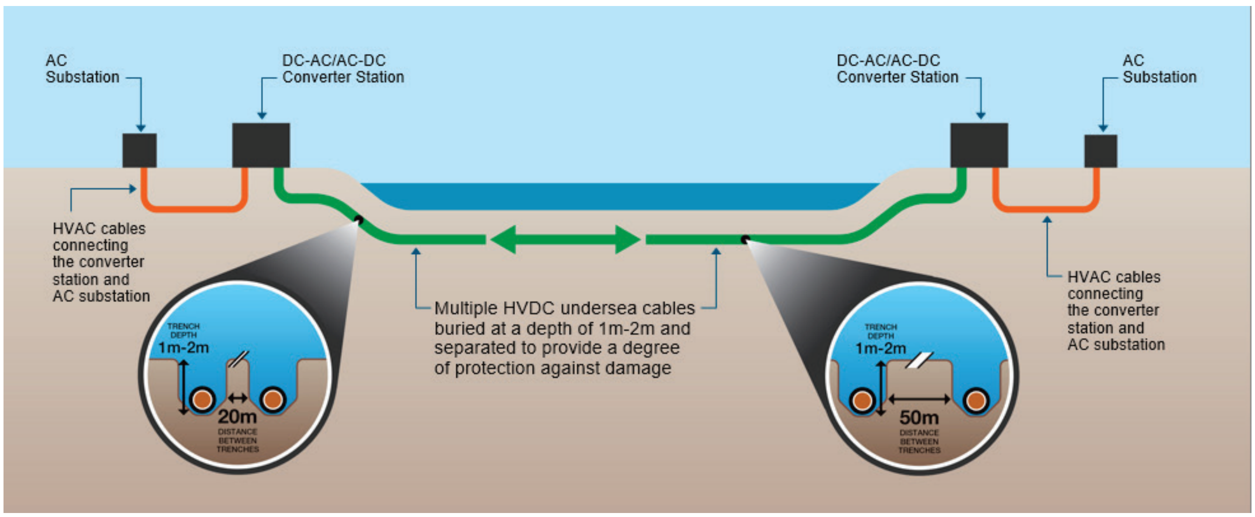

Figure 9. Components of an interconnector system, adapted from National Grid and NSN Link (2014).

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.

4.4 Cost Estimates

The costs of long-distance interconnectors are significant, requiring long-duration financial instruments and well-funded investors. Noting the potential routes, hazards, mitigations, and repair costs, a simple cost model of a conceptual long-distance ASEAN interconnector was constructed based on the work of Gordonnat and Hunt (2020). The costs of HVAC substations, and underground cabling are not included in the model. Cable and converter supply dominate the capital outlay, followed by installation and protection, mitigation, and enhancement (PM&E), as indicated in Figure 10.

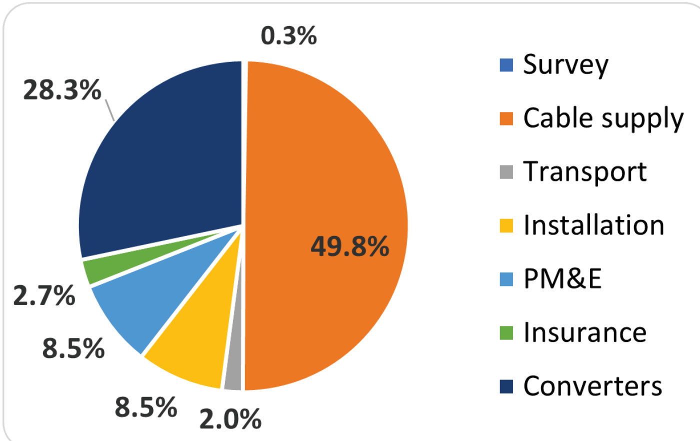

Figure 10. Capital outlay sources for a long-distance ASEAN interconnector.

The overall capital costs of several conceptual ASEAN interconnector routes fall between $1.22 and $4.86 billion USD ($2023), depending on the distance (Figure 11). These costs do not assume cable failures during the 25-year project lifespan.

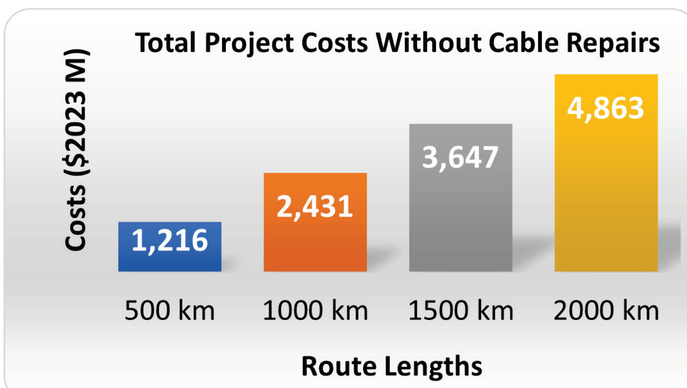

Figure 11. Total capital costs of potential interconnector cable by route length. Costs of onshore HVAC substations and transmission links are not considered.

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 USD was used, approximated from reported subsea power cable repairs in the United Kingdom (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 on a case-by-case basis. These costs are relatively small compared to the capital outlays shown in Figure 12. However, as the frequency of these repairs are increased, the overall project costs may grow by 4 to 6% for the longest and shortest routes, respectively (Figure 12).

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 range from $5000 to $50000 per MWh (Energy Systems Integration Group 2022). In addition, project downtime would be costly due to the opportunity costs associated with 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.

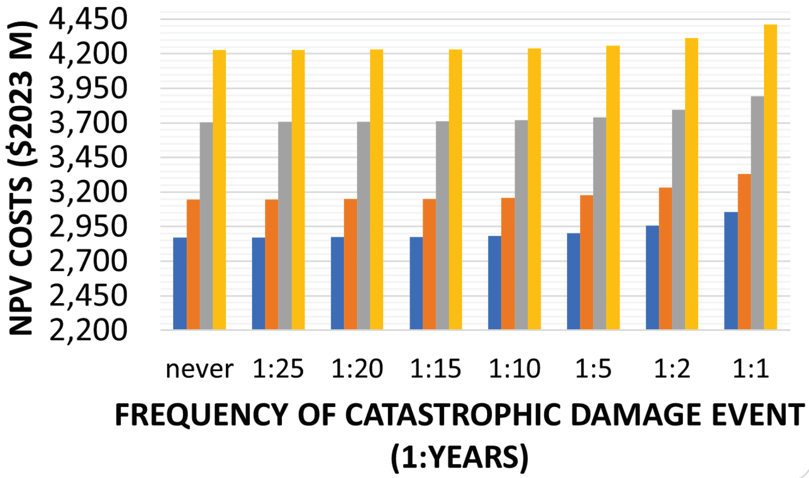

Figure 12. Total project costs for four different interconnector routes with different distances and other characteristics with varying frequencies of cable failures incurring repair costs.

5 Socio-economic Impacts of Regional Connectivity

5.1 Background

Regional power interconnection is important for regional decarbonization efforts in Southeast Asia, as it would enable power trading across countries, optimize renewable energy use, and reduce reliance on fossil fuels. Subsea cables have demonstrated the capacity to transport over 2 GW of power, highlighting their potential for cross-border power connections to integrate a higher share of renewable energy resources into a country's energy mix.

The development of the ASEAN Power Grid not only supports environmental and energy-related goals but also holds significant potential for socio-economic benefits across the region. This literature review provides an overview of the socio-economic impacts of interregional transmission, with a focus on case studies that are most applicable to ASEAN. Understanding these impacts is crucial for assessing the full value of the ASEAN Power Grid as both an energy and economic enabler for Southeast Asia.

5.2 Socio-economic Benefits of Regional Interconnection

Regional low-carbon power interconnections have the potential to spur job creation, improve access to affordable electricity, increase investments to support economic growth, increase power supply and resiliency, and improve human health outcomes. Understanding these socio-economic benefits will be essential as ASEAN member states continue to advance clean energy deployment and interregional transmission infrastructure.

5.2.1 Transmission Infrastructure and Renewable Energy Jobs

Investments in interregional transmission and associated renewable energy projects can provide direct employment opportunities and support additional investments in other sectors. Employment opportunities include:

- Short-term jobs in **constructing** interconnection infrastructure.
- Long-term employment in the **operation and maintenance** (O&M) of energy systems and electricity distribution networks.
- Additional jobs in **manufacturing** clean energy and interconnection-related equipment.

Reduced electricity costs for homes and businesses can also drive additional economic activity and indirect job creation due to increased consumption and productivity. Regional interconnection construction and additional investments in renewable energy may also result in construction-period-induced jobs. This may include, for example, employment opportunities in the retail, food service, and child-care sectors (Lantz et al. 2021).

Case Study: U.S. Offshore Wind Workforce Assessment

There are limited studies on the potential economic impacts of increasing subsea interconnections in ASEAN; however, a review of international analyses and examples can provide an indication of potential job creation impacts. The National Renewable Energy

Laboratory (NREL) modeled the workforce needs to develop 30 GW of U.S. offshore wind capacity by 2030 (Stefek et al. 2022). This study estimated that the development of 30 GW of offshore wind would result in between 15,000 and 58,000 full-time equivalent (FTE) jobs, excluding induced jobs in communities supported by offshore wind activity.

Table 1 provides a summary of the job estimates associated with the construction and operation of interconnectors from Stefek et al. (2022). This includes jobs related to maritime construction, export cable and substation manufacturing, port and staging workers, and operations and maintenance. The range of employment is dependent on the amount of domestic content (ranging from 25% to 100%).

