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Unavailability Calculation For North Sea Energy Island Using Fault Tree And Monte Carlo Simulation

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Abstract

The Danish government has approved a plan to develop an Energy Hub at an artificial island in the North Sea. The project is currently in the planning phase, and the final topology still needs to be selected. Calculating system unavailability, a crucial metric for comparing topological designs is vital for estimating and evaluating the overall system performance. This paper considers the use of Fault Tree Analysis for unavailability calculations. In traditional Fault Tree Analysis, uncertainties are typically presented deterministically, where single failure rates are assigned for the components. In the paper, we suggest expanding the treatment of uncertainties for more informed decision support. To achieve this, we integrate Fault Tree Analysis with Monte Carlo simulations and sensitivity analysis. Using the extended Fault Tree Analysis, risks associated with the Energy Hub Denmark's Energy Island can be effectively analysed and used to estimate and compare unavailability for alternative topologies. Using a case study, we show that the considered topology is likely unavailable for 218 min/year. The results indicate a need for a modified design with higher redundancy, which could bring unavailability time down to 18 min/year. This study demonstrates that unavailability calculation using Fault Tree Analysis has the potential to aid the topology decision-making when combined with techniques allowing for a broader uncertainty treatment.

Keywords: energy hub, fault tree analysis, Monte Carlo simulation, sensitivity analysis, unavailability

1. Introduction

The Danish government has approved a plan to develop an Energy Hub at an artificial Energy Island in the North Sea (referred to in this paper as the Energy Island), approximately 80 km off the coast of Denmark. It will be a hub, i.e., a connection point, for electricity production from surrounding offshore wind farms. The plan is to start operation by 2030, with an initial capacity of 3 GW, and to expand to 10 GW in the future(Agency, 2022). However, there are remaining activities that need to be done to clarify the topology (system design).

The Energy Island is set to become the largest source of electricity generation within Denmark's electricity grid. It has interconnections with other countries, making it important to design for high availability. This also gives unavailability a key role when evaluating and comparing the various topological designs under consideration for the planned Energy Island.

A way to analyse the unavailability is to use Fault Tree Analysis (FTA), an established method within reliability engineering. FTA is a deductive technique often applied during the design phase, which can be used to identify potential system failures and root causes through logical trees and use these to estimate the probability of occurrence (Cristea and Constantinescu, 2017; He et al., 2007). This traditional way of carrying out FTA is deterministic, giving a limited description of uncertainties. The focus of traditional FTA is on point values when calculating probabilities, which do not fully reflect the uncertainties and the range of probabilities that could affect these outcomes (He et al., 2007; Kabir, 2017; Roth et al., 2015).

To overcome such a limitation in traditional FTA, an extended method is suggested in this paper where stochastic analysis is opted for. A broader availability picture can be achieved by combining the FTA with Monte Carlo simulations and sensitivity analyses (Contini et al., 2009; Gascard and Simeu-Abazi, 2018; Rao et al., 2009). This allows for a broader probabilistic description in the calculation of system unavailability, where a range of underlying uncertainties can be reflected in component failure rate data through statistical distributions. This should improve the FTA method beyond the estimation of point values, as the range of possible outcomes can then be expressed. The benefit of the extended method is discussed in the paper through analysis of unavailability for a specific topology case. As such, the discussion adds value to the discourse on how to use FTA when assessing the performance of selected topologies at the Energy Island. This paper contributes to the discussion on how to improve treatment of uncertainties related to reliability data collection, exchange, and analysis in line with (ISO14224, 2016).

The objective of this paper is to study how to make use of FTA in the calculation of unavailability and how to express uncertainties in the calculations for complex systems, e.g., for the North Sea Energy Island. Based on the system unavailability calculation, modifications can be suggested to the topology considered. Added redundancy should be considered if supported by cost and availability. Through this analysis, we aim to support the decision-making process in selecting a suitable topology.

2. Description of Energy Island and its topology

The Energy Island is currently in the design stage, with the preferred electrical topology to be clarified. The selection of electrical topology is important as it influences the reliability, stability, robustness, and cost of the project. The topology comprises interconnected circuits and components, including hundreds of wind turbines, their electrical parts, safety devices, and transmission lines connecting the Energy Hub to the onshore grid. This network can be arranged in different ways. The ideal topology combines robust safety features, resistance to component failures, and cost-efficiency in materials.

