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Technical Risk Assessment of the 20 kV Submarine Cable Network Development on Tunda Island, Banten

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Abstract

The construction of a 20 kV submarine cable network in Tunda Island is a strategic project to enhance the reliability of the electricity supply. This project faces significant technical risks that require structured risk management. This study aims to identify, analyze, and prioritize technical risk mitigation strategies using a combination of Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and the Analytical Hierarchy Process (AHP). The FMEA results identified ten technical failure modes, with the top three risks based on the Risk Priority Number (RPN) being: Cable jointing failure (RPN 345.31 - Extreme category), Repair/logistics delay (RPN 294.00 - High category), and Mechanical damage to the submarine cable (RPN 231.56 - High category). These findings indicate that human technical and operational aspects, particularly the jointing process and logistical readiness, are the main critical points. The FTA analysis of the critical risks (R4, R10, R1) revealed that the root causes of failure are heavily influenced by human and operational factors, such as non-compliance with installation procedures, the use of non-standard splicing materials, and limitations in logistics and complex administrative bureaucracy. Through AHP, the most dominant mitigation criteria were found to be Electrical System Reliability (weight 0.3389) and External Risk Control (weight 0.2777). Based on this weighting, the most effective and globally prioritized mitigation strategy is the Establishment of Anchor Prohibition Zones and Community Socialization (global weight 0.3722), followed by the Installation of Concrete Mattress (global weight 0.3138). This strategy emphasizes the importance of physical protection combined with regulatory and community participation roles. This research provides a significant contribution in the form of a structured and prioritized technical risk mitigation framework, which can serve as a guide for PLN UID Banten to ensure the safe, efficient, and sustainable execution of the project in a complex maritime environment.

Keywords:
Technical Risks; Submarine Cable; FMEA; AHP; 20 KV Network; Tunda Island.

INTRODUCTION

Tunda Island is a small island located in the Java Sea, which is north of Banten Bay. Administratively, this island is included in the area of Serang Regency, Banten. The area of Tugda Island is about 300 hectares. And with the population of Tunda Island reaching 1500 people. Tunda Island can actually be used as a very interesting tourism object to study. Tunda Island has beautiful and natural sea views that can attract tourists to visit (Acaroglu & Marquez, 2022; Aven, 2016; Carlson, 2012; Ferreira & Leite, 2012; Gordonnat & Hunt, 2020). The landscape landscape is a measurable parameter of aesthetic quality. Because it is the main reason for tourists to visit an area. With sailing activities with views of the sea and dolphins, fishing, snorkeling, diving, watching the sunset and sunrise are interesting tourism potentials.

The electricity demand of Tunda Island continues to increase along with population and economic growth, while the isolated system is an electricity system located on the Tunda island and its location is relatively far from the mainland, so it still uses diesel power plants (PLTD) as an electric energy producer. Electricity management is carried out independently by Village-Owned Enterprises (Bumdes). The people of Tunda Island enjoy electricity for only 6 hours per day, with the price of electricity tariffs quite expensive, reaching Rp 11,000 / kwh. Meanwhile, PT PLN (Persero) currently sells electricity at a rate of Rp 1,400 / kwh (Institute, 2013; Kerzner, 2017; Pisani & Villacci, 2011; Thomson et al., 2014; Yusuf et al., 2019).

Precisely in 2020 the Covid-19 outbreak hit Indonesia, making tourists visiting Tunda Island very lonely. So that Bumdes cannot cover existing operational costs. In 2021, community leaders came to PT PLN UID Banten to ask to supply electricity to Tunda Island. Due to BlackOut due to damaged PLTD engines. So that some people enjoy electricity by buying small individual generators (Purvins et al., 2018; Simmons, 2010; Taormina et al., 2018; Q. Wang et al., 2019; W. Wang et al., 2021).

Responding to the demands of the people of Tunda Island who need an electricity system, PT PLN (Persero) UID Banten plans to build a 20 KV submarine cable network to meet the island's electricity needs. The construction of the submarine cable network is expected to be a more efficient and environmentally friendly long-term solution to answer electricity needs in the region.

However, investment in the construction of a submarine cable network is not without risks. There are a number of factors that can affect the success of this project, including technical, financial, environmental, and regulatory risks. Submarine cable installations face significant challenges, such as erratic sea conditions, potential damage from natural disasters or maritime activities, and complex maintenance processes. In addition, the high initial investment cost and the need to comply with various applicable regulations are also important considerations in project planning (Gulski et al., 2021; Li et al., 2020; Mazzanti et al., 2021; Okpokparoro & Sriramula, 2023; Zhao et al., 2020).

Therefore, a comprehensive technical risk analysis is needed to identify and manage potential obstacles that may arise during the construction and operational process. By conducting this analysis, it is hoped that an effective mitigation strategy can be produced, so as to minimize risks and ensure the success and sustainability of investment in the construction of a 20 KV submarine cable network on Tunda Island.

Most marine cable research focuses on HVDC systems, cross-border interconnections, or large-scale renewable energy transmission. Research related to medium-voltage (20 kV) submarine cables in isolated systems is still limited. There is little research on the integration of the FMEA-FTA-AHP method in the context of submarine cable installation, especially focusing on the technical risks of construction projects. Research on the location of small islands in Indonesia is very limited, especially related to the technical risks of the construction of submarine cables combined with logistical and operational limitations. The technical mitigation strategy of submarine cables has not been studied in a structured manner using multi-criteria weighting, including the evaluation of the effectiveness of methods such as concrete mattresses and no-anchorage zones. There is no practical technical risk mitigation framework for PLN UID Banten, which can be used as a guideline for the construction of submarine cables in complex maritime areas.

Based on the above explanation, the following problem formulation is obtained:
1. What are the main technical risks that can occur in the construction of the submarine cable network on Tunda Island?
2. What is the most dominant aspect that most influences the success rate of the construction of the delayed island submarine cable?
3. What are the mitigation strategies that can be applied to manage risks in the construction and operation process of the submarine cable network on Tunda Island?

The objectives of conducting this feasibility study research are as follows:
1. Analyzing the risks on the technical aspects related to the construction of a 20 kV submarine cable network on Tunda Island.
2. Analyzing the risks of the dominant technical aspects affecting the success rate of the construction of the Tugda Island submarine cable
3. Formulate mitigation strategies to minimize risks in the construction and operation process of the submarine cable network, thereby supporting the success and sustainability of the project investment.