Table 1. Manufacturing and Supply Chain Employment Estimates and Qualifications

Job Category	Average Employment (FTE/Year)*	Qualifications Required of Work Force
Maritime Construction: vessel crew to install subsea cable and wind turbines	500 – 2,100	Majority of roles require a Bachelor's degree and/or specialized training
Export Cable Manufacturing: workers for producing subsea export cable	650 – 2,600	Minimum of GED or high-school diploma for factory roles; Bachelor's degree required for safety and oversight roles
OSW Substation Manufacturing: workers for building substation the enables transmission to onshore grid	40 – 100	GED or high school diploma for rolling, welding, and coating roles; specialized training for technicians; advanced degrees for oversight roles
Port and Staging: includes terminal crews and portside logistics and management	400 – 1,600	No requirements for laborers; port and terminal crew generally require minimum GED or high school diploma and/or specialized training; management roles require minimum of an Associate or Bachelors degree
Operations and Maintenance: long-term operations and maintenance (wind technicians, plant managers)	100 – 500 (2024) 600 – 2,300 (2030)	Marine crew requires GED or high school diploma; more senior roles require Associates degree; other wind plant roles require specialized training and/or Bachelor's degree

The job benefits associated with the development and operation of interconnectors is modest compared to the potential economic benefits associated with the renewable energy manufacturing jobs enabled by increased transmission capabilities in the region. Table 2 presents the employment potential of offshore wind manufacturing (by component) (Stefek et al. 2022).

Total workforce needs are expected to grow as the industry and supply chains develop and, in several cases, the workforce will need to meet additional qualifications to be suitable for available jobs. As illustrated in Table 1, most roles require a minimum of a high school diploma along with specialized training. In some cases (e.g., with maritime construction) the workforce is expected to develop slowly, relying first on installation strategies with foreign-flagged installation vessels and a larger international workforce.

Table 2. Manufacturing and Supply Chain Employment Estimates by Component

Component	Workforce Contribution	FTE/Year Equivalent*
Rotor Blades	7.5%	900 – 3,675
Nacelle	38.7%	4,644 – 18,963
Towers	10.2%	1,224 – 4,998
Monopiles	8.8%	1,056 – 4,312
Transition Piece	5.4%	648 – 2,646
Jacket	3.4%	408 – 1,666
Gravity-Based Foundation	2.7%	324 – 1,323
Semisubmersibles	14.9%	1,788 – 7,301
Substation Topside	0.3%	36 – 147
Array Cable	2.7%	324 – 1,323
Export Cable	5.4%	648 – 2,646

* Range is dependent on amount of domestic content (25% to 100%).

Extrapolating from this assessment, 2.4 GW of offshore wind and corresponding transmission investments in the ASEAN region would yield approximately 7,500 FTE job years. Based on the minimum qualifications required in many of the job categories, these would be higher quality, better compensated opportunities. The distribution of economic benefits amongst ASEAN countries is highly dependent on the availability of a skilled workforce as well as the necessary infrastructure (e.g., vessels) in the region. If specialized infrastructure and renewable energy manufacturing supply chains are not established within ASEAN, international parties will accrue some of the economic benefits.

5.2.2 Electricity Costs Savings and Economic Growth

Regional interconnections can provide significant cost savings for energy consumers. Interconnections allow countries with varied energy resources to share electricity, reducing generation fuel costs by connecting lower-cost power plants to regional demand centers via interregional transmission (Stenclik and Deyoe 2022). Transmission can also support rural electrification programs, improving electricity availability for individuals, families, and businesses (UNDESA 2006). For example, previous analysis completed for the ASEAN Integrated Energy Market Study (as shown in Table 3) found that an integrated energy market would reduce total system costs by 3-3.9% and increase real gross domestic product (GDP) by 1-3% (ACE 2013). By promoting renewable energy deployment, transmission can also decrease countries' reliance on fossil fuels and enable the use of clean energy with low marginal costs. This can reduce financial risks from fuel price volatility.

Table 3. ASEAN Integrated Energy Market Study GDP Impacts

Country	Real GDP Increase (percent)
Cambodia	0.81
Indonesia	1.9
Laos	1.08
Malaysia	3.46

Philippines	2.19
Singapore	2.14
Thailand	2.41
Vietnam	3.13
Other Southeast Asia	4.57

5.2.3 Investments and Economic Growth

Regional interconnections can drive significant investments in the energy sector, promoting economic growth across ASEAN. Expanded interconnections can foster innovation and upgrades in power transmission technology, stimulate local industry development through improved power supplies, resource optimization, and reduced generation costs, and build a clean energy supply chain, driving smart manufacturing and supporting emerging industries (Yi et al. 2018).

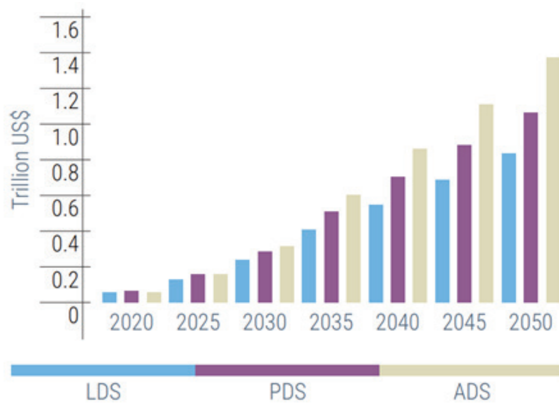

Figure 13. R&D Investment Development Trend

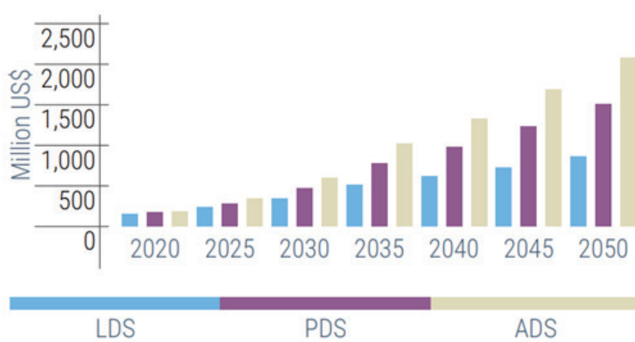

Figure 14. Development Trend of Total Investment of Power Supply

The United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) outlined three power scenarios: 1) Low Speed Development Scenario (LDS), 2) Progressive Development Scenario (PDS), and 3) Accelerated Development Scenario (ADS) to strategize methods for implementing ASEAN interconnection to support energy transition and assess the anticipated benefits (Yi et al. 2018). Estimates found that the most ambitious, ADS scenario resulted in an additional $2 billion USD in annual research and development (R&D) investment by 2050 or approximately double the LDS scenario (Figure 13). Under the ADS scenario, accumulated investment in the power supply was estimated to each $1.4 trillion USD by 2050 (Figure 14).

By creating cost savings and spurring additional economic growth regional connectivity can also support reinvestments in public services, such as education, healthcare, or targeted business or sector investments. New revenue for electricity exporting countries can also be reinvested into these public services (UNDESA 2006).

5.2.4 Power Supply Resilience and Reliability

Regional interconnections can help planners prepare for macroeconomic volatility, extreme weather, and other unexpected events, while minimizing impacts on consumers and businesses.

Regional interconnections can also help reduce the frequency and duration of load shedding events, which can increase costs for manufacturers and other businesses. As shown in Figure 15, load shedding can result in significant productivity impacts by requiring investments in backup power supplies, disrupted communications, and equipment malfunctions. In Nepal, for load shedding resulted in a 6.9% reduction in industrial output and a total loss of $14.5 billion USD ($2016) in GDP between 2008 and 2016 (Timilsina and Steinbuks 2021).

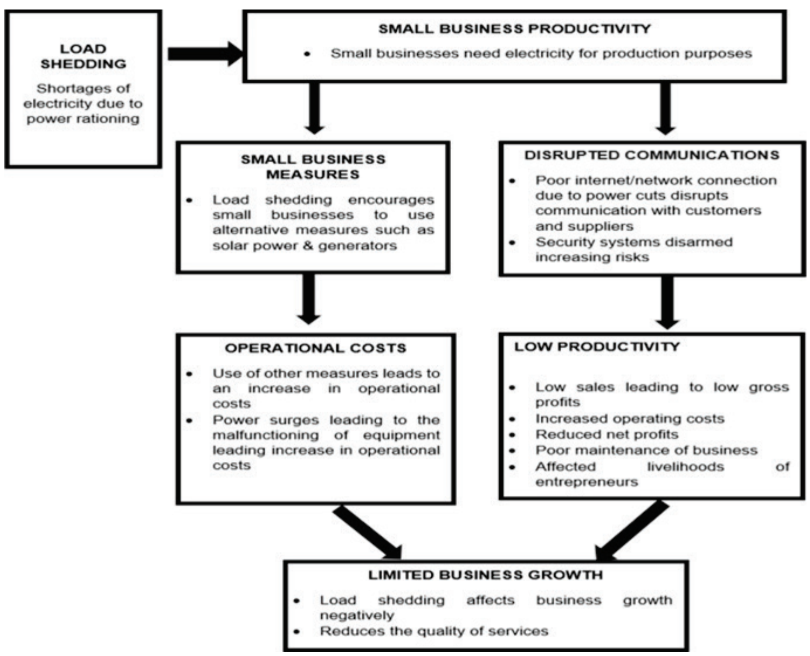

Figure 15. Load Shedding Impacts Conceptual Framework

5.2.5 Air Quality and Public Health

Air pollution from energy is a leading cause of increased health risks and premature death and can strain limited public health resources. Local air pollution can also reduce economic productivity and quality of life in the ASEAN region. For example, a 2023 analysis of Cambodia, Indonesia, and Thailand found that if unabated the cost of air pollution would be equivalent to between 1.6% and 2.1% of each country's GDP by 2030 (Klimont 2023). By supporting renewable energy deployment, regional interconnections can improve air quality and reduce adverse economic and quality of life impacts (Clack, Goggin, and Choukulkar, 2020; Klimont, 2023; Ravi et al. 2023). Under the AIMS III Optimum and High Target RE scenarios, most citizens (91% in Optimum RE and 99% in High RE) in ASEAN countries would breathe cleaner air (Ravi et al. 2023).