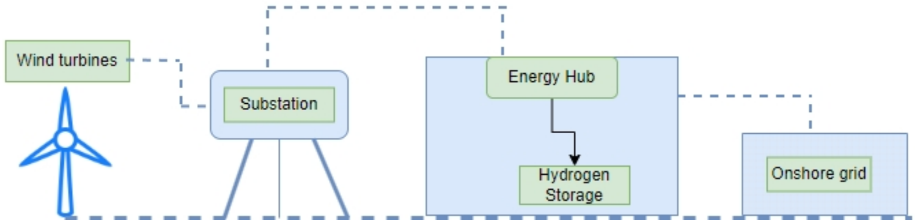

Fig. 1. Four main parts of the Energy Island.

Figure 1. shows the general topology for the Energy Island with four main parts, i.e., offshore wind farm, substation, Energy Hub, and onshore grid, all connected through the undersea cable. Figure 2. gives a more detailed presentation, showing the main components and subunits of the topology in focus, including:

- Busbar; A junction that gathers and distributes electric power between incoming and outgoing lines.
- Converter; Changes electricity from DC to AC or vice versa.
- Transformers; Adjust voltages to suit the receiving grid's requirements.
- Circuit Breaker (CB); Automatically shuts off electricity to prevent overload, fires, or damage.
- Cables; Carry electricity through conductor’s wires.
- Substation; Houses critical electrical equipment like transformers and circuit breakers for voltage transformation.

A case topology is constructed based on reviews carried out at the Technical University of Denmark, Energinet, and the International Conference on Clean Electrical Power (Das and Cutululis, 2017; Flytkjær, 2023; Lagier and Ladoux, 2015). In this, each wind turbine in the illustration in Figure 2 counts for 10, meaning there are, in total, 100 offshore wind turbines connected to the Energy Island. Each wind turbine string is connected to the busbars (5 strings on each) by circuit breakers. These turbines will collect the energy and then transmit it to substations where the voltage is adjusted before being sent to the Energy Hub. Power-to-X (PtX) technology will be placed in the Energy Hub to convert renewable energy into various storable gaseous forms, such as hydrogen energy storage. The Energy Hub also serves as a point of connection for distributing electrical energy to other nations and international territories through undersea cables. After the Energy Hub, the converted energy is transported to an onshore platform, where it undergoes further processing and distribution to meet national and international energy demands.

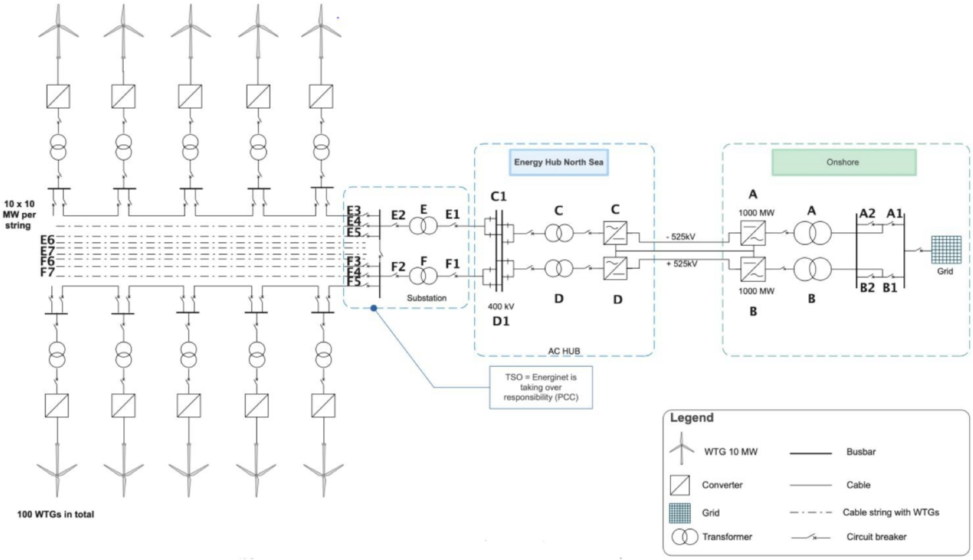

Fig. 2. Detailed topology illustration – Energy Island; based on (Das and Cutululis, 2017; Flytkjær, 2023; Lagier and Ladoux, 2015).

