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FOCUS ARTICLE

Reliability analysis of offshore grids—An overview of recent research

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For the future, a large-scale expansion of offshore wind energy is expected in Europe. To collect this wind energy and to enable electricity trading between countries, an offshore network will be implemented in the North Sea. Maintaining a high level of security of supply at affordable costs is one of the key objectives in the design and operation of power systems and therefore, the reliability of offshore grids is an important topic of discussion. Whereas onshore, the security of supply is assured by reliability criteria like *n*-1 redundancy, the same *n*-1 redundancy might not be an economical solution for offshore networks. For todays (small) offshore networks, *n*-1 redundancy is hardly economically justifiable, seen from a wind farm owner's point of view. The question then arises how the reliability of large-scale offshore networks should be evaluated and what measures can be taken to maintain a high security of supply onshore. This paper aims at discussing this topic by reviewing the results of recent research work. It is found that whereas for smaller offshore networks reliability evaluation is mainly an economic analysis seen from a wind farm owner's point of view, for large-scale offshore networks, it is necessary to consider the interaction of offshore–onshore networks in reliability analysis. It is proposed to analyze the reliability of combined offshore–onshore power systems in an integrated approach, such that various (offshore and onshore) measures can be considered to find the most economical solution.

This article is categorized under:
- Wind Power > Systems and Infrastructure
- Energy Infrastructure > Systems and Infrastructure
- Energy Systems Economics > Systems and Infrastructure

KEYWORDS
offshore grids, offshore networks, power system reliability, probabilistic reliability analysis, wind energy

1 | INTRODUCTION

For the future, a large-scale expansion of renewable energy is expected. In its targets for 2020, the European Union aims at 20% of renewable energy generation (European Commission on Climate Action, 2009). New energy sources such as wind, solar, and biomass will become major contributors of renewable electricity generation (European Commission on Climate Action, 2006). Large-scale centralized generation like offshore wind will be combined with small-scale local generation like solar photovoltaic (van der Meijden, 2012). For Western Europe, wind energy is probably the most promising renewable source for the near future. For example, Ecofys mentions a potential of 230 GW offshore wind capacity by 2045, of which 180 GW deployed in the North Sea (Ecofys, 2017), while European Wind Energy Association (EWEA) mentions an installed

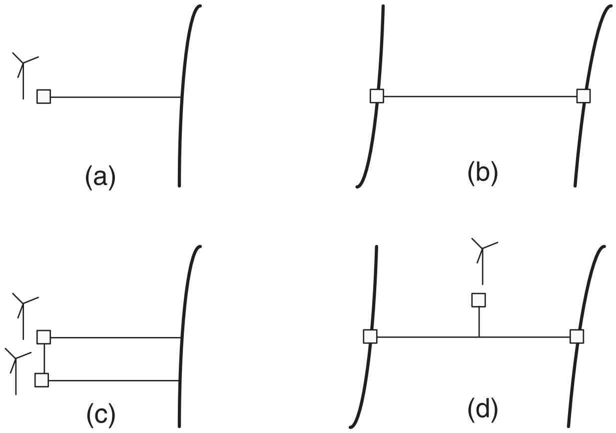

FIGURE 1 Connection of offshore wind farms and submarine interconnections

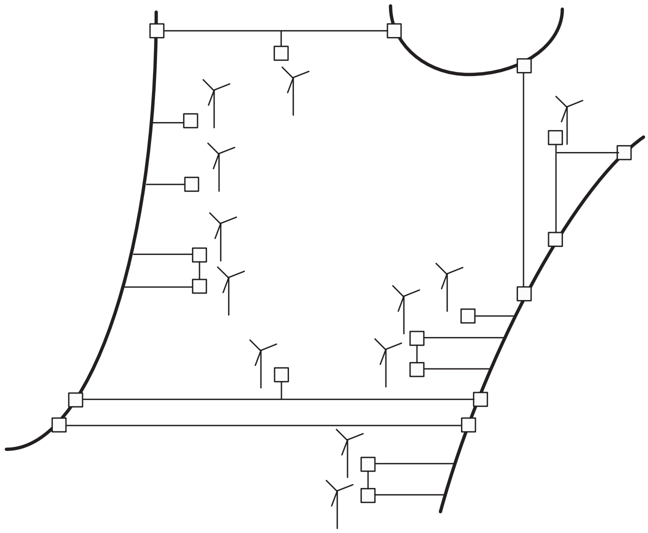

FIGURE 2 Possible development of offshore networks in the North Sea

capacity between 250 and 390 GW in its wind scenarios for 2030 (EWEA, 2015). To collect this amount of offshore wind energy, an offshore network will be created.