With the implementation of this research, it is hoped that this research can provide the following benefits:
1. For PT. PLN (Persero) Banten
   To be the material for evaluation and guidelines in planning, implementing, and managing marine cable network projects on Tunda Island, including risk identification and effective mitigation strategies.
2. For the People of Tunda Island
   Providing long-term solutions to meet the need for stable, affordable, and environmentally friendly electricity, thereby improving the quality of life and supporting local economic growth.
3. For the Government.
   Provide input related to energy policy and infrastructure planning to support the sustainable development of remote areas.

The limitations of the problem in this study are:
1. The research was only carried out on the construction project of a 20 kV medium voltage submarine cable that connects the electricity system of Tunda Island, according to field observation data and technical documents from PLN UID Banten. This research only focuses on the technical aspects related to the design, installation, and reliability of submarine cables.
2. The risk analysis is focused on the initial installation and operation stages of the submarine cable, including the laying process, the stability of the cables on the seabed, jointing, and post-installation conditions. The planning stages of permitting and civil construction outside the cable line are not analyzed in depth.
3. The study only addresses technical risks that impact the reliability of submarine cable operations, including risks to the underwater environment, human activities at sea, and installation characteristics. Financial, socio-economic, legal, and regulatory risks were not included in the scope of the study.
4. Research data was obtained through field observations, bathymetric surveys, sediment conditions, interviews with PLN technical personnel, and project technical documents.

This study did not conduct laboratory testing of cable materials or numerical simulation of the design.

METHOD

Types of Research

This study used a combination of the FMEA-FTA method to answer the research objectives**.** Failure Mode and Effects Analysis (FMEA) is a systematic method for identifying, analyzing, and managing potential failures that can occur in a system. In the context of the construction of a submarine cable network, research using FMEA is classified as applied and analytical research that aims to identify technical risks, assess their severity, and develop mitigation measures. This approach is very effective in minimizing technical risks and ensuring the success of the submarine cable project. This method helps evaluate the failure mode in detail with clear priority, while the FTA provides a logical analysis of the main causes of failure. With the combination of these two methods, submarine cable projects can be designed more reliably, efficiently, and resilient to extreme environmental risks as well as human activities.

And this study also uses the AHP method**.** The AHP method is one of the methods used to assist decision-makers in choosing or determining priorities from various alternatives based on a number of criteria. In the context of the investment risk analysis of the construction of a 20 kV submarine cable network, it allows for an in-depth understanding of issues involving many stakeholders (investors, the public, and regulators). This method helps to generate innovative solutions through risk exploration from the perspective of users and project actors to identify, analyze, and mitigate investment risks in the construction of a 20 kV submarine cable network.

The combination of FMEA, FTA, and AHP methods provides a holistic and effective approach in analyzing the risks of submarine cable network construction. FMEA and FTA ensure that all potential risks are systematically identified, while AHP supports mitigation prioritization based on relevant criteria.

Research Stages

The research stage in the construction of the submarine cable aims to ensure the success of the project technically, economically, and environmentally. Each stage involves an in-depth analysis that serves as the foundation for efficient and sustainable planning, implementation, and operation of submarine cables.

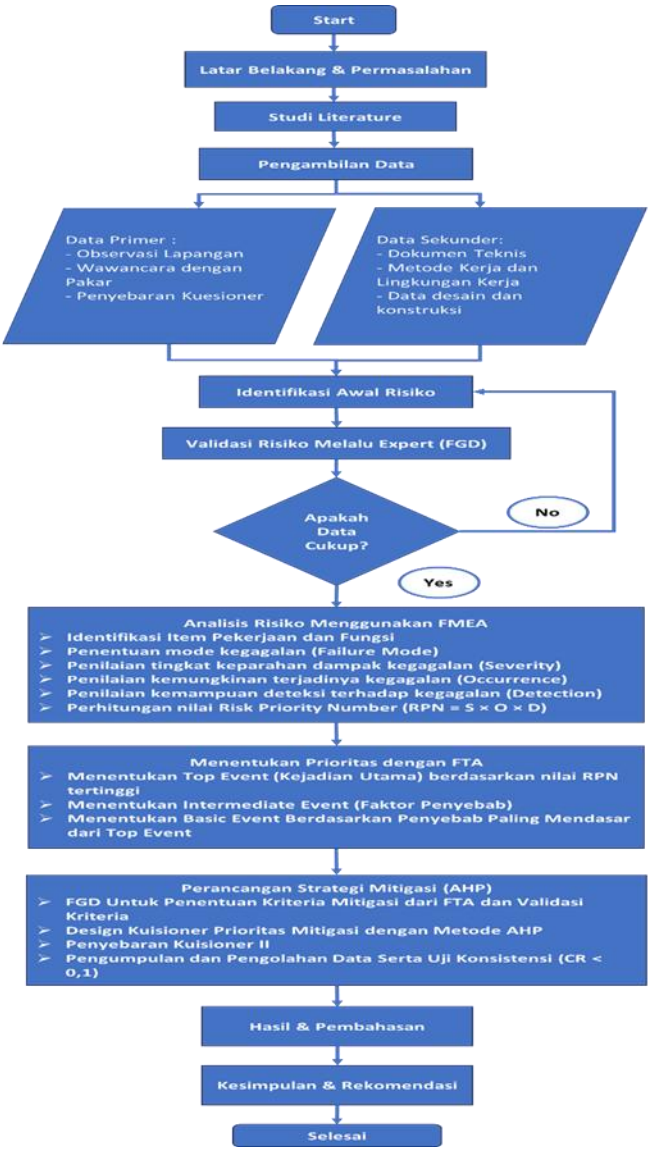

Figure 1. Research Stage Flowchart

Stages of Data Collection and Processing

Studi Literature

The literature study aims to Identify the conceptual framework related to the construction of submarine cables and the risks that may arise. The activities are as follows.

1. Review references regarding risks related to technical, environmental, operational, and other aspects in the construction of submarine cables.
2. Search literature as a supporting material for the calculation of *Failure Mode and Effect Analysis* (FMEA), *Fault Tree Analysis* (FTA) and *Analytical Hierarchy Process* (AHP) methods.
3. Review regulations related to the installation of submarine cables. Some of the regulations come from the Law on Shipping, the Law on Marine, the Government Regulation on Marine Buildings and Installations, the Decree of the Ministry of Maritime Affairs on Submarine Cables, the Regulation of the Minister of Communication and Information Technology on the Implementation of Submarine Cable Communication Systems.