2.1. Reliability aspects

The nature of Energy Island introduces a range of potential failure modes. A failure mode refers to the manner in which failure occurs (ISO 14224:2016). These can be caused by, e.g., system breakdowns, software errors, human error, natural disasters, or cyber-attacks. Further, single failure events can result in ripple effects (cascading failures) throughout the system, which, in the worst case, can develop into a catastrophic failure. catastrophic failure is failures that prevent the system from fulfilling its purpose (Faber, 2002), where the total consequences depend on the extent and duration of the power outage. For the Energy Island case, we aim to identify how failures within the system can initiate a 'chain reaction' that spreads across the entire system and can lead to a catastrophic failure, i.e., complete power loss in this case.

In a complex system like Energy Island with hundreds of components, multiple failures can occur. Some can be quickly repaired, while others might require long repair times. Information about availability is relevant for assessing overall performance. As already indicated, FTA can be used to carry out such an assessment.

3. Traditional FTA for the Energy Island case

FTA is a deductive approach that can be used to analyse how a 'top event' can occur (e.g., system failure). With the selected 'top event' failure mode as a starting point, a path is drawn downward to identify potential root causes, which can further be used to develop strategies for mitigating risks. The FTA allows for the estimation of failure probabilities, including both individual failures and common cause failures. Starting with the top-level "undesired event" and breaking it down into its contributing factors (lower level), Boolean logic is used to analyse the event probabilities. This process involves breaking down lower-level failures into smaller parts and continuing this breakdown until no further lower levels are possible. For a more detailed FTA description, see (IEC61025, 2006; Vesely et al., 1981).

The traditional FTA was adopted for the selected topology case described in Section 2. 'No power delivered to the grid (onshore)' was selected as the 'top event.' To create the fault tree, we started by focusing on the connection point to the grid, asking: "If there is no power here, how could that happen?" By asking this question, a path could be drawn back through the topology ending in the wind turbines. This led to the final fault tree, which became extensive, and it was decided to limit the focus to items "being in a failed state," leaving some events undeveloped. This represents a full-scale FTA from the onshore grid to the offshore wind farm. However, given the fault tree size and the detailed nature of the full-scale FTA, only parts are detailed in this paper. These give an example of the FTA for the first part of the onshore system for illustrative purposes in Figure 3, while a complete FTA can be found in(Bhandari and Bendixen, 2023).

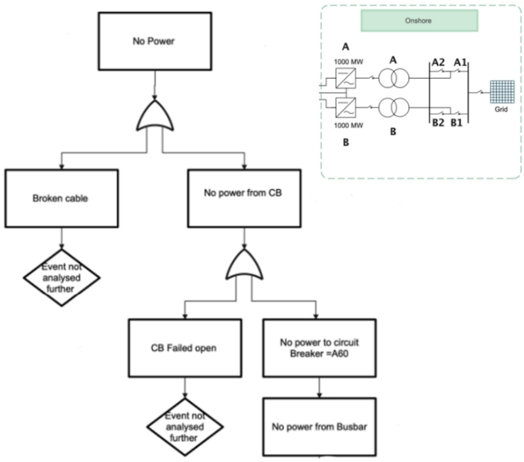

Fig. 3. FTA of the Onshore System for illustrative purposes (system shown in the top right box).

A steady-state condition unavailability formula is used for the FTA, where the expectation of time to failure (E*T*) is assumed to be much higher than the expected repair time (E***R)***, i.e., E*T* >> E*R*. For the calculation of the two metrics, failure and repair rates are assumed to be constant over time. The mean unavailability $\bar{A}_{AVG}$ (asymptotic unavailability) can then be calculated based on the failure rate (λ) and E*R*, where E***R*** can be expressed as a function of the repair rate (μ), as shown in Equation 2. The ER represents the mean downtime associated with the failure events. See also argumentation in (Schweitzer et al., 1997).

$$\bar{A}_{AVG} = \mathrm{E}R/(\mathrm{E}T + \mathrm{E}R) \quad (1)$$

$$\bar{A}_{AVG} \approx \lambda/\mu = \lambda\,\mathrm{E}R \quad , \text{where } \mu = 1/\mathrm{E}R \quad (2)$$

4. Extended FTA analysis

FTA can be used to estimate event probabilities, given that data on failure rates and repair times are available. However, in traditional FTA, probabilities are presented as exact point values. Accurately determining these is a challenging task when data is insufficient or there needs to be better knowledge about potential failures. This is particularly crucial during the design phases when modifications are still being done, making it challenging to obtain failure rate estimates. When quality data is not available, failure rates and probability values could be elicited from experts such as designers and field operators. However, even with expert input, there will still be significant uncertainties, especially when the system is in the planning phase. There is a call for developing a new methodology that can effectively account for the subjectivity and uncertain aspects of failure data within the frame represented by traditional FTA (Jaderi et al., 2013; Mahmood et al., 2013; Mansour et al., 2013).