The development of offshore networks is roughly sketched in Figures 1 and 2. Traditionally, offshore wind farms were connected individually to the shore, as shown in topology a in Figure 1. Alternating current (AC) connection is preferred for wind farms located relatively near to the shore, whereas high-voltage direct current (HVDC) is preferred for wind farms located farther from the shore (typically from about 80 km). Submarine interconnections, as shown in topology b in Figure 1, can connect power systems of different countries. If the distance is short, for example in the connection of islands, AC technology can be used, while for longer distances, HVDC is used. Examples of submarine HVDC connections are NorNed and BritNed. When in the future wind farms located farther from the shore are connected, alternative configurations are preferred. For example, topology c in Figure 1 illustrates that it can be beneficial to interconnect the offshore substations of two wind farms that are located relatively near to each other. Furthermore, topology d in Figure 1 shows that a far-shore wind farm can be connected by a three-terminal HVDC network. Figure 2 shows a possible scenario for the development of offshore grids in the North Sea. It is expected that in the future, the different topologies as shown in Figure 1 will be combined to create one offshore network.

Regarding offshore network topologies, various research institutes have designed a variety of possible configurations (de Decker, Woyte, Schödwell, Völker, & Srikandam, 2009). This variety of possible configurations is illustrative for the search for the most optimal offshore topology. In addition, several publications describe optimization approaches to find the most optimal network topology (Ergun, van Hertem, & Belmans, 2012; Torbaghan, Gibescu, Rawn, & van der Meijden, 2015; Trötscher & Korpås, 2011). Although these optimization approaches consider different aspects (such as market aspects, network losses, restricted areas), reliability aspects (such as random component failures) are generally omitted from the studies. As offshore network components have a much longer repair time than onshore components, the unavailability of offshore components is larger than that for onshore components. This can have a significant impact on the reliability of the onshore power system and the choice for a certain offshore network configuration. An important topic of discussion and open research question is the level of redundancy within offshore networks. Full n-1 redundancy, as common practice in onshore transmission networks, might not be an economical solution as the additional costs of the infrastructure are larger than the extra revenue because of less lost wind energy. No redundancy might lead to large amounts of lost wind energy, while large wind capacity outages can have a substantial impact on the security of supply in the onshore power system.

Although the reliability of offshore networks has been described in some earlier publications, most publications only discuss offshore reliability conceptually or concentrate on the optimal configuration of wind turbines within an offshore wind farm. For example, the reliability of offshore wind farm topologies has been discussed in (Athamna, Zdrallek, Wiebe, & Koch, 2014; Dahmani, Bourguet, Machmoum, Guerin, & Rhein, 2014; Huang & Fu, 2010; Lumbreras & Ramos, 2013; Tuinema, Gibescu, & Kling, 2010; Liu & Islam, 2008; Zhao, Chen, & Blaabjerg, 2009). Reliability studies about the most optimal connection of multiple wind farms are less common. For example, the most optimal configuration for the connection of offshore wind farms was considered in (Banzo & Ramos, 2011; Bresesti, Kling, Hendriks, & Vailati, 2007; Tuinema et al., 2010). A third topic is the impact of offshore networks on the reliability of onshore power systems. While this impact might be small for limited amounts of offshore wind (Leita da Silva, Sales, da Fonseca Manso, & Billinton, 2010; Tuinema et al., 2010), this can be different for larger offshore wind capacities. As sudden capacity outages of offshore wind can endanger the electricity supply onshore, it is of interest to study how severe these capacity outages are, also in comparison to other possible capacity outage causes. For example, the variability of wind power and the accuracy of wind forecasts are important factors for large-scale offshore wind energy too (Rohrig & Lange, 2007). When the penetration level of wind energy increases, the need for operating reserve might increase as well (Zhang & Chowdhury, 2009). These are all factors which must be taken into account in reliability analysis of offshore networks.

This paper describes the progress of a research on offshore network reliability. The focus is on optimal configurations for near-shore networks and the impact of large-scale offshore wind on the reliability of onshore power systems. Questions that will be addressed are whether it is economical to implement some level of redundancy in offshore networks and whether it would be necessary to implement full *n*-1 redundancy in larger offshore networks. The results of these studies provide general insight into reliability aspects of offshore networks. Possible challenges for future reliability analysis of offshore networks will be discussed as well.

2 | NEAR-SHORE WIND NETWORK CONFIGURATIONS

While HVDC is preferred for wind farms located far from shore, near-shore wind can still effectively be connected by AC technology. Traditionally, offshore wind farms were connected individually to the shore. However, as the number of offshore wind farms increases, it might be better to collect the wind energy of several wind farms at an offshore substation connected to the shore. This also offers the opportunity to increase the reliability of the offshore network by installing redundancy. This section discusses the possibilities for improvement of the reliability of near-shore network configurations.