Problem Formulation and Reset Method

Based on the existing background and problems and the literature studies that have been carried out, it is known that there are many risks that hinder the construction of the ship. At this stage, the formulation of the problem was prepared which began to identify technical risks that could affect the success of the 20 KV submarine cable construction project on Tunda Island. It was followed by using FMEA and FTA methods to analyze the failure modes and the main causes of risk in the submarine cable construction project. For the AHP method, it can be used to prioritize risks based on severity, frequency of occurrence, and detection ability.

Stage of Field Data Survey and Inventory

Survey and inventory of field data to find out the flow of the construction process of the Tunda Island submarine cable network. Identification of risk events is carried out using references from several literatures, observations, interviews and *brainstorming* with several experts to find out the source of risk that causes the risk event. Each source and occurrence of risk is arranged based on;

1. *What*, what's the risk
2. *Where*, where the risk occurs
3. *How*, how does the risk occur in that place.
4. *Why*, why can these risks occur

Based on the list of identified risks, Questionnaire I was prepared using the FMEA method. This questionnaire I is to find out the opinions of respondents on the *severity* values (severity/impact caused), *occurrence* (how often the incident occurs) and *detection* (how far the risk event can be detected). Questionnaire I was given to the leaders and members of the 3 sections studied as well as the leaders of other related sections. With the distribution of this questionnaire I, an assessment of *the weights of Severity*, *Occurrence* and *Detection* of each risk event can be obtained

a. Identification of Systems and Components

Identify all elements related to the project, such as:

1. Marine cables (core, shielding, insulation layer).
2. Protection system (underwater ducts, protective materials).
3. Installation location (marine zone, depth, ocean current).
4. Mounting equipment (ships, cable tensioner devices).

b. Identification of Risk Events

Record all potential failures, such as:

1. Technical, i.e. Cable damage during installation, cable connection failure.
2. Environment: Disturbances due to ship activity, underwater earthquakes, or ocean currents.
3. Operational: Human error, failure of the mounting tool.

c. Questionnaire Design with FMEA Method

- Compile questionnaires to collect risk data from experts and stakeholders.
- Data was collected for the Severity (S), Occurrence (O), and Detection (D) parameters.

d. Questionnaire Dissémination and Data Collection

- Collect data from experts, technical teams, and previous project documentation.

Data Management Stage

After data was obtained from the distribution of questionnaire I, a *Risk Priority Number* (RPN) was calculated. The RPN is obtained from the calculation of *the Severity* x *Occurrence* x *Detection value.* The next step is to rank the RPN from the highest to the lowest. Risk events with high RPN, indicate that these risks must be followed up so that they do not recur or can reduce their impact. For this reason, mitigation measures are needed against these risk events.

Top Event Determination Stage

1. The first step in FTA is to determine *the top event*, which is the main failure that is the focus of the analysis. *Top events* are the end result of a series of failures that can interrupt or stop system operations.

2. After the top event is determined, the next step is to identify intermediate events, which are the causative factors that directly cause the top event. Intermediate events are often the result of several basic events.

Steps:

1. Use logic gates, such as AND gates for Top events only occur if all related basic events occur at the same time.
2. OR Gate: Top events occur if one of the basic events occurs.
3. Connect intermediate events with basic events using this logical connection.
4. Determining *Basic Events* , i.e. *Basic events* are the main direct cause of the risk being analyzed. These events cannot be further broken down and can often be measured or managed.
   a. Identify all the basic events on which each *intermediate event is based*.
   b. Connect these basic events to *intermediate events* using the appropriate symbols in the fault tree diagram.
5. Create a Fault Tree Diagram
   a. All top events, intermediate events, and basic events are linked in the form of a fault tree diagram.
   b. This diagram visualizes the logical relationship between the various factors that cause failure.
6. Calculating the Probability of Failure
   a. Assign a probability value to each basic event based on historical data, expert input, or technical simulations.
   b. Calculate the probability of events from intermediate events and top events using probability logic.
7. Analysis and results

That is, interpret the probability of the top event and the minimum cut sets to understand the most critical risks.

Mitigation Planning Stage

At this stage, mitigation measures were identified by conducting *a Focus Group Discussion* (FGD) with the leadership and several members of related sections. The result of this FGD is in the form of a list of various proposed mitigation measures for the risks with the highest RPN. To find out the priority of mitigation steps that need to be carried out, it is carried out by distributing Questionnaire II. The questionnaire is arranged in the form of a paired comparison matrix. The distribution of Questionnaire II was carried out to the Directors, Managers and Heads of related Sections. The data from the collection of Questionnaire II will be analyzed using the AHP method so that the priority order of risk mitigation steps can be known.

Conclusion and Recommendation Stage

It is the final stage of the research that explains the results of the research obtained. It is hoped that the problems that you want to know from this research can be answered. Furthermore, recommendations are given for mitigation steps that need to be taken by the company so that existing problems can be avoided or reduced in the future.

RESULTS AND DISCUSSION

Risks on the Technical Aspects of the Construction of a 20 Kv Submarine Cable Network on Tunda Island

The assessment of potential technical risks in the 20 kV voltage submarine cable network construction project on Tunda Island was carried out through the application *of the Failure Mode and Effects Analysis* (FMEA) method which was compiled based on the results of the evaluation of four experienced experts in the field of submarine cable installation and maintenance. This approach is designed to explore the various possible technical failures that can arise during the construction and operational phases. Through a systematic analysis process, each potential failure is assessed from three main aspects, namely the severity of the impact (*Severity*), the frequency of occurrence (*Occurrence*), and the system's ability to detect the symptoms of failure (*Detection*). The three parameters are combined quantitatively to produce a Risk Priority Number (RPN) which functions as a measure of risk management priority. A higher RPN value indicates the need for immediate mitigation measures as such risks have the potential to have a major impact on system reliability. Thus, the FMEA method not only helps to identify the sources of technical problems, but also provides an empirical basis for more informed decision-making in the risk management of submarine cable projects.