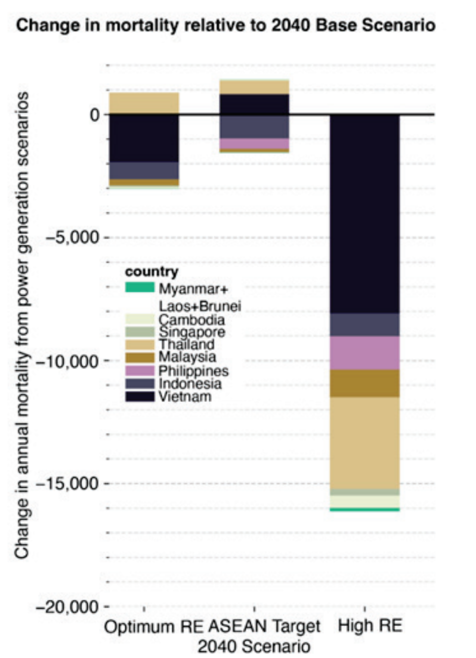

Figure 16. Modeled changes in Projected Mortality under AIMS III Scenarios

Modeling by Ravi et al. 2023, found that each alternative AIMS III renewable energy and interconnection scenarios lead to a decrease in regional, net PM2.5-caused annual mortality relative to the Base scenario in 2040. Mortality reductions were greatest for Vietnam under the modeled Optimum and High renewable energy scenarios (Figure 16).

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Appendix A. ASEAN Energy and Transmission Landscape

A.1 Interregional Transmission

Grid connectivity secured through regional interconnectors enables a host of benefits such as generation capital cost savings, production cost savings, resource adequacy and resilient power supply, risk mitigation and energy security, emissions reductions, renewable energy integration, and jobs and economic development (Deyoe, Stenclik, and Lasher 2024; Stenclik and Deyoe 2022).

However, policy, regulatory, financial, economic, and technical challenges can often present obstacles to successful interregional transmission development (DNV 2024; Simeon and Rose 2024). These challenges can include:

- Diverse policies, regulations, and standards across domestic power grids,
- Varied priorities and political uncertainty, which may delay needed decision-making,
- Lengthy regulatory and permitting processes for new or upgraded grid infrastructure,
- Uncoordinated interregional grid planning and grid stability concerns from variable renewable energy,
- Uncertain funding sources, ownership structures, and remuneration mechanisms,
- Limited technical capacity to operate cross-border long-distance interconnections, and

Transmission equipment supply-chain constraints

Interregional Transmission Benefits: Generation Capital and Production Cost Savings

Interregional transmission can provide significant capital and production cost savings. Generation capital cost savings can be caused by avoided or deferred generation capacity investments, access to lower-cost or higher-resource potential generation sites, and access to policy incentives for renewable energy capital investments. Production cost savings can be caused by avoided costs for fuel, cycling, and other variable costs of power generation, displacement of higher-cost suppliers with those with lower incremental production costs, reduced transmission energy losses, reduced congestion due to transmission outages, and reduced costs for operating reserves and other ancillary services (Pfeifenberger et al. 2021; Stenclik and Deyoe 2022).

Interregional Transmission Benefits: Resource Adequacy and Resilient Power Supply

Interregional transmission can support a more reliable and resilient energy system. Resource adequacy is the ability of the supply-side, demand-side, and transmission resources to meet demand. Interregional transmission can help avoid or defer costs of reliability projects for new or aging infrastructure, reduce the risk of load loss, and reduce margins required for planning reserves. Grid resilience refers to the system's capability to limit extreme events' impacts through efforts to prepare for, anticipate, absorb, adapt to, and recover from them. Interregional transmission can support resilience by reducing customer impacts due to adverse conditions (e.g., extreme weather events) and reducing the severity of events requiring load shedding to maintain grid operations (Deyoe, Stenclik, and Lasher 2024).

Interregional Transmission Benefits: Risk Mitigation and Energy Security

Interregional transmission can help planners prepare for macroeconomic volatility, extreme weather, and other unexpected events, while minimizing costs. Interregional transmission can also help planners respond to different scenarios in an evolving energy sector. Regarding fuel prices, transmission can reduce reliance on fossil fuel generation and the associated financial costs to hedge against fuel price volatility. Regarding load growth, the electrification of the building and transportation sectors will likely increase loads and without transmission to supply renewable energy to meet these loads, more costly generation units are likely to be run. Regarding plant retirements, transmission that brings cheaper electricity generation online reduces the potential for uneconomic generation to remain online. Regarding local capacity, transmission brings lower cost resources into a region and thus does not require the development of suboptimal resources to serve local electricity demand (Pfeifenberger et al. 2021; Stenclik and Deyoe 2022).

Interregional Transmission Benefits: Emissions Reductions

Interregional transmission can be a key enabler to achieving a low-emissions grid while maintaining reliability at least cost. Benefits may include reduced localized emissions (e.g., SO_2, NO_x, particulates, mercury), improved air quality and public health outcomes, and reduced greenhouse gas emissions from better integrated renewable energy and the avoided dispatch of high-emission generation resources (Clack, Goggin, and Choukulkar 2020; Pfeifenberger et al. 2021). Figure A- 1 shows the avoided emissions in 2040 for the ASEAN RE Target Scenario, Including Interregional Transmission Expansion (ASEAN and HAPUA 2021).

AVOIDED EMISSIONS - ASEAN RE TARGET SCENARIO		
	CO_2	N_2O (in CO_2 eq)
	Million Tons	Thousand Tons
Coal	70,216	55
Oil	3,734	1
Natural Gas	16,902	1

Figure A- 1. Avoided Emissions in 2040 for the ASEAN RE Target Scenario, Including Interregional Transmission Expansion.

Interregional Transmission Benefits: Jobs and Economic Development

Investments in interregional transmission can provide direct employment opportunities and support additional investments in renewable energy projects. Reduced electricity costs for homes and businesses can also drive additional economic activity and job creation due to increased consumption and productivity. Figure A- 2 shows employment scenarios for regional transmission expansion in the eastern United States (Clack, Goggin, and Choukulkar 2020).

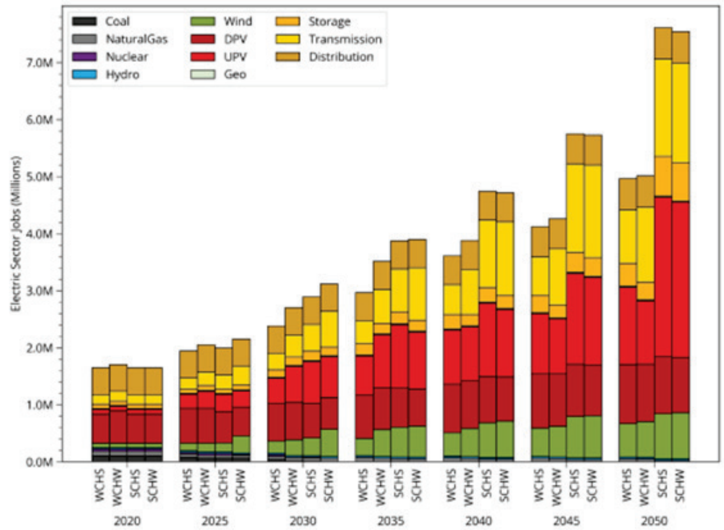

Figure A- 2. Employment Scenarios for Regional Transmission Expansion in the Eastern United States.

Select Case Studies of Interregional Transmission: United Kingdom and Norway

The United Kingdom-Norway North Sea interconnector is a 700 km HVDC interconnector developed by National Grid and Statnett. This project was developed under the UK Ofgem cap and floor regime, which sets a yearly maximum and minimum level revenue that the interconnector can earn over a 25-year period to reduce risks and encourage investment. The interconnector participates in implicit day-ahead capacity allocation, coupling the day-ahead markets of the UK and the NO2 bidding zone in Norway (Ofgem 2021a; Ofgem 2021b). A schematic of this interconnector is shown in Figure A- 3 (Stattnet and National Grid n.d.).

Figure A- 3. UK-Norway North Sea Interconnector Schematic.

Select Case Studies of Interregional Transmission: India and Nepal

The India-Nepal interconnector is a 400 kV HVDC transmission line between Muzaffarpur and Dhalkebar. Electricity is traded on India's Day-Ahead Market of the Indian Exchange Market (IEX). Imports and exports are governed by India's Guidelines for Import/Export (Cross Border) of Electricity – 2018. India also shares existing high-capacity transmission lines with Bangladesh, supporting additional resource sharing (Adhikari and Pandey 2023; Ministry of Power n.d.). A schematic of this interconnector is shown in Figure A- 4 (McBennett et al. 2019).

Figure A- 4. India-Nepal Grid Interface Schematic

Select Case Studies of Interregional Transmission: France and Spain

The France-Spain Pyrenees interconnector is a 65 km underground HVDC interconnector developed by RTE (French utility) and REE (Spanish utility). The interconnector was developed with support from the EU European Energy Programme for Recovery and the European Investment Bank. System operators participate in annual auctions for cross-border transmission capacity rights. Bidders can establish physical energy exchanges throughout the year or benefit from positive price differences for day-ahead markets (Red Eléctrica 2023). A schematic of this interconnector is shown in Figure A- 5 (European Investment Bank 2015).

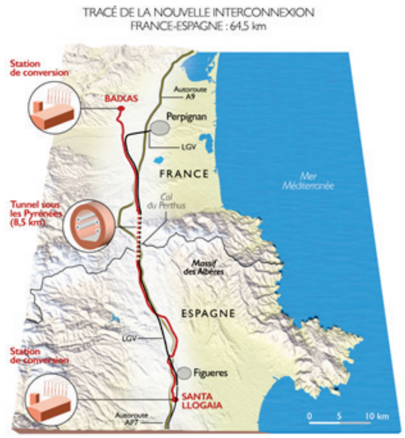

Figure A- 5. France-Spain Pyrenees Interconnection Schematic.

Select Case Studies of Interregional Transmission: Australia and Singapore

The Australia-Asia PowerLink interconnector is a proposed 4,300 km HVDC interconnector between Australia and Singapore, coupled with solar and battery storage. The interconnector has an estimated capacity of 1.75 GW, or up to 15% of Singapore's electricity demand, which could support energy security for Singapore. Additional planning is underway before final investment and funding arrangements are concluded. This includes securing environmental approval and commercial agreements to underpin demand. Australia's Northern Territory Environment Protection Agency is reviewing the proposal's environmental impact (Infrastructure Australia 2024). A schematic of this interconnector is shown in Figure A- 6 (SunCable n.d.).