2.1 | Hub-at-sea principle

When multiple offshore wind farms are located relatively near to each other, it can be beneficial to collect the wind energy at an offshore substation. Such a hub-at-sea offers the opportunity to increase the reliability of the connection, but can also be economically attractive because of standardization of the used components. Consider the situation illustrated in Figure 3. On the left, four wind farms are connected individually, while on the right, the wind farms are connected to an offshore substation. As this section considers AC connection of the wind farms, it is assumed that the number of cables to the shore is still four as the cable capacities are matched to the installed capacity of the wind farms.

Figure 4 shows two typical graphs of the power production of an offshore wind farm. On the left, an excerpt of a time series is shown. On the right, the power duration curve (PDC) is shown, which is created by sorting the time series values from largest to smallest. It can be seen that the installed capacity of the wind farm is 250 MW. The time series shows that there are periods with maximum or zero production. The PDC shows that about 1,000 hr/year, there is maximum power production and 4,000 hr/year, there is minimally 100 MW wind power. The total area below the curves is the total generated wind energy in a year (E_1).

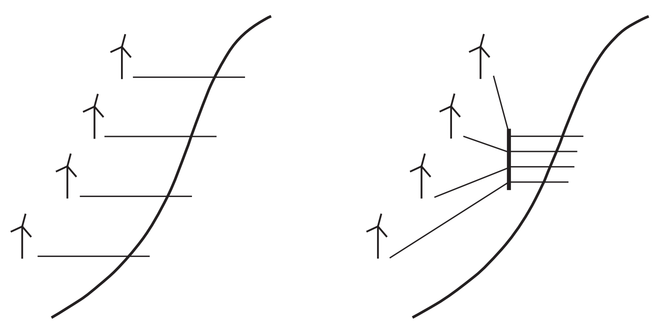

FIGURE 3 Two possible configurations of near-shore wind farms

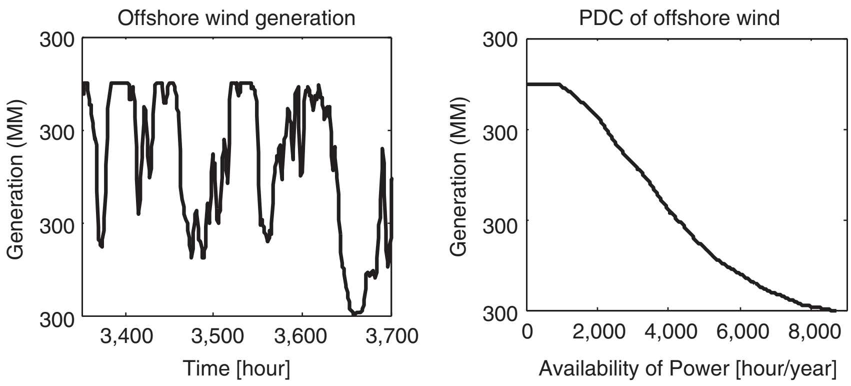

FIGURE 4 Characteristics of an offshore wind farm

Considering the situation shown in Figure 3, where four similar wind farms are connected to an offshore substation, the PDCs of the wind farms can be stacked as illustrated in Figure 5. The installed capacities of the wind farms and the cable capacities are all 250 MW. In this case, we assume that the distance from the wind farms to the offshore substation is much smaller than the distance between the offshore substation and the shore. Therefore, we can concentrate on the reliability of the four cables between the offshore substation and the shore. The cables between the wind farms and the substation as well as the components of the substation are assumed fully reliable.

If one of the four cables to the shore fails, the total transmission capacity reduces to 750 MW. In the situation where the four wind farms are connected individually, this means the loss of one complete wind farm. In the situation with the offshore substation, still a part of the wind energy can be transported to shore if allowed by the cable capacities. Figure 5 shows that, in this case, an amount of wind energy E_{1b} can be saved. An amount of wind energy E_{1a} is lost anyway, because of the capacity limit of the cables during periods with high wind generation. This illustrates that the amount of lost wind energy could be roughly halved, depending on the reliability of the components in the network. Although highly simplified, this example illustrates how a hub-at-sea can be used to reduce the amount of lost wind energy.

2.2 | Near-shore configurations

A practical case study of near-shore network configurations was discussed in the study by Getreuer, Tuinema, Rueda Torres, and van der Meijden (2016). This study considered the case study of the development of near-shore wind energy in the Netherlands.