The results of data processing using *the Failure Mode and Effects Analysis* (FMEA) method showed ten technical failure modes that have the potential to affect the success of the construction of a 20 kV submarine cable network on Tunda Island. Each risk was analyzed by considering three main parameters, namely the severity of the impact, the frequency of occurrence, and the ability to detect failures. The Risk Priority Number (RPN) value is obtained from the multiplication of the three parameters and is used to determine the risk mitigation priority. Here is a table of technical risk ratings based on FMEA analysis

Table 1. Failure Risk Rating Based on FMEA Analysis

Risk Code	Technical Failure Mode	Rata-rata Severity (S)	Rata-rata Occurrence (O)	Rata-rata Detection (D)	RPN
R4	Cable jointing failure	8.50	6.50	6.25	345.31
R10	Repair/logistics delays	7.00	6.00	7.00	294.00
R1	Mechanical breakdown of submarine cables	9.50	6.50	3.75	231.56
R7	Disturbances due to human activities	7.25	6.25	4.00	181.25
R5	Cables shifted on the seabed	6.75	5.75	4.50	174.66
R6	Cathodic protection failure	8.00	4.00	4.25	136.00
R3	Deformation due to high hydrostatic pressure	7.75	3.50	4.00	108.50
R2	Corrosion of metal protective layer	6.50	3.25	4.50	95.06

Risk Code	Technical Failure Mode	Rata-rata Severity (S)	Rata-rata Occurrence (O)	Rata-rata Detection (D)	RPN
R9	Natural disasters (earthquake, tsunami, liquefaction)	4.00	3.50	4.00	56.00
R8	Disturbances due to marine life	2.75	2.50	3.25	22.34

Source: Processed research data using the FMEA method based on questionnaires and expert evaluations of the PLN UID Banten submarine cable project

Table 1 indicates that most risks with high RPN values are derived from human technical and operational aspects, rather than from natural environmental factors. These findings show that the success of the 20 kV submarine cable network construction project on Tunda Island is highly dependent on the quality of implementation, accuracy of installation procedures, and the readiness of logistics and maintenance systems. Therefore, the mitigation strategy that is prepared needs to be focused on improving the competence of technical personnel, controlling material quality, and optimizing operations and supply chain management.

Table 2. Risk Level Analysis of Failure Risk

Risk Code	Technical Failure Mode	Rata-rata Severity (S)	Rata-rata Occurrence (O)	Rata-rata Detection (D)	RPN	Probability (%)	Level Risk
R4	Cable jointing failure	8.50	6.50	6.25	345.31	**32.5%**	**Extreme**
R10	Repair/logistics delays	7.00	6.00	7.00	294.00	**30%**	**High**
R1	Mechanical breakdown of submarine cables	9.50	6.50	3.75	231.56	**32.5%**	**High**
R7	Disturbances due to human activities	7.25	6.25	4.00	181.25	**31.25%**	**Moderate**
R5	Cables shifted on the seabed	6.75	5.75	4.50	174.66	**28.75%**	**Moderate**
R6	Cathodic protection failure	8.00	4.00	4.25	136.00	**20%**	**Moderate**
R3	Deformation due to high hydrostatic pressure	7.75	3.50	4.00	108.50	**17.5%**	**Moderate**
R2	Corrosion of metal protective layer	6.50	3.25	4.50	95.06	**16.25%**	**Low**
R9	Natural disasters (earthquake, tsunami, liquefaction)	4.00	3.50	4.00	56.00	**15%**	**Low**
R8	Disturbances due to marine life	2.75	2.50	3.25	22.34	**12.5%**	**Low**

Source: Processed research data (FMEA risk level analysis) based on field survey data and expert respondent assessments

Based on the results of the analysis presented in Table 4.16, the three technical failure modes with the highest Risk Priority Number (RPN) values were identified as the most critical risk sources in the 20 kV submarine cable network construction project on Tunda Island. These three risks have different but interrelated characteristics in influencing the reliability of the underwater electricity transmission system. The following discussion elaborates in depth on the main causes, technical implications, and mitigation directions that need to be taken to reduce the level of risk.

Failure in the cable connection process or *jointing* is the highest priority risk because it has the largest RPN value, which is 345.31. A high average *Severity* (S) value of 8.50 indicates that if this failure occurs, the impact on the electrical system will be very serious and potentially cause a complete disruption to the power supply. In addition, an *Occurrence* (O) value of 6.50 indicates that the likelihood of this failure is quite frequent, especially if the installation process does not follow standard procedures. In the technical context, the connection of the submarine cable serves to ensure electrical continuity and mechanical resistance between cable segments. This process requires a high level of precision, especially at the stage of connecting the conductor core, insulation layer, as well as external protection that must be completely seawaterproof. Based on the results of interviews with experts, it was found that the main causes of joint failure came from two dominant factors, namely inconsistencies in installation procedures and the use of *splicing* materials that did not meet quality standards.

The three risks with the highest Risk Priority Number (RPN) values, namely cable joint failure (R4), repair and logistics delays (R10), and mechanical damage to submarine cables (R1), are the main focus in risk control and mitigation. All three represent important stages in the project cycle, from the installation process, operational management, to protection against external disturbances at sea. By understanding these three key risks thoroughly, mitigation strategies can be directed more on target. Efforts to improve the quality of human resources, planned logistics management, and technical control in the field will be key in maintaining the sustainability of the project. The success of the construction of a 20 kV submarine cable network on Tunda Island is ultimately determined by the synergy between careful technical management and consistent risk management from the planning to operational stages.

The Most Dominant Aspects Affecting the Success Rate of Tugda Island Submarine Cable Construction

The analysis of the most dominant aspects that affect the success of the construction of the 20 kV submarine cable network on Tunda Island was carried out using the Fault Tree Analysis (FTA) approach. This method is used to trace the root causes of failure hierarchically and systematically through mapping the logical relationships between events that have the potential to cause major failures or top events. In this study, the peak event analyzed was the failure of the cable connection, because the results of the previous Risk Priority Number (RPN) calculation showed that the failure of the connection was the mode of failure with the highest level of risk in the project.

Fault Tree Analysis (FTA) is used to trace the cause-and-effect relationship between various factors that can trigger cable connection failures in the 20 kV submarine cable network construction project on Tunda Island. This method helps to systematically map the sequence of events from the most basic *events* to the top *event*, i.e. cable connection failures. This approach not only serves to identify the sources of risk, but also to understand the interactions between technical, human, and environmental factors that collectively affect the reliability of submarine cable systems. This approach is used to trace the root cause of failure from the results of previous quantitative findings, namely Failure Mode and Effects Analysis (FMEA). Based on the results of the FMEA, three modes of technical failure with the highest Risk Priority Number (RPN) value were obtained, namely cable connection failure (R4), delay in repair or logistics (R10), and mechanical damage to submarine cables (R1). These three risks were then selected as the focus of further analysis through the FTA to determine a deeper cause-and-effect relationship and identify the dominant factors influencing the overall success of the project.