Figure A- 6. Australia-Asia Interconnection Schematic

Select Case Studies of Interregional Transmission: Morocco and United Kingdom

The Morocco-United Kingdom Xlinks interconnector is a proposed 4,000 km HVDC subsea project to connect Morocco's solar resources and the United Kingdom's wind resources. National Grid has secured an agreement for two 1.8 GW connections, and this interconnector is identified as a UK National Infrastructure Project due to its size and potential benefits.

Developers are conducting pre-application consultations and environmental assessments with stakeholders (Xlinks n.d.; Planning Inspectorate n.d.). A schematic of this interconnector is shown in Figure A- 7 (Data from RE Data Explorer).

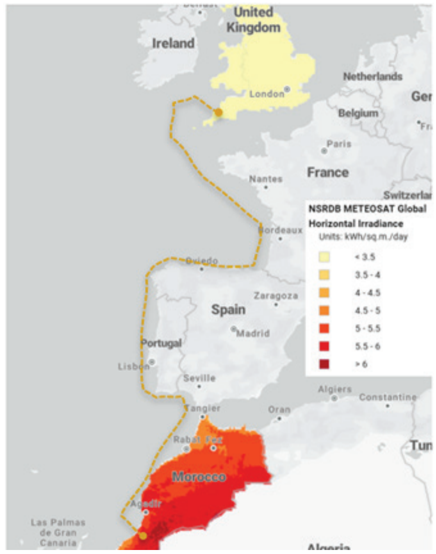

Figure A- 7. Morocco-United Kingdom Interconnection Schematic.

Transmission Cost Comparison

HVDC (high-voltage, direct current) transmission lines are the economical solution for long-distance asynchronous interconnections and long-distance submarine cables, compared to HVAC (high-voltage, alternating current) lines. HVDC technology has higher terminal costs, and thus higher initial costs, compared to HVAC technology. However, HVDC lines are more efficient and less expensive per unit of length. Thus, for longer distances, HVDC lines are generally lower cost compared to HVAC lines, though costs can be highly route specific. This trend is shown in Figure A- 8 (Czernorucki et al. 2022).

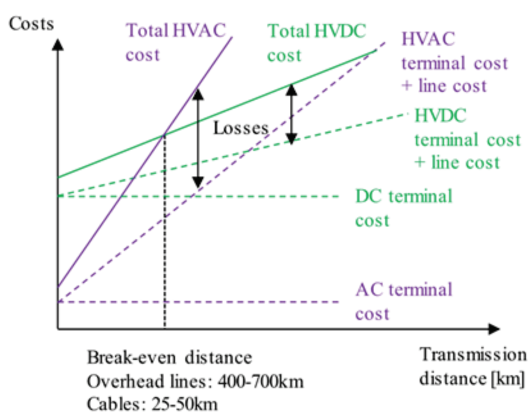

Figure A- 8. Comparative Cost of HVDC and HVAC Transmission Lines (Overhead Lines and Submarine Cables) as a Function of Line Length.

A.2 ASEAN Energy and Transmission Landscape

Renewable Energy and Electricity Demand in ASEAN

The solar resource (i.e., global horizontal irradiance, direct normal irradiance, and direct horizontal irradiance) is strong throughout all of ASEAN, and particularly in regions such as central Myanmar, central Thailand, eastern Cambodia, southern Vietnam, and Java Indonesia. A map of solar resource data in Southeast Asia is shown in Figure A- 9 (Maclaurin et al. 2022). The spatial resolution of the data is 2 km by 2 km and the temporal resolution is 10 minutes.

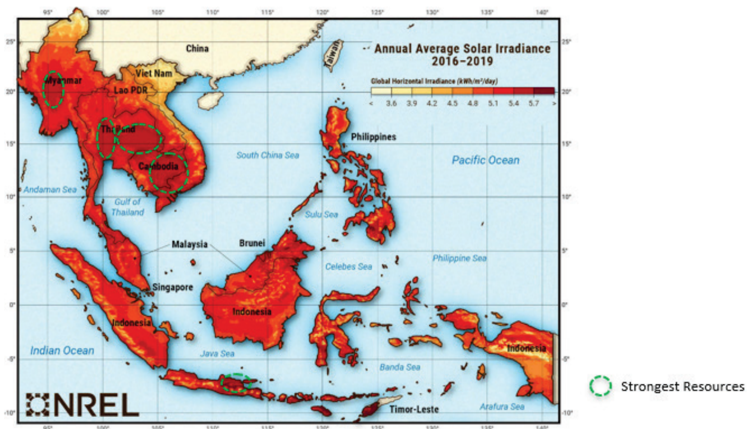

Figure A- 9. Southeast Asia Solar Resource Data.

The wind resource (i.e., wind speed) is strong in certain regions of ASEAN, particularly in southern Laos, southern Vietnam, off the coast of southern Vietnam, off the coast of northern Philippines, and Mindoro Philippines. A map of wind resource data in Southeast Asia is shown in Figure A- 10 (NREL 2023). The spatial resolution of the data is 3 km by 3 km and the temporal resolution is 15 minutes.

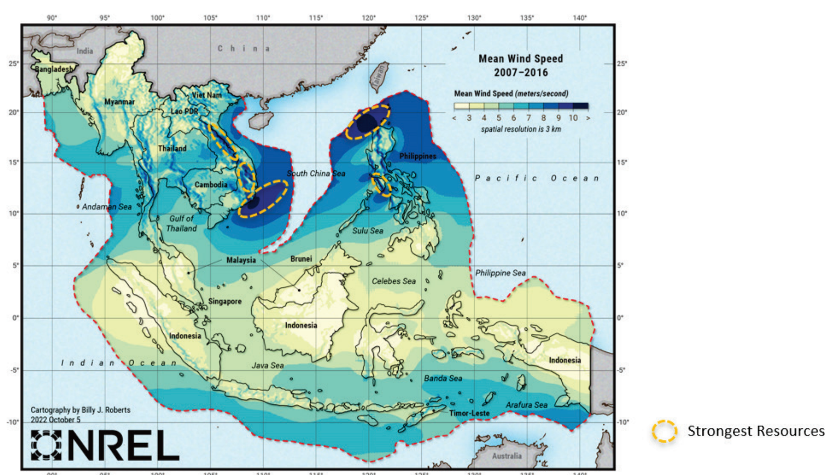

Figure A- 10. Southeast Asia Wind Resource Data.

Southeast Asia also has significant hydropower resources. According to the Global Power Plant Database version 1.3.0 (June 2021), Vietnam has the largest capacity of hydropower in ASEAN (approximately 17 GW), followed by Indonesia (approximately 5 GW) and Thailand (approximately 4 GW). A map of this hydropower plant data is shown in Figure A- 11 (World Resources Institute 2021).

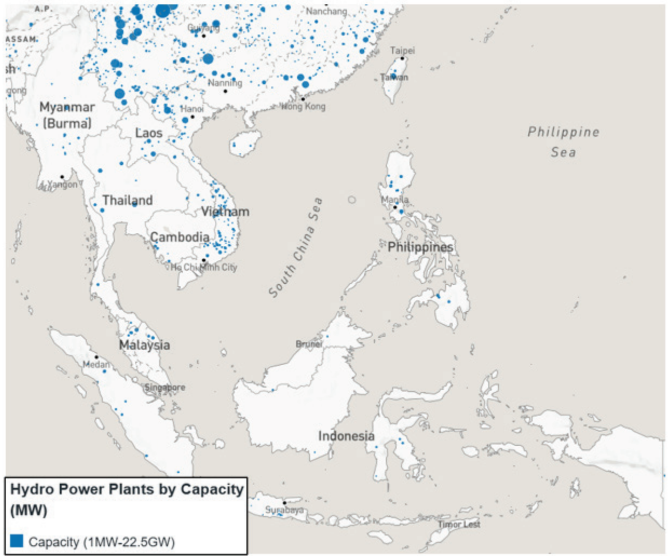

Figure A- 11. Southeast Asia Hydropower Plant Data.

There is also a large technical potential for floating solar PV sited on reservoirs (including hydropower and non-hydropower reservoirs) in ASEAN, led by Thailand (33 – 65 GW), Malaysia (23 – 54 GW), and Vietnam (21 – 54 GW). A map of this floating solar technical potential data is shown in Figure A- 12 (Joshi et al. 2023).

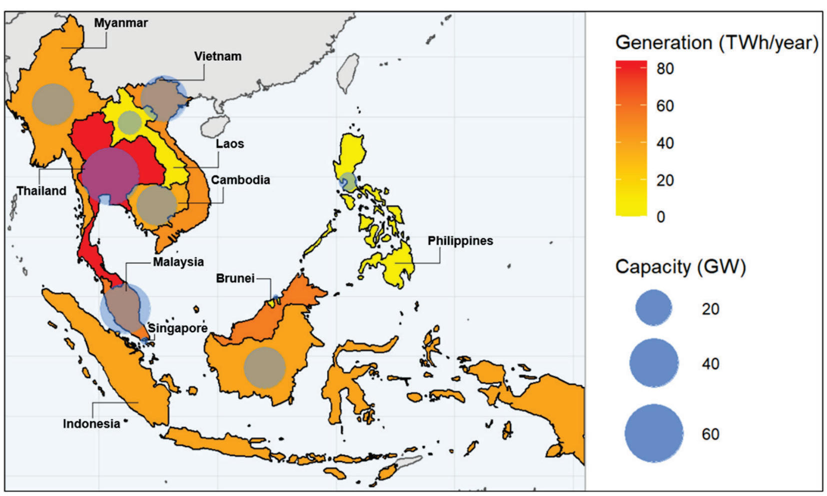

Figure A- 12. Southeast Asia Floating Solar PV Technical Potential on Reservoirs.

ASEAN electricity demand is expected to grow over the next decade. These trends are shown in Figure A- 13.