A way to extend the method involves utilising simulations, which run a large number of simulations to see how random variation affects outcomes. In addition, integrate sensitivity analyses, which explore how different inputs being uncertain can impact the FTA results. Integrating these two techniques allows for a more informed description of the FTA and, in this case, the system unavailability. Further details on how to carry out this extended analysis are described below.

4.1. Reliability data

Several data sources were identified for the assessment of parameter values, giving a basis for a probabilistic expression of λ and ER for components used in the modelling. The statistical mean and standard deviation (SD) were computed for each. Experts were consulted if fewer than three sources were identified, i.e., some of the numbers presented in Table 1. also included expert judgments. However, the range of sources and inclusion of experts will not remove uncertainty. Especially for novel systems such as Energy Island, there will be a period before it is proven in use. Monte Carlo simulations were carried out to describe uncertainties in the FTA based on the distribution and parameter values assessed.

Table 1. Probabilistic data set for the Energy Island system (selection).

Location (FTA ref.)	Component	Distribution (mean values)	Data source and comments
Offshore Wind farm (A1)	Wind turbine	Lognormal; λ=0.26; E*R*=0.03; (*)	(Sheng, 2013); The source contains data on three different levels of failure rate and repair time.
Offshore Wind farm, Energy, and Onshore grid (A2/ 41/ 47)	Converter (tripped)	Uniform; λ(high)=0.005; λ (low)=0.06, E*R* (high)=0.15; E*R* (low)=0.008	(Fischer et al., 2019; Huang et al., 2019); Sources give different λ and E*R* values.
Offshore Wind fram (A4/ 8)	Circuit Breaker (fail open)	Lognormal; λ=0.0026; E*R*=0.035; (*)	(Lindquist et al., 2008; Sheng, 2013; Wang, 2012)
Energy Hub (A6)	Transformer (tripped)	Lognormal; λ=0.018; E*R*=0.03; (*)	(Huang et al., 2019; Ruddy et al., 2016; Solver et al., 2008)
Offshore wind farm Substation (A10/ 25/ 26)	Cable (broken)	Uniform; λ(high)=0.08; λ (low)=0.008; E*R* (high)=0.246 E*R* (low)=0.082	(Huang et al., 2019; Ruddy et al., 2016)
Substation, Energy Hub, and Onshore (A12/ 17/ 21/ 33/ 39/ 51)	Circuit Breaker - GIS	Uniform; λ(high)=0.024; λ(low)= 0.006, E*R* (high)= 0.3; E*R* (low)= 0.02	(Ruddy et al., 2016; Solver et al., 2008)
A15 (Substation)	Busbar (tripped)	Lognormal; λ= 0.004; E*R*=0.031; (*)	(Barbosa et al., 2019; Huang et al., 2019; Nack, 2005)
(Substation and Energy Hub A19/35)	Transformer (tripped)	Lognormal; λ=0.02; E*R*= 0.40; (*)	(Huang et al., 2019; Nack, 2005; Retterath, 2004) Amused distribution would follow the normal log distribution.
Energy Hub and Onshore grid (A29/ 59)	Busbar (tripped)	Lognormal; λ=0.007; E*R*= 0.01; (*)	(Barbosa et al., 2019) This paper has contained the different levels of λ and E*R* values then this (Retterath, 2004) (Nack, 2005)
Energy Hub (A45)	Cable (broken)	Lognormal; λ=0.025; E*R*=0.059; (*)	(Hatziargyriou et al., 2011; Huang et al., 2019)
Onshore grid (A53)	Transformer (tripped)	Uniform; λ(high)=0.08; λ(low)=0.01; E*R* (high)=0.005; E*R* (low)=0.0017	(Huang et al., 2019; Ruddy et al., 2016; Solver et al., 2008; Wang, 2012; Xie et al., 2022)
Onshore grid (A57/ 61)	GIS (fail open)	Uniform; λ(high)=0.006; λ(low)=0.001; E*R* (high)=0.005; E*R* (low)=0.0017	(Huang et al., 2019; Solver et al., 2008)
Onshore grid (A63)	Cable (broken)	Lognormal; λ=0.0063; E*R*= 0.06; (*)	(Hosseini, 2020; Huang et al., 2019; Wang, 2012)