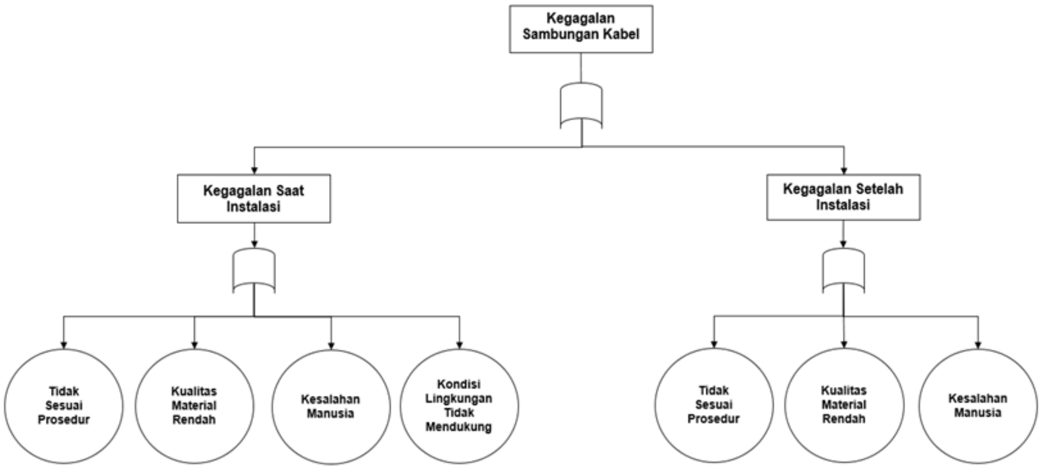

Figure 2. FTA Cable Connection Failure

Figure 2 shows the Fault Tree Analysis (FTA) structure for the peak event of a cable connection, which is one of the failure modes with the highest Risk Priority Number (RPN) value based on the results of the FMEA analysis. This structure illustrates the logical relationship between various causal events that can result in a failure of the 20 kV submarine cable connection on Tunda Island. At the highest level, the top event, which is cable connection failure, is broken down into two main groups of causes, namely failure during installation and failure after installation. These two categories reflect two important phases in the life cycle of a submarine cable connection: the initial installation phase and the operational phase once the system is activated. The relationship between the peak event and the two main causes is described using the OR logic gate, which means that the occurrence of either event is enough to cause an overall cable connection failure.

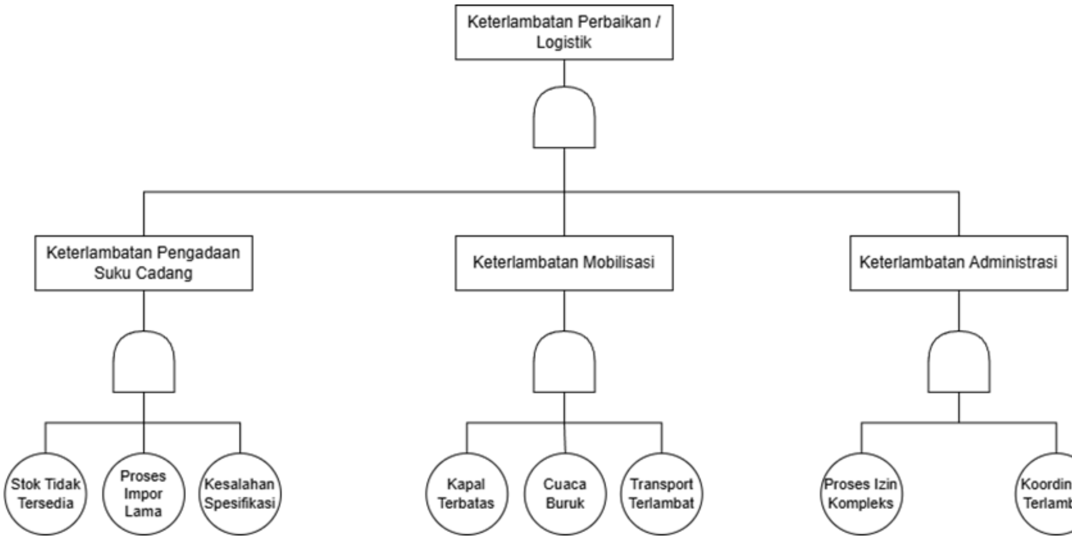

Figure 3. FTA Repair Delays/Logistics

Figure 3 35 explains that the Fault Tree Analysis (FTA) analysis of repair or logistical delays shows that this problem is one of the most significant sources of technical risk in the construction of a 20 kV submarine cable network on Tunda Island. Based on the calculation results obtained from the integration of the FMEA method, the Risk Priority Number (RPN) value for the repair delay category reached 294.00, which indicates a high level of risk to the smooth implementation of the project. Through the FTA approach, this delay is positioned as the top event that is analyzed deductively by tracing various causative factors down to the level of *basic events*.

The structure of the fault tree that was formed showed that the delay in repair originated from three main groups of causes, namely delays in the procurement of parts, delays in mobilization, and administrative obstacles. At the stage of parts procurement, delays often arise due to unavailable component stock, long import waiting times, and incompatibility of material specifications with field needs. This condition caused repair work to be delayed due to the unavailability of the necessary components on time. Meanwhile, at the mobilization stage, the delay was caused by the limited number of special vessels for transporting underwater equipment, extreme weather in the Tunda waters, as well as technical obstacles in transportation that slowed down the departure of the field team. Administrative barriers also contribute greatly to delays, especially due to complex licensing processes, slow interagency coordination, and bureaucracy that is still manual, thus lengthening waiting times before work can be carried out.

FTA logic analysis shows that the relationships between causes in the fault tree are mostly connected by *the OR* logic gates. This means that the occurrence of just one of the underlying causes is enough to cause a peak event in the form of a delay in repair. Thus, each causal element has a direct contribution to the increased probability of project delays.