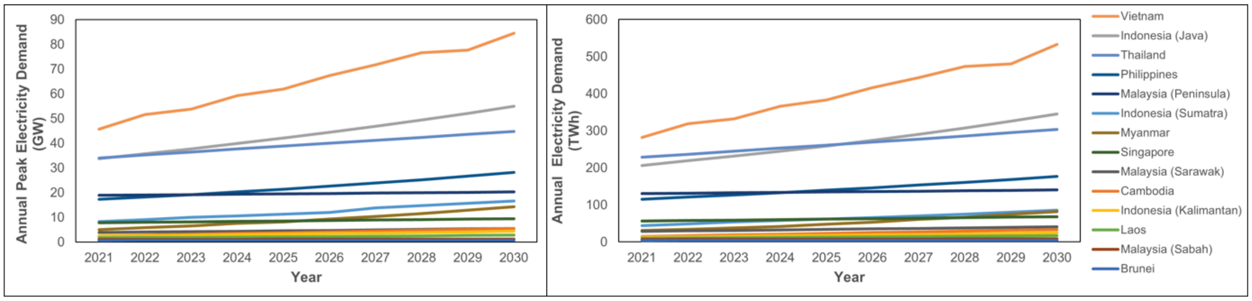

Figure A- 13. Annual Peak Electricity Demand (GW) and Electricity Demand (TWh) in ASEAN. Data from the ASEAN Interconnection Masterplan Study (AIMS III) Phase 1 & 2 Update (ASEAN Centre for Energy 2023).

Transmission Interconnections in ASEAN

DNV also conducted a study on regional cooperation and modeled transmission interconnection expansion in Southeast Asia (DNV 2024). Compared to the AIMS III Study (ASEAN and HAPUA 2021), the DNV ASEAN Interconnection study focuses on a 2050 net-zero scenario for the region, including options for hydrogen to be used as a seasonal storage option. The AIMS III study does not look at interconnector capacity required for full decarbonization. Overall interregional transmission capacity rises from 104,605 MW (AIMS III High RE Scenario in 2040) to 2,155,000 MW (DNV Regional Cooperation Scenario in 2050), approximately 21-fold increase (Figure A- 14). The DNV study does not set limits on the amount of interconnection capacity that can be built along the AIMS III transmission corridors, and includes an additional corridor between Indonesia (Kalimantan) and Indonesia (Sulawesi). Vietnam, Cambodia, Malaysia, Indonesia (Sumatra), and Indonesia (Sulawesi) are key exporters of electricity.

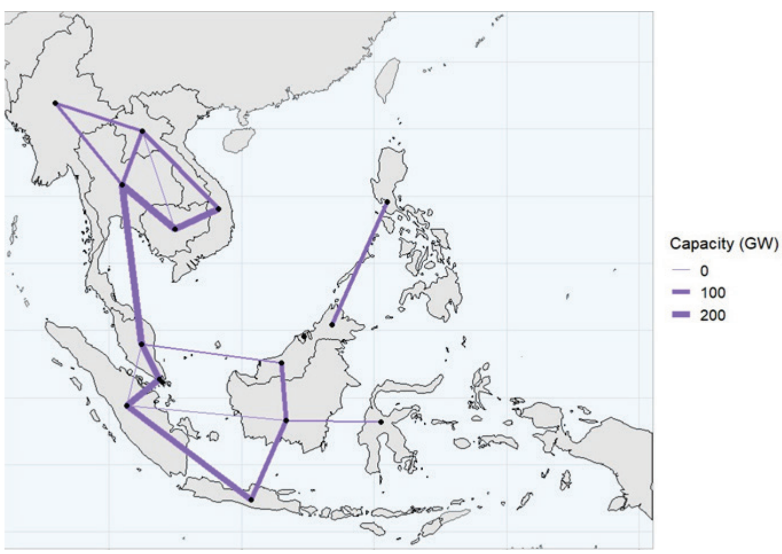

Figure A- 14. Interregional Transmission in Southeast Asia – DNV Regional Cooperation (2050). Note: the transmission routes shown in the figure are representative lines connecting regions in Southeast Asia and are not exact routes.

Appendix B. Regional Interconnections in the ASEAN Region

B.1 Background on AIMS III Study

This analysis builds off the ASEAN Interconnection Masterplan Study (AIMS) III, which consisted of both capacity expansion planning and grid performance analysis (ASEAN and HAPUA 2021). The objectives of this study were to (1) provide a new and updated master plan for the ASEAN power grid as a reference for member states, (2) evaluate the techno-economic viability of potential cross-border interconnections and renewable energy expansion, and (3) enhance energy connectivity and market integration in ASEAN to achieve energy security, accessibility, affordability, and sustainability. The study considered four primary scenarios: (1) Base Scenario (based on established power development plans), (2) Optimum Renewable Energy (RE) Scenario (based on optimizing renewable energy and interconnection capacity), (3) ASEAN RE Target Scenario (based on achieving ASEAN's 2025 target of 23% renewable energy in the primary energy mix), and (4) High RE Target Scenario (based on achieving higher levels of renewable energy penetration by 2040). Compared to the AIMS III study, this analysis updates the inputs to reflect recent renewable energy targets and considers both land and subsea interconnections.

B.2 Methodology

The temporal resolution of the model uses sample days instead of a full year of dispatch. The power plants for each node in the model are aggregated based on fuel and type. Transmission is represented via a zonal topography and simplified into a "pipe-and-bubble" model, as opposed to a full alternating current (AC) power flow representation or a more simplistic "copper-plate" representation. The model input data was validated with the previous AIMS III model inputs along with the latest publicly available information on renewable energy targets and power development plans.

B.3 Technology Cost and Electricity Load Assumptions

For this assessment, the technology cost assumptions are based off the National Renewable Energy Laboratory's (NREL) Annual Technology Baseline (ATB) (NREL 2024). This data assumes gradual capital cost declines over time for coal, solar photovoltatics (PV), wind, and natural gas, with relatively steady costs over time assumed for hydropower and biomass (Figure B- 1).

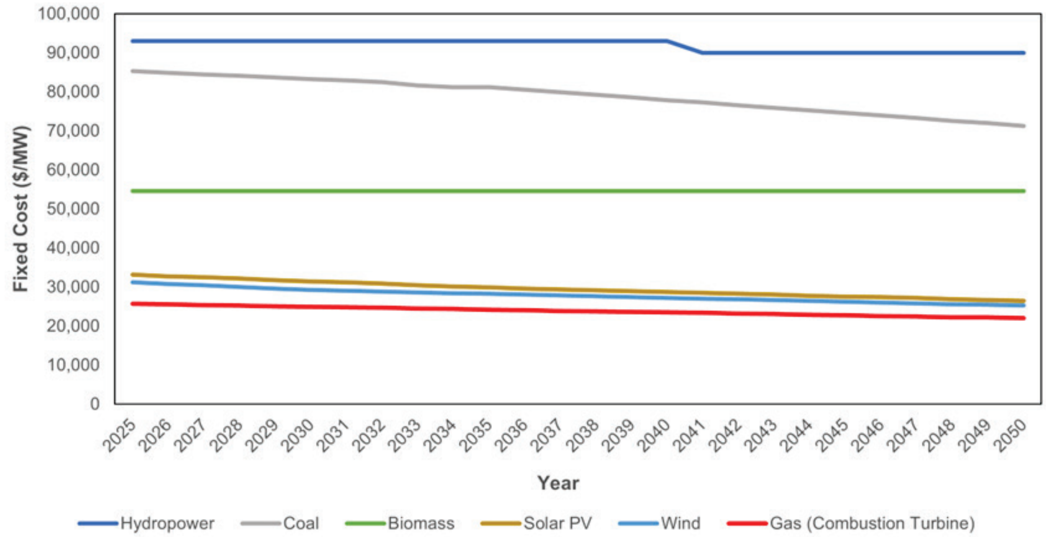

Figure B- 1. Fixed Costs (US$/MW) for Select Technologies in Analysis

Regarding assumptions for electricity demand, load projections were used for the entire time horizon (2025-2050) at an hourly basis. Hourly load profiles for representative days were generated via a clustering approach. Figure B- 2 shows a comparison of the peak electricity demands used in this analysis to the data used in the AIMS III study.

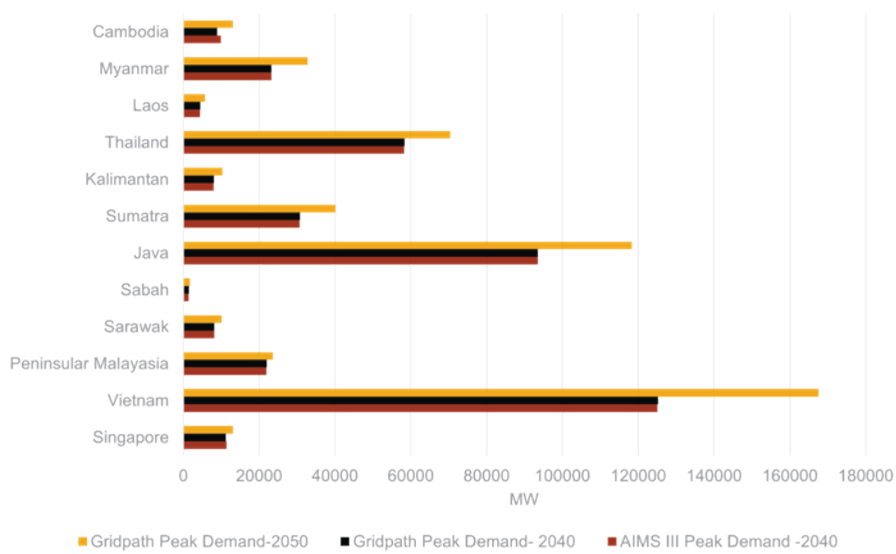

Figure B- 2. Peak Demand in AIMS III Study Compared to GridPath Model Used in this Analysis

B.4 Inputs: Capacity and Transmission

Certain capacities of electricity generation technologies are prescribed in the model for each country and sub-region (i.e., specified externally) based on the current fleet, targets, or other data sources. Renewable energy deployment goals for ASEAN countries by 2050 are based on their respective development plans. In order to meet ASEAN renewable energy targets and net-zero goals, the GridPath model will then build or retire capacity as needed to minimize total system costs. The generator candidates for each node in the model are shown in Figure B- 3.