** Indicates that SD is assumed as 20% of the calculated statistical mean values*

4.2. Monte Carlo simulations

To encompass uncertainties in collected data, we ran 10,000 Monte Carlo simulations, probabilistically changing the underlying inputs of the system (λ and E*R* for each component) based on the assigned distribution. This was done for all the 27 individual components (in total, 37 inputs for λ and E*R*). In each run, we changed all input values such that each input was generated from the assumed statistical distribution for that input, for example, in situations where we found various data sources with different values for the failure rate of wind turbines. In this case, we computed the mean and standard deviation. The failure rate of the wind turbine is assumed not to have one fixed value but rather a random value that follows a log-normal distribution curve with a mean of computed mean and variability of computed standard deviation. The wind turbine failure rate value would then change for each Monte Carlo iteration. As only two sources of information were available for the parameter specification, it was assumed that their failure rates and repair times would follow a uniform distribution between the minimum and maximum values obtained.

Monte Carlo simulation resulted in 10,000 unavailability results for the system. The distribution of these can be used to calculate the expected unavailability and relevant intervals. Monto Carlo simulation improves the uncertainty description and allows for a more informative analysis of the system's behaviour. This is considered better than relying on point estimates not showing the full range of possible outcomes.

Figure 4. shows the distribution for the Energy Island system unavailability produced by the Monte Carlo simulations for the topology we selected, where frequency is plotted against the number of simulations. On average, the system is estimated to be unavailable for approximately 218 min/year. At the lowest, the system will be unavailable for 205 min/year., and at the highest, 235 min/year.

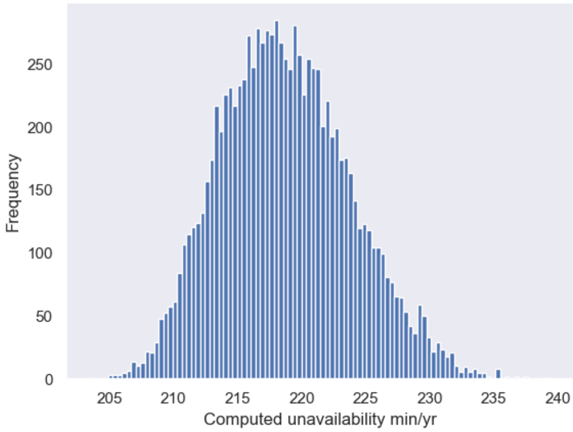

Fig. 4. Results - Computed unavailability (min/year) from Monte Carlo simulations.

4.3. Sensitivity analysis

After running the Monte Carlo simulation, it was identified that the unavailability rate for this topology case was significantly higher than the planning target 2032 that was used as a benchmark for the topology. This suggests a need for improvements to the topology. One way is to identify which components are susceptible to the results and, as such, are adding vulnerability to the system. An effective way to identify vulnerabilities is through sensitivity analysis, which entails changing the input values in the model and analysing how much this will change the results. For the sensitivity analysis, we changed each input value (unavailability value) in the model by 10 %, kept all other values constant, and computed the change contribution to the system's unavailability time.

This sensitivity analysis revealed the most vulnerable components in Energy Island are the onshore cable, along with the transformer, circuit breaker, and busbar. The onshore cable is the far most vulnerable, giving almost 20 min change in system unavailability when changed by 10 %. In fact, the probability of unavailability caused by a broken cable in the onshore station is 20 times higher than for failures in the other components. Hence, the cables are clearly an important component in the topology. This is especially true for offshore cables, which have a longer repair time compared with onshore cables. Besides, in the studied topology, there is a redundancy in offshore cables and not in onshore cables. Figure 5. shows that the cables represent the most vulnerable component in the topology.

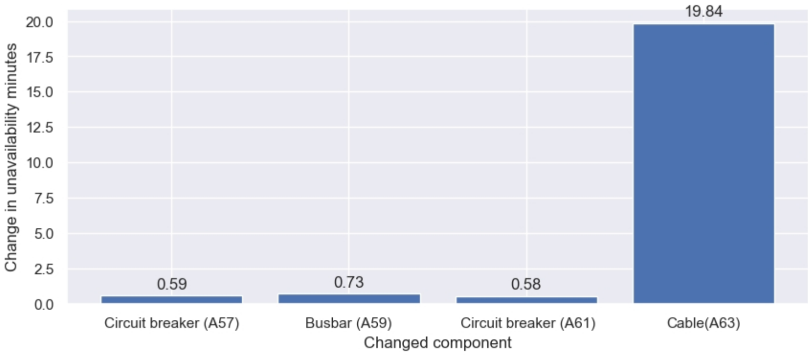

Fig. 5. Results - Sensitivity analysis (10 % change) for selected FTA parameters.