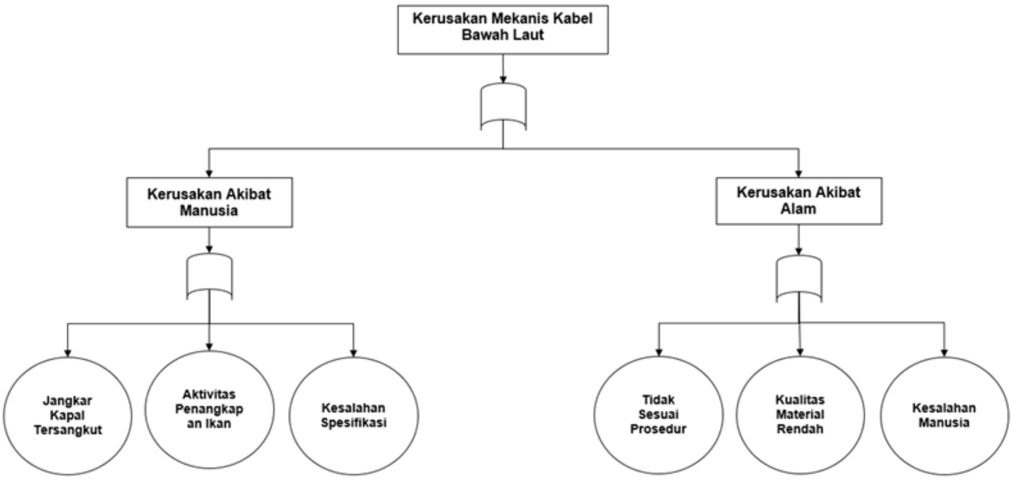

Figure 4. FTA Mechanical Breakdown of Submarine Cables

Figure 4 classifies the Fault Tree Analysis (FTA) of the risk of mechanical damage to the submarine cable to identify the root causes that directly contribute to the occurrence of physical disturbances in the 20 kV submarine cable system on Tunda Island. Based on the results of previous data processing, this risk is included in the main category with a *Risk Priority Number (RPN)* value of 231.56, occupying the third position after connection failures and delays in repairs or logistics. This position suggests that although the probability level is relatively lower than the previous two risks, the impact caused by mechanical damage on the continuity of the electrical system is significant as it can lead to the complete disconnection of undersea transmission lines.

Figure 4.36 shows that mechanical damage to submarine cables can be caused by two large groups of causes, namely human damage and natural damage. Human damage includes the activity of stranded vessel anchors, uncontrolled fishing activities around the cable line, as well as technical specification errors at the design or installation stage. Meanwhile, natural damage is caused by the movement of the seabed, marine abrasion that occurs due to currents and sediments, and bites of marine life that can damage the protective layer of cables. These two groups of causes form a deductive structure that contributes to the likelihood of mechanical failure.

Based on the results of this logic mapping, several *Minimum Cut Sets* (MCS) were obtained which are the most critical causes, including the anchoring of the ship on the cable line, fishing activities using heavy equipment around the cable protection area, specification errors, bites or activities from marine life, abrasion due to ocean currents and sediments, and seafloor movements that cause excessive pressure on the cable structure. These six MCS are direct causes that cannot be simplified further and have a significant contribution to the probability of system failure.

The results of the application of the Fault Tree Analysis (FTA) method to the three *main top events* with the highest Risk Priority Number (RPN) values, obtained the mapping of the critical root cause or Minimal Cut Set (MCS) which is the dominant source of risk in the 20 kV submarine cable electricity system on Tunda Island. The table above shows that each failure mode has different causes according to the characteristics of the process and its environment.

Joint failure (R4) is categorized as a process and physical failure because it is mainly caused by technical and operational factors such as non-following jointing procedures, poor material quality, and mechanical stress and corrosion of the joints due to unfavorable environmental conditions. Meanwhile, repair delays (R10) are included in the category of logistics, mobilization, and administrative failures because they are affected by limited resources and systemic obstacles, such as unavailable spare parts stock, long import process lengths, limited repair ships, bad weather, and complex coordination and licensing processes. The mechanical damage of the submarine cable (R1) is classified as an external failure caused by a combination of human and natural factors. Uncontrolled ship anchoring and fishing activities are the dominant causes, followed by natural influences such as seafloor movement, ocean current abrasion, and bites of marine life that can damage the protective layer of the cable. Design specification errors also worsen the physical resistance of the cable to environmental stress.

The results of this FTA summary show that the three failure modes have complementary root causes: R4 emphasizes the weaknesses of technical processes, R10 points to systemic problems in the logistical and administrative aspects, while R1 highlights external threats from human activities and natural conditions. This mapping serves as a strong analytical basis for the integration stage with the Analytical Hierarchy Process (AHP) method, where criteria and alternative mitigation strategies are compiled based on *the most critical Minimum Cut Set* to ensure the effectiveness of risk control at each stage of the project.

Mitigation Strategies to Minimize Risk in the Construction and Operation Process of Submarine Cable Networks

Based on the results of the Fault Tree Analysis (FTA) of the three main failure modes, a number of critical root causes (*Minimal Cut Set*) were obtained that directly contributed to the technical risks of the construction of a 20 kV submarine cable network on Tunda Island. To formulate priorities for handling these risks, a follow-up analysis was carried out using the Analytical Hierarchy Process (AHP) method. This method is used to determine the most effective mitigation strategy by considering various technical, operational, and economic criteria in a measurable and systematic manner.

The AHP criteria were determined based on the results of the integration between Fault Tree Analysis (FTA) analysis, focus group discussions (FGDs), and interviews with experts. This approach is done to ensure that each assessment criteria reflects the technical conditions in the field while also taking into account the practical views of experienced parties. The results of the FTA were used to identify the root causes of the most critical risks, while the inputs from the FGD and interviews provided empirical validation of the relevance and priority of each criterion. Thus, the five criteria used in the AHP analysis are considered to represent technical, administrative, and strategic aspects that affect the effectiveness of risk mitigation of the 20 kV submarine cable project on Tunda Island.

After determining the criteria, the next step is to determine some alternatives obtained from the results of the expert interviews. The interview aimed to explore the most realistic and effective forms of action in reducing the technical risks that have been identified through the FTA. Based on the results of the interview, three main alternatives were agreed, namely the installation *of Concrete Mattress* as physical protection of the cable, the establishment of a no-anchor zone through the coordination of maritime agencies, and the socialization and education of coastal communities to reduce risks due to human activities around the cable line. These three alternatives are then used in the AHP structure to analyze their priority levels against each mitigation criterion. The following figure is the hierarchical structure of AHP based on objectives, criteria, and alternatives.