	SGP	VNM	MYSPM	MYSSAB	MYSSAR	IDNJAV	IDNSUM	IDNKAL	KHM	LAO	MMR	THA
Gas CC (combined cycle)	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
Gas CT (combustion turbine)	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
Solar	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Wind		✓				✓	✓	✓	✓	✓	✓	✓
Coal		✓				✓	✓	✓	✓	✓	✓	✓
Hydro		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Hydrogen	✓											
Battery	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Geothermal						✓	✓					
Biomass									✓			

Figure B- 3. Generator Candidates for Model Nodes

Note: SGP: Singapore, VNM: Vietnam, MYSPM: Malaysia (Peninsula), MYSSAB: Malaysia (Sabah), MYSSAR: Malaysia (Sarawak), IDNJAV: Indonesia (Java), IDNSUM: Indonesia (Sumatra), IDNKAL: Indonesia (Kalimantan), KHM: Cambodia, LAO: Laos, MMR: Myanmar, THA: Thailand

Existing transmission is also prescribed in the model. Figure B- 4 displays the overall transmission topology, including existing and candidate. Figure B- 5 displays the regions/nodes on a map.

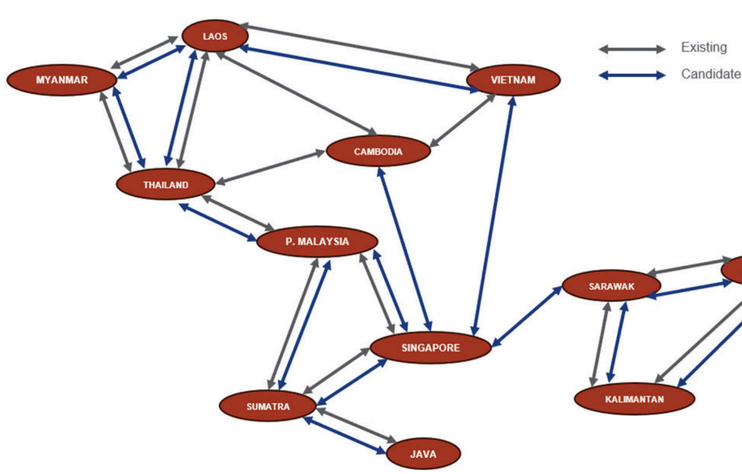

Figure B- 4. Existing and Candidate Transmission Lines in Model

Figure B- 5. Nodes in Southeast Asia for Analysis

Appendix C. Interconnector Feasibility

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

C.1 Data layers used in conceptual route assessments

Table C- 1. Data layers used in conceptual route assessments.

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 DEM	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/

C.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 C- 1, Table C- 2). This may be because newer cables are increasingly buried as a means of protection against external threats.

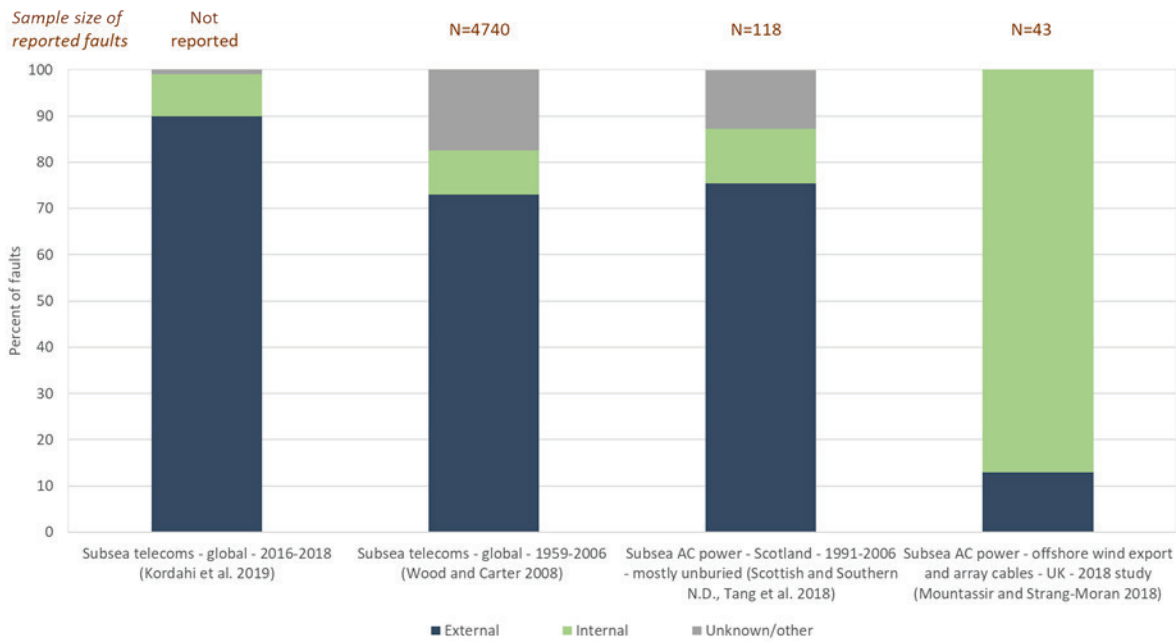

Figure C- 1. Share of subsea cable faults by cause category (external, internal, or unknown/other).

Table C- 2. 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 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 2006-2015. However, the sample size of reported subsea HVDC faults is very small.

C.3 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 summary figure. Some absolute numbers were inferred from information about sample size and share of faults. Some results in the table have been rounded.

C.4 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 HVAC 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).

C.5 Crossings

The conceptual cable routes 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.

C.6 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 C- 2 illustrates a combination of these measures for a subsea cable crossing a pipeline.

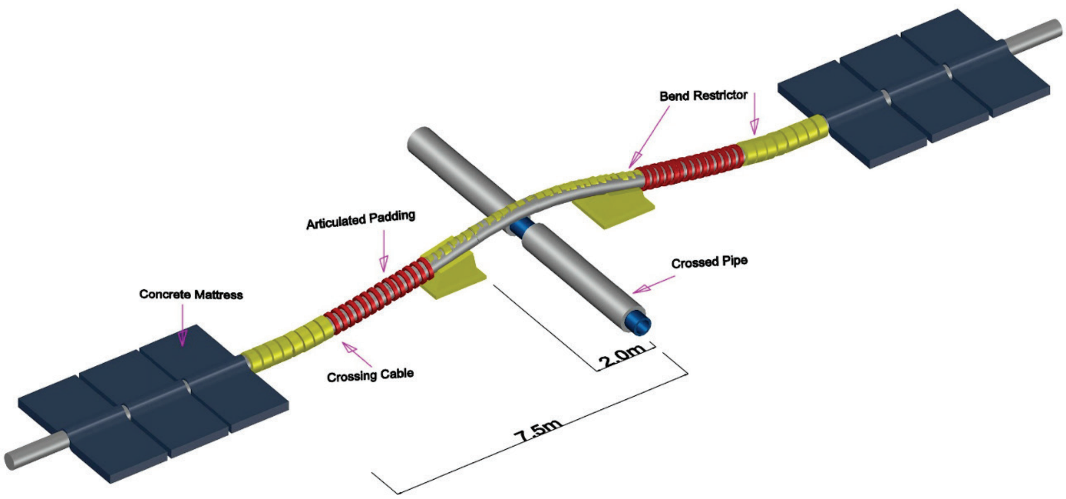

Figure C- 2. A combination of point protections for a subsea cable crossing a pipeline (Reda, Rawlinson et al. 2020).

C.7 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 towards 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.

C.8 Shipping data

Shipping data would be a key input for a cable burial risk assessment. Figure C- 3 shows vessel traffic density for the region of interest, from a 2015 dataset (Halpern, Frazier et al. 2015).

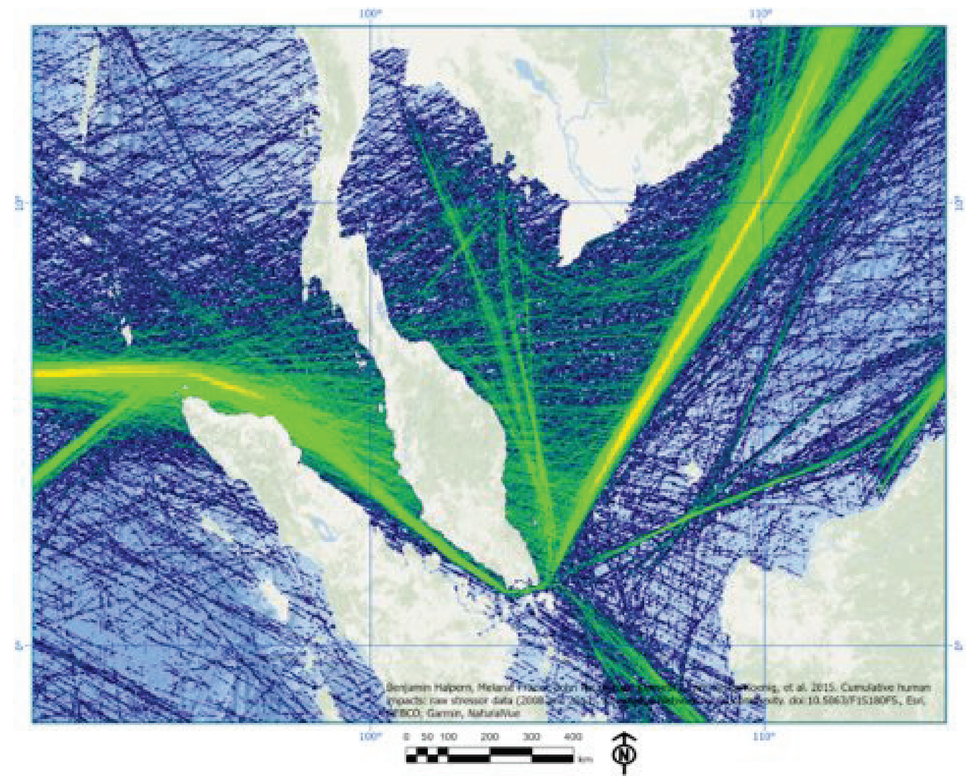

Figure C- 3. Illustrative vessel traffic density for region of interest (data from Halpern, Frazier et al. 2015).