2.2.1 | Caste study description

Figure 6 shows the configuration as considered. As can be seen, there are two offshore platforms, each connecting 700 MW offshore wind capacity at medium voltage (MV) level. On the platforms, the voltage is transformed up to 220 kV. Each platform is connected by two 350-MW cables to an onshore substation. There are several options to create redundancy. For example, it is possible to install branch couplers between the two connections of a platform. This can be realized on the offshore platforms (BC1 & BC2), or in the onshore substation (BC3). In addition, it is possible to interconnect both platforms by hub couplers. These can be between the offshore platforms (HC1 & HC2), or in the onshore substation (HC3). Please note that BC1 and HC1 are at MV level, while BC2, BC3, HC2, and HC3 are at EHV level.

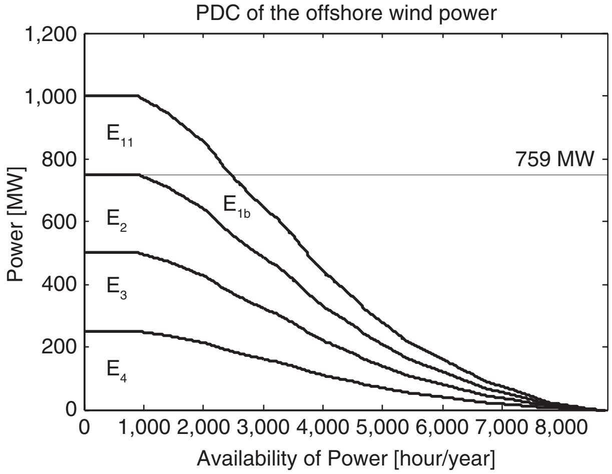

FIGURE 5 Hub-at-sea principle explained with power duration curves

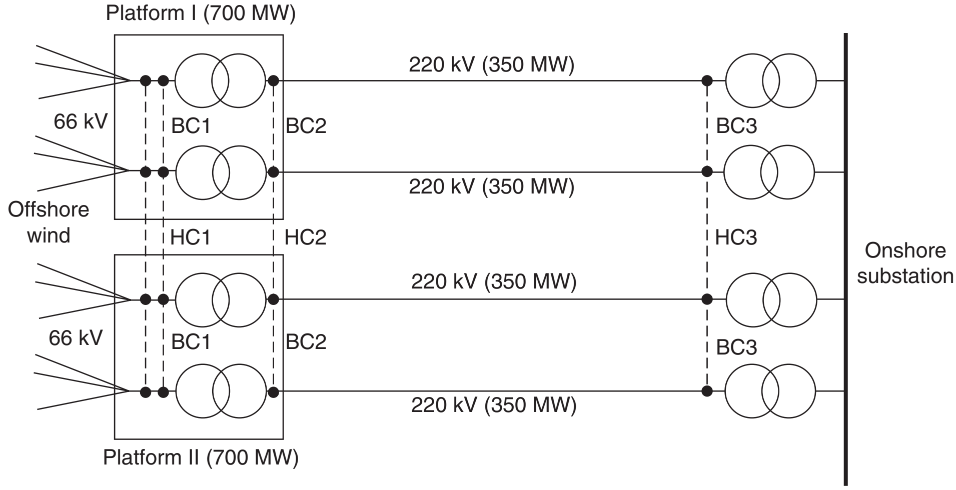

FIGURE 6 Overview of near-shore grid configurations with optional branch and hub couplers (Getreuer et al., 2016)

2.2.2 | Net present value approach

The possible configurations as mentioned were analyzed using a net present value (NPV) approach, as illustrated in Figure 7. This NPV model takes various input parameters into account:

- **Energy price parameters**: These are market energy prices, energy fees, and energy subsidies.
- **Hourly wind energy production**: A year scenario is used for the hourly wind production.
- **Component parameters**: These include failure rates and repair times of the components, power ratings, and thermal time constants of the components.
- **Technical configurations**: These are the possible configurations as mentioned before.
- **Economic parameters**: These are the interest rate and investment time, needed to calculate the NPV.

The NPV model led to a ranking of possible offshore configurations, based on their NPV.

2.2.3 | Results of the analysis

With the NPV model, the reliability of various possible configurations was analyzed and the lost/saved energy and NPV were determined per configuration. From all possible branch and hub coupler combinations, three options were the most realistic and promising: BC1 & HC1, BC2 & HC2, and BC3 & HC3. In Figure 8, it is shown that 14.9 GWh/year of wind energy is lost because of network failures if no branch and hub couplers are installed. It is also shown how much of this energy can be saved by installing branch and hub couplers. As can be seen, BC1 & HC1 have the largest effect. As these couplers are located the closest to the source, they create redundancy for the largest part of the offshore network.

Figure 9 shows the NPVs of the configurations. For example, it can be seen that 6.85 million euro of lost wind energy can be saved by installing branch couplers BC1, at an investment cost of 1.30 million euro. By also installing hub couplers HC1, an extra 3.01 million euro of lost wind energy is saved, at an investment cost of 1.70 million euro. This finally leads to a NPV