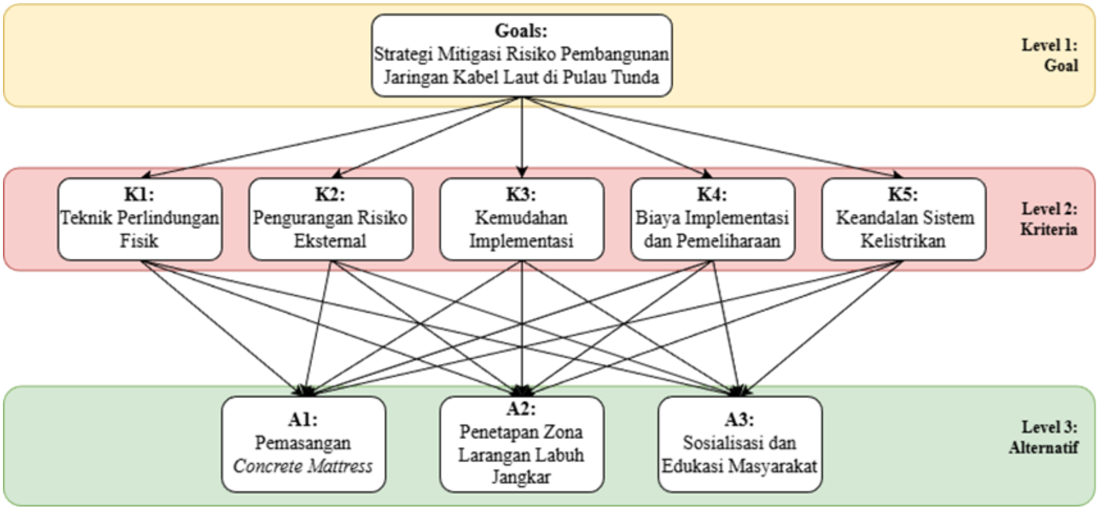

Figure 5. AHP Hierarchy Structure Mitigation Strategy

The hierarchical structure of AHP is arranged in three levels, as shown in Figure 5 The first level (Level 1) is the main objective of the research, namely the determination of risk mitigation strategies for the construction of the submarine cable network on Tunda Island. The second level (Level 2) contains five main criteria that are the basis for the assessment, namely physical protection techniques (K1), external risk reduction (K2), ease of implementation (K3), implementation and maintenance costs (K4), and electrical system reliability (K5). These five criteria were compiled based on the results of integration with the findings of the FTA which identified the relationship between the root cause of the risk and the aspects that need to be controlled. Furthermore, the third level (Level 3) contains three alternative mitigation strategies proposed, namely the installation *of Concrete Mattress* (A1), the determination of the anchorage prohibition zone (A2), and community socialization and education (A3). These three alternatives were chosen because they represent a relevant technical, administrative, and social approach to reduce the probability of damage or delay in repairing submarine cables. The relationship between each criterion and the alternative is illustrated through a network of linkages that shows that each alternative has a different contribution to the achievement of the project's key risk mitigation objectives.

The *Analytical Hierarchy Process* (AHP) analysis was used to determine the level of relative importance between criteria in the risk mitigation strategy for the construction of a 20 kV submarine cable network on Tunda Island. The assessment was carried out by ten internal experts consisting of representatives from PLN UID Banten, a project planning team, and marine experts with experience in the fields of underwater construction, risk management, and maintenance of electrical infrastructure. Each criterion in the hierarchical structure was compared in pairs using the Saaty scale (1–9), then the results of the assessment from all respondents were combined using *the Aggregate Individual Judgments* (AIJ) method based on geometric averages to obtain a consistent, objective, and measurable priority weight.

Table 3. Alternative Global Weighting Results

Peringkat	Alternatif	Global Weight
1	Determination of Anchorage Prohibition Zone (A2)	0.3474
2	Socialization and Education of Coastal Communities (A3)	0.3388
3	Pemasangan *Concrete Mattress* (A1)	0.3138

Source: Processed research data using the Analytical Hierarchy Process (AHP) method derived from expert judgments and Focus Group Discussion (FGD) results

The overall synthesis results of the *Analytical Hierarchy Process* (AHP) method resulted in a global priority that shows the order of effectiveness of the risk mitigation alternatives as a whole. Based on the calculation results, the determination of the Anchor Anchor Prohibition Zone (A2) is an alternative with the highest global weight of 0.3474, followed by Coastal Community Socialization and Education (A3) with a weight of 0.3388, and the Installation *of Concrete Mattress* (A1) with a weight of 0.3138. The relatively small difference in weight between the three alternatives shows that all of these strategies have an important role in supporting the success of technical risk mitigation of the construction of the submarine cable network on Tunda Island, but the level of priority differs depending on the priority dimension of effectiveness.

The determination of the Anchor Anchorage Prohibition Zone (A2) emerged as an alternative with the highest priority level because it has consistent advantages in the External Risk Reduction Criteria (K2), which is one of the most influential criteria in maintaining the sustainability of submarine cable operations. This strategy is considered the most effective in suppressing potential external disturbances that are the main cause of cable damage, such as collisions or tugs of ship anchors. Through zoning policies, risks can be controlled preventively before they have a direct impact on the electricity system.

Coastal Community Socialization and Education (A3) ranks second with a global weight that is only slightly lower than A2. This shows that the role of local communities in supporting the effectiveness of mitigation has almost the same influence as regulatory policies. A3 is considered superior in the aspects of Ease of Implementation (K3) and Implementation and Maintenance Costs (K4), because it can be implemented with minimal resources but provides a wide social impact. This strategy strengthens the participatory dimension in risk mitigation by increasing public awareness of the importance of maintaining underwater electricity infrastructure. Community involvement in maintaining the no-anchor area is a key factor in ensuring the sustainability of the zoning policy that has been implemented.

The *installation of Concrete Mattress* (A1) is in third place with a global weight of 0.3138. Despite its position below the other two alternatives, this strategy still has a significant contribution especially in guaranteeing the reliability of the electrical system (K5). The physical protection provided *by Concrete Mattress* serves as the last layer of defense against mechanical faults that can result in structural failure. However, its limitations lie in its high cost and complex technical resource requirements, so its implementation is more precisely focused on the cable line segment with the highest level of risk.

Considering the overall results, it can be concluded that the most effective and adaptive mitigation strategy for the submarine cable construction project on Tunda Island is the implementation of the Anchor Anchorage Prohibition Zone (A2) as a top priority, supported by Coastal Community Socialization and Education (A3) as a participation-based support strategy, as well as the Installation *of Concrete Mattress* (A1) as additional technical protection in high-risk areas. This combinatorial approach reflects a multi-layered mitigation system that synergistically integrates regulative, social, and technical aspects to improve the reliability and sustainability of Tunda's underwater electricity system.

The relatively slight difference in global weights is not a weakness of the method, but rather reflects the homogeneity of expert judgment and the equality of importance of all criteria for the success of submarine cable technical risk mitigation. This is consistent with the characteristics of complex underwater electrical systems, where every aspect affects each other.