5. Discussion

The extended analysis gives an advantage to the understanding of the unavailability, where underlying uncertainties can be better expressed and investigated. Based on the findings in the FTA with extended analysis, identifying components having a major influence on the unavailability for the topology in focus, added redundancy can be considered for selected components. The effect can then be measured by performing an extended analysis, including Monte Carlo simulations, which capture this added redundancy. For example, a redundancy solution for the onshore cables could have the potential to significantly reduce the unavailability for Energy Island.

The unavailability results for a modified topology, where added redundancy is suggested, are illustrated in Figure 6. Redundancy was added only to the onshore cable, making the revised topology unavailability much less than the planning target value used as a benchmark. On average, the revised design is estimated to be unavailable for approximately 18 min/year, and at the lowest, the system will be unavailable for min/year., and at the highest, 35 min/year.

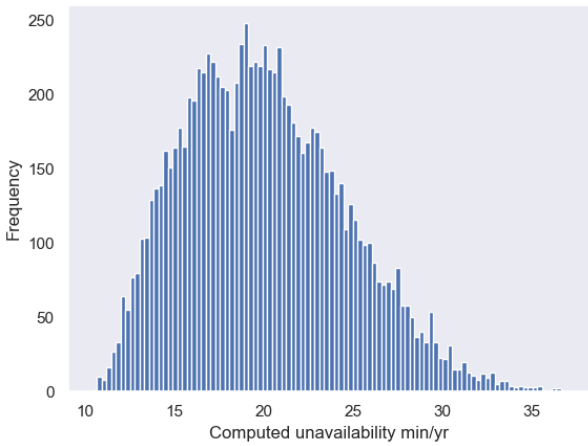

Fig. 6. Results - Computed unavailability (min/year) from Monto Carlo simulations for the modified design with redundancy in the onshore cable.

To put the results obtained from the extended FTA into perspective, the results were benchmarked against the planning target given in a report on energy transmission demands and requirements in Denmark (Energinet, 2023). The planning target is a recommendation given by Energinet to the decision-makers. The planning target for 2032 is 38 interruption min/year. This corresponds to the security of supply at 99,993% (SAIDI – System

Average Interruption Duration Index), which effectively equals about 38 min/year. Outage per annum for each consumer for the entire Danish network. The 38 min/year for each consumer can be assigned as follows: 31 min/year to the distribution network operators and 7 min/year to the transmission system operator Energinet (Energinet, 2023).

The system level unavailability calculation shows that the topology's predicted unavailability time is longer than the planning target. In other words, if the system fails, it will lead to power outages for a longer time. Prolonged outages can be a matter of concern as they may need to align with the planning target recommended by Energinet. Hence, there is an incentive to take steps to improve availability so that the target is met. The need is also supported by the findings from the sensitivity analysis and the lack of robustness in the original design. The FTA gives a traceable and transparent analysis depicting the influence of individual and also sets of component failures while making it relatively simple to study the effects of, e.g., adding redundancy for the onshore cables. This redundancy can be built into the model so that backup systems or additional cables onshore backup systems can take over seamlessly if they fail.

The next step would be to incorporate costs, giving another perspective on the effects; in this case, the estimated economic loss of a system is unavailable for 218 min/year. This could be linked to the savings made by implementing redundancy in the onshore cable. The savings could be significant, but such a decision should also consider the uncertainties associated with the actual cost of cables and Energinet's rate of return for investment decisions.

6. Concluding remarks

The use of FTA analysis for the topology case is considered to show a way to assess unavailability. However, the uncertainty described in the traditional way can be claimed to produce a picture that is too narrow. To improve this picture, it is suggested that probabilistic handling be allowed utilising Monte Carlo simulations. These simulations, as demonstrated for the case, can be used to address the uncertainty inherent in the reliability data, giving a broader uncertainty presentation. The use of sensitivity analysis allows for a further investigation of the framework, the model, and different parts of the system. It represents a more informative FTA for decision-making, such as identifying the optimal topology for Energy Island. The FTA combined with both Monte Carlo simulations and sensitivity analysis represents a technique for systematic integration of uncertainties into the assessment of reliability or unavailability. The results could, in this case, inform decision-makers about the strength of the topology considered and influence the selection of topology for complex projects like Energy Island.

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