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 C- 4 shows example AIS data as part of a cable burial risk assessment (Carbon Trust, 2015).

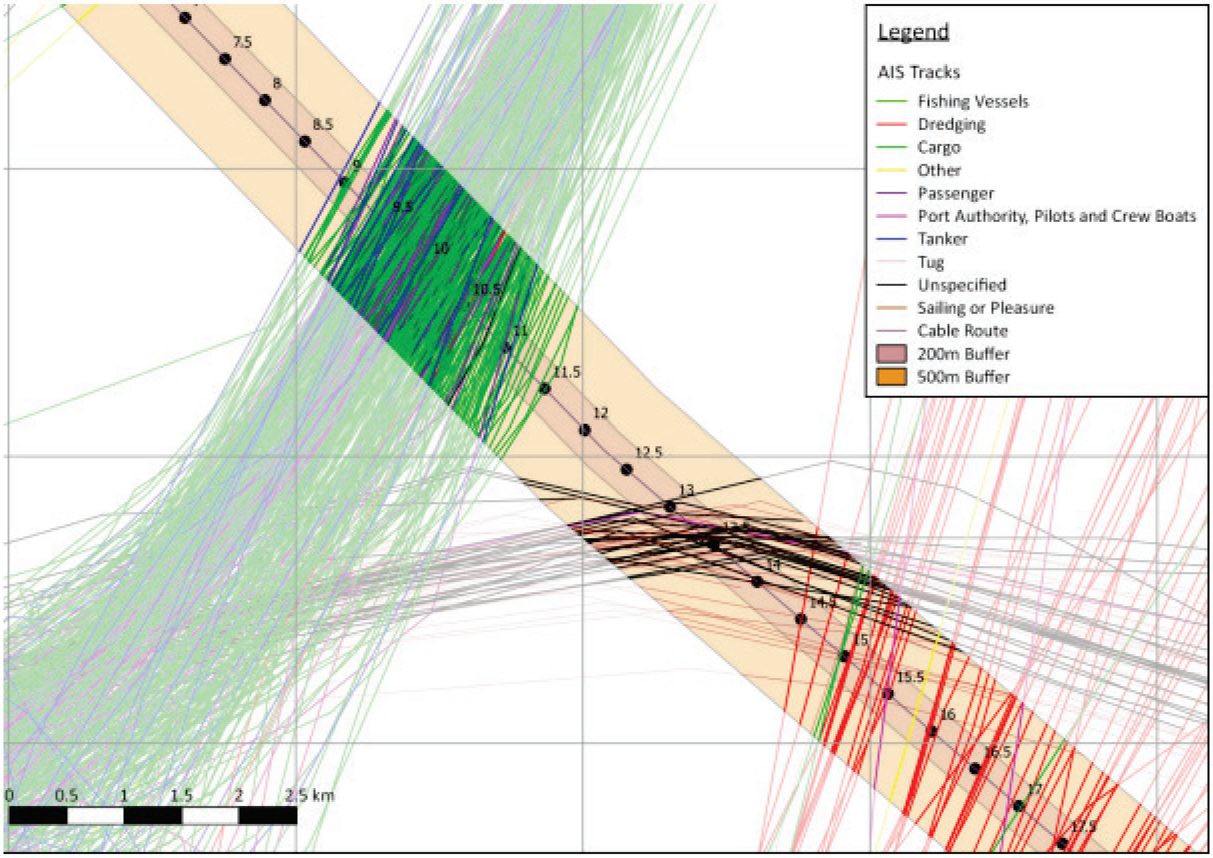

Figure C- 4. Example automatic identification system (AIS) shipping data as an input to a cable burial risk assessment. Black dots indicate cable kilometer posts. Image from Carbon Trust (2015).

C.9 Cable Technologies

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 C- 5.

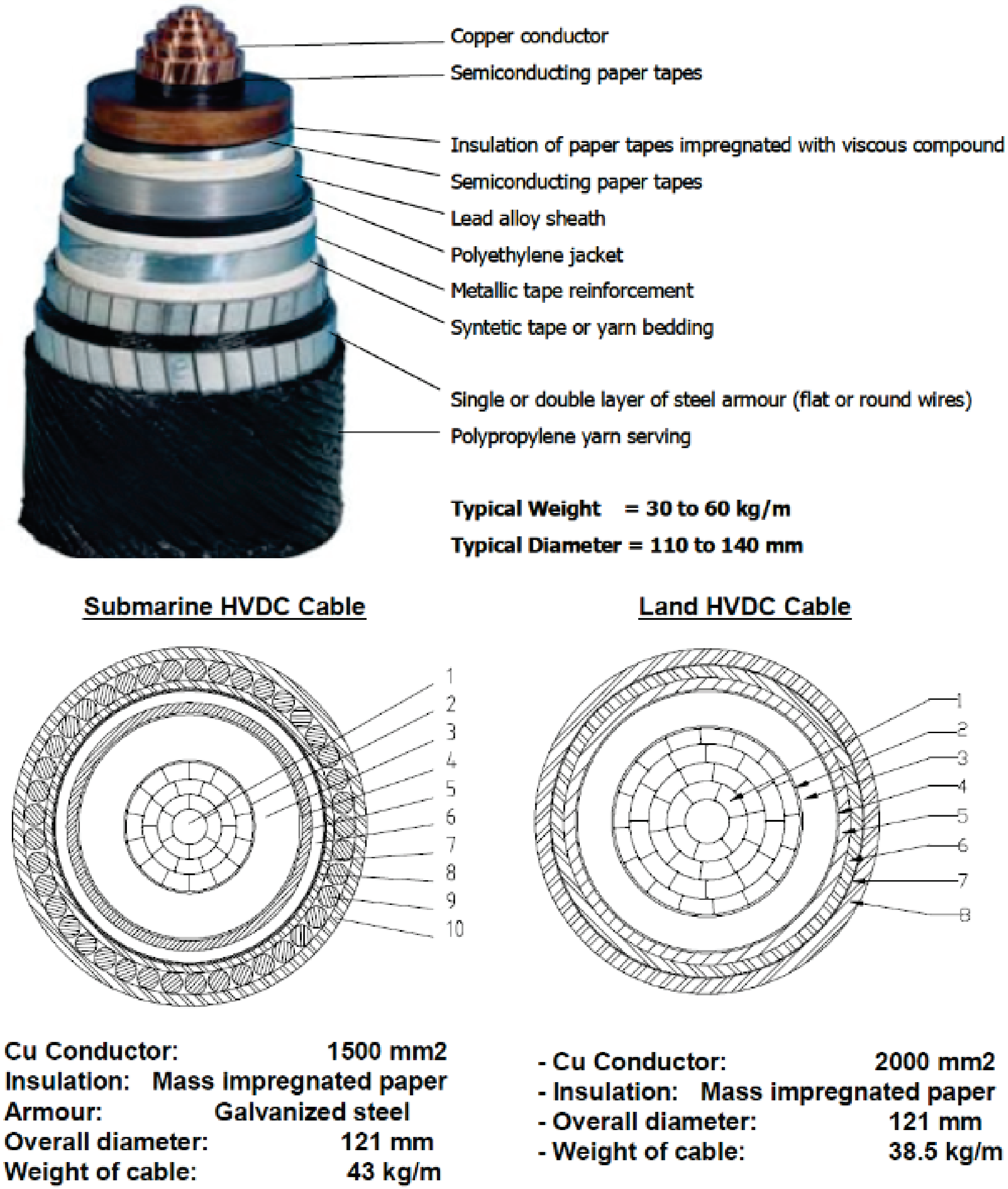

Figure C- 5. Mass impregnated HVDC cable cross section (ENTSO-E 2023).

C.10 HVDC Configurations and Technologies

Bipolar HVDC configurations were discussed above. Additional detail is provided in this section concerning HVDC bipoles and their alternatives, as they are summarized in Figure C- 6. 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, Costinaș 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 multi-directional power flow control within the network.

C.11 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: line commutated converter (LCC) and 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 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.