CONCLUSION

The research successfully identified the four most dominant modes of technical failure using FMEA and FTA. The highest level of risk failure is the damage to the cable connection (installation) with an RPN of 345.31 and a probability of 32.56%. Failures with the second and third risk levels are operational failures related to delays, repairs, and mechanical damage to submarine cables. The findings confirm that risk mitigation in the installation, mechanical, and operational aspects must be a top priority. The FTA analysis successfully identified the three dominant root causes that determine the success rate of the project, which derives from the highest risk of FMEA: connection failure (R4), repair delay (R10), and mechanical breakdown (R1). The first factor is a technical failure, with the wiring being the most critical point. The second factor is logistical and administrative failures, which significantly hamper the speed of repair response. The third factor is external interference from human and natural activities that weakens the physical resistance of the cable. Thus, these findings meet the second objective of the study by affirming that the success of the project depends on three main pillars: the accuracy of technical procedures, the readiness of the supporting systems (logistics and administration), and the control of external environmental risks. Based on these findings, the integration of AHP's analysis determined that the most effective mitigation strategy was a synergistic combinative approach. This strategy integrates the determination of the Anchor Anchorage Prohibition Zone (A2) as the most impactful regulatory solution (weight 0.3474), supported by community socialization and education (A3) as an efficient preventive approach (weight 0.3388), and strengthened by the installation of physical protection such as *concrete mattress* (A1) as a technical solution to ensure the reliability of the system in high-risk areas (weight 0.3138). Thus, this study emphasizes that effective risk control cannot depend on a single solution, but must be through a combination of regulatory, social, and technical strategies that are implemented in a layered and sustainable manner. The combination of these three strategies ensures that risks from human, environmental, and technical factors can be controlled in layers and sustainably in accordance with the characteristics of the waters of Tunda Island. Overall, this study succeeded in developing a framework for assessing and managing technical risks that are systematic, measurable, and adaptive to the characteristics of the waters of Tunda Island. The integration of FMEA, FTA, and AHP methods allows for the objective determination of risk priorities and mitigation strategies based on technical, economic, and operational considerations. The results of this study are expected to be a reference for PLN UID Banten in the planning, implementation, and maintenance of submarine cable projects in order to achieve a reliable, efficient, and sustainable electricity system.

BIBLIOGRAPHY

Acaroglu, H., & Marquez, F. P. (2022). High voltage direct current systems through submarine cables for offshore wind farms: A life-cycle cost analysis with voltage source converters for bulk power transmission. *Energy*, *249*, 123713. https://doi.org/10.1016/j.energy.2022.123713

Aven, T. (2016). *Risk Assessment and Risk Management: Basic Concepts and Principles*. Springer.

Carlson, C. S. (2012). *Effective FMEAs: Achieving Safe, Reliable, and Economical Products and Processes Using Failure Mode and Effects Analysis*. John Wiley & Sons.

Ferreira, J., & Leite, P. (2012). Reliability and Risk Assessment in Submarine Cables. *Electric Power Systems Research*, 76–83.

Gordonnat, J., & Hunt, J. (2020). Subsea cable key challenges of an intercontinental power link: Case study of Australia–Singapore interconnector. *Energy Transitions*, *4*, 169–188. https://doi.org/10.1007/s41825-020-00030-z

Gulski, E., Jongen, R., de Heus, M., Rakowska, A., Siodla, K., & Gaal, H. (2021). Discussion of electrical and thermal aspects of offshore wind farms' power cables reliability. *Renewable and Sustainable Energy Reviews*, *151*, 111580. https://doi.org/10.1016/j.rser.2021.111580

Institute, P. M. (2013). *A Guide to the Project Management Body of Knowledge (PMBOK Guide)* (5th ed.). Project Management Institute.

Kerzner, H. (2017). *Project Management: A Systems Approach to Planning, Scheduling, and Controlling* (12th ed.). Wiley.

Li, H., Teixeira, A. P., & Guedes Soares, C. (2020). A two-stage failure mode and effect analysis of offshore wind turbines. *Renewable Energy*, *162*, 1438–1461. https://doi.org/10.1016/j.renene.2020.08.001

Mazzanti, G., Landini, M., & Kandia, E. (2021). Issues and challenges for HVDC extruded cable systems. *Energies*, *14*(15), 4504. https://doi.org/10.3390/en14154504

Okpokparoro, S., & Sriramula, S. (2023). Reliability analysis of floating wind turbine dynamic cables under realistic environmental loads. *Ocean Engineering*, *278*, 114594. https://doi.org/10.1016/j.oceaneng.2023.114594

Pisani, C., & Villacci, D. (2011). *A Novel AHP Framework for Decision Making*. Project Management Institute.

Purvins, A., Sereno, L., Ardelean, M., & Efthimiadis, T. (2018). Submarine power cable between Europe and North America: A techno-economic analysis. *Journal of Cleaner Production*, *186*, 131–145. https://doi.org/10.1016/j.jclepro.2018.03.095

Simmons, D. (2010). *Functional Safety in the Process Industry: A Handbook for the Practitioner*. IDC Technologies.

Taormina, B., Bald, J., Want, A., Thouzeau, G., Lejart, M., Desroy, N., & Carlier, A. (2018). A review of potential impacts of submarine power cables on the marine environment: Knowledge gaps, recommendations and future directions. *Renewable and Sustainable Energy Reviews*, *96*, 380–391. https://doi.org/10.1016/j.rser.2018.07.026

Thomson, P. R., Raby, A., & Hann, M. (2014). Operational Risk Management for Subsea Cable Projects. *Ocean Engineering*, 126–134.

Wang, Q., Guo, J., Wang, Z., Tahchi, E., Wang, X., & Zukerman, M. (2019). Cost-effective path planning for submarine cable systems. *IEEE Communications Magazine*, *57*(1), 60–66. https://doi.org/10.1109/MCOM.2018.1701232

Wang, W., Yan, X., Li, S., Zhang, L., Ouyang, J., & Ni, X. (2021). Failure of submarine cables used in high-voltage power transmission: Characteristics, mechanisms, key issues and prospects. *IET Generation, Transmission & Distribution*, *15*(9), 1387–1402. https://doi.org/10.1049/gtd2.12117

Yusuf, I., Soebagio, & Ashari, M. (2019). Risk Management and Maintenance Strategy for Subsea Cables in Indonesia. *Journal of Electrical Engineering*, 112–124.

Zhao, X., Li, Z., Zhang, Y., Guo, C., & Li, B. (2020). Technical and economic demands of HVDC submarine cable technology for global energy interconnection. *Global Energy Interconnection*, *3*(2), 120–131. https://doi.org/10.1016/j.gloei.2020.05.004