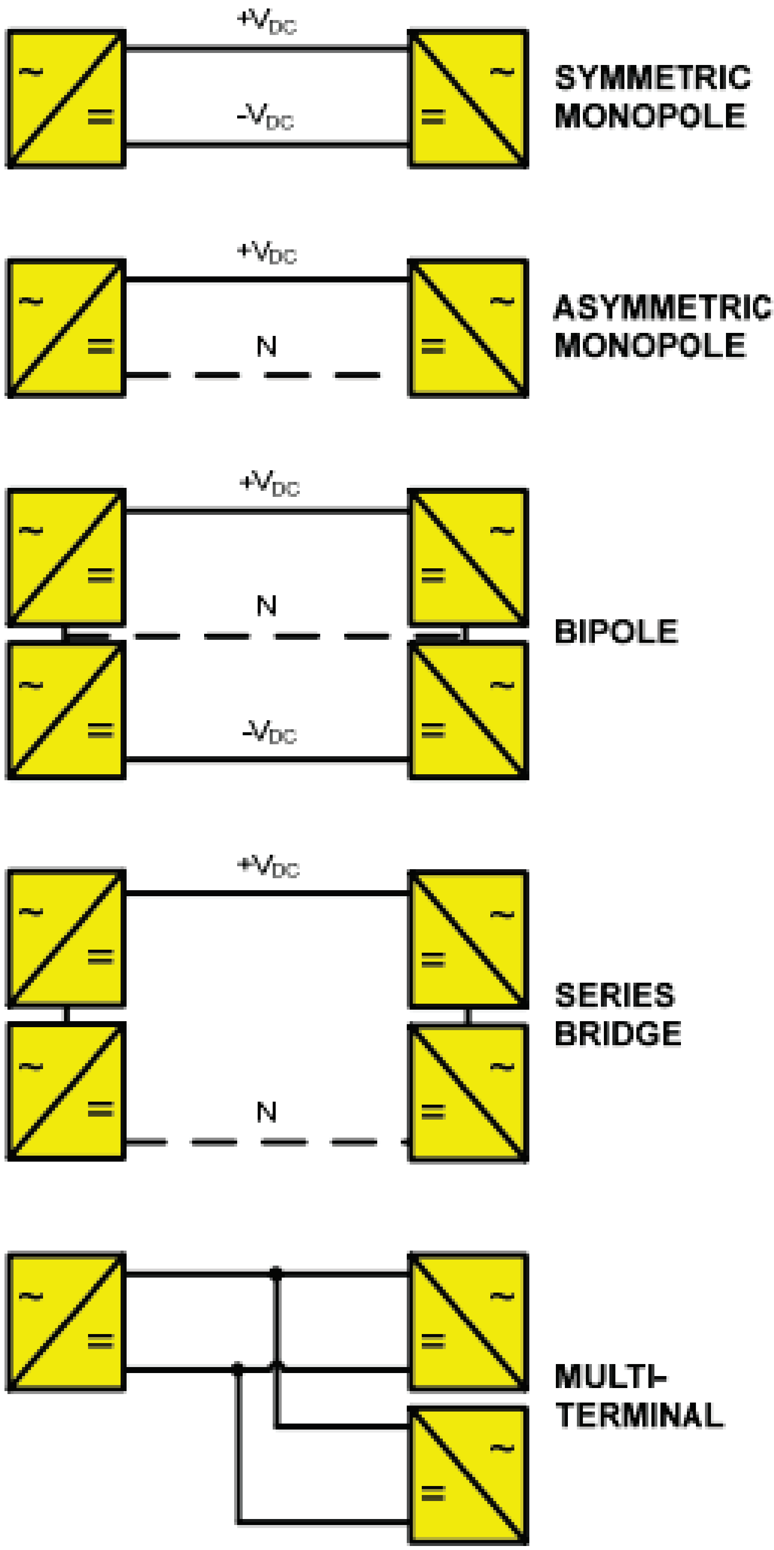

Figure C- 6. Common system topologies (Sellick and Åkerberg 2012).

Appendix D. Socio-economic impacts

D.1 Case Study: Offshore Wind and Subsea Cable Infrastructure Development in California

California's strategic plan for offshore wind development focuses on utilizing subsea cables to transmit power from offshore wind farms to onshore substations and long-distance load centers. The development of this domestic offshore wind industry in California will generate thousands of jobs in construction, manufacturing, maritime services, and environmental monitoring, providing substantial economic benefits for communities near ports and coastal areas. CADEMO, for example, is an offshore wind project designed to be California's first commercial floating wind farm. With a target of becoming operational by 2027, CADEMO will include four 15 MW floating turbines, producing around 60 MW of clean energy annually. Subsea transmission cables from the Morro Bay Wind Energy Area (WEA) will deliver offshore wind-generated power from CADEMO to the bulk transmission grid, supporting California's 2030 and 2045 renewable energy targets. As shown in Table D- 1 and Table D- 2, the workforce required for offshore wind projects includes jobs in wind farm operations, maintenance of turbines, subsea cables, and substations (CADEMO 2023).

Table D- 1. CADEMO Project Economic and Workforce Benefits (Construction Phase)

Impact Categories	Jobs (FTE)	Earnings (Millions)	Output (Millions)	GDP (Millions)
Onsite	20	$2.0	$2.0	$2.0
Supply Chain	677	$66.1	$156.5	$84.7
Induced	225	$13.1	$44.7	$27.0
Total	**922**	**$81.2**	**$203.4**	**$113.7**

Table D- 2. CADEMO Project Economic and Workforce Benefits (Operations Phase)

Impact Categories	Jobs (FTE)	Earnings (Millions)	Output (Millions)	GDP (Millions)
Onsite	4	$0.4	$0.4	$0.4
Supply Chain	12	$1.1	$3.9	$1.8
Induced	7	$0.4	$1.3	$0.8
Total	**23**	**$2.0**	**$5.6**	**$3.1**

Case Study: Job Creation through Transmission Development in Brazil

The Belo Monte Ultra High Voltage Direct Current (UHVDC) transmission project, pictured in Figure D- 1, has also driven significant job creation in Brazil. Phase I created over 9,000 direct jobs and more than 21,000 indirect jobs during construction. Phase II generated around 16,000 jobs in construction and related sectors (GEIDCO 2023). By transmitting clean hydropower from the Amazon Basin to load centers in southeastern Brazil, it also meets the electricity needs of over 22 million people, enhancing productivity and job opportunities in major cities like São Paulo and Rio de Janeiro.

Figure D- 1. Rio Converter Station of Brazil Belo Monte. 800 kV UHVDC Phase II Project

D.2 Case Study: Economic Benefits from Nepal-India Electricity Trade

Analysis completed by the South Asia Regional Initiative for Energy Integration (SARI/EI), found that electricity trade between Nepal and India could enhance socioeconomic development for both countries by utilizing Nepal's untapped hydropower resources, providing a stable supply of renewable energy and promoting regional interconnection (SARI/EI 2016). Export revenues and investments from power trade could contribute to a 39% higher GDP in Nepal by 2045, compared to a 14% gain with delayed capacity additions (Figure D- 2). India benefits from reduced electricity system costs by decreasing the need for additional generation capacity, leading to lower investment requirements to meet its energy demand. Accelerated power trade also would result in a reduction in India's cumulative GHG emissions (Figure D- 3).

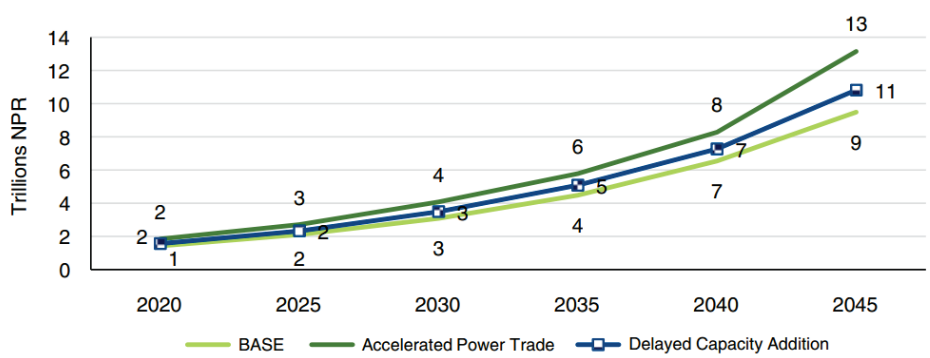

Figure D- 2. Growth of Nepal's GDP

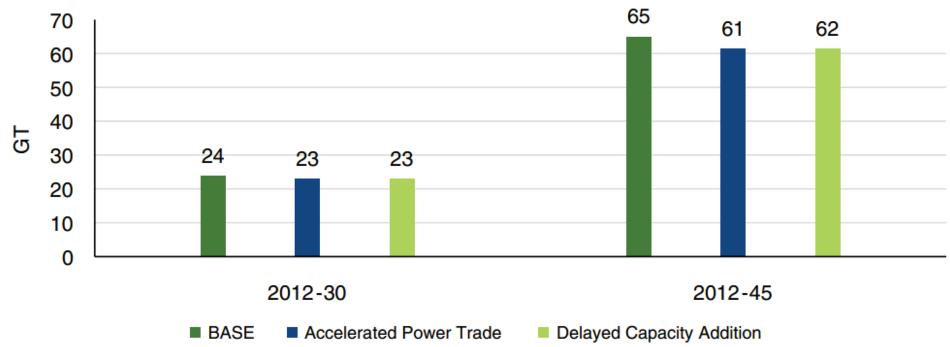

Figure D- 3. Impact of Electricity Trade on India's Cumulated CO2 Emissions from Power Sector

D.3 Case Study: Baltic Integration into the Nord Pool Market - Lowering Electricity Prices through Interconnection

The integration of the Baltic countries into the Nord Pool wholesale market resulted in significant electricity price reductions. This integration was made possible by the construction of the Estlink 1 and 2 HVDC lines (1,000 MW combined capacity) connecting Estonia and Finland, and the 700 MW NordBalt HVDC line between Lithuania and Sweden (IEA 2019). Upon reaching full capacity, wholesale electricity prices in Lithuania aligned with Sweden's, demonstrating the impact of interconnection on price convergence and reduced electricity prices (Figure D- 4).

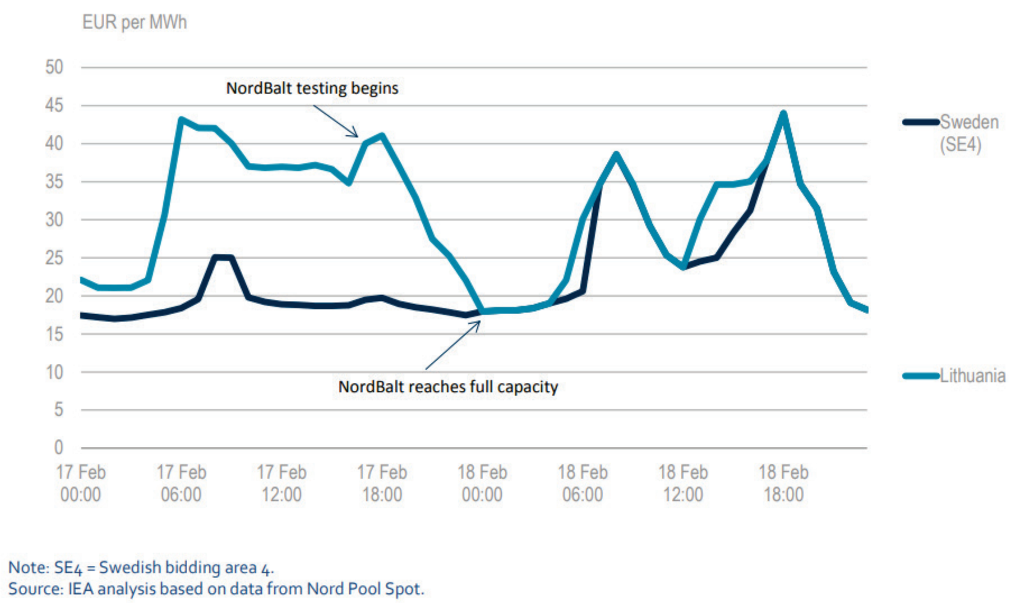

Figure D- 4. Impact of NordBalt on Wholesale Electricity Prices, Sweden and Lithuania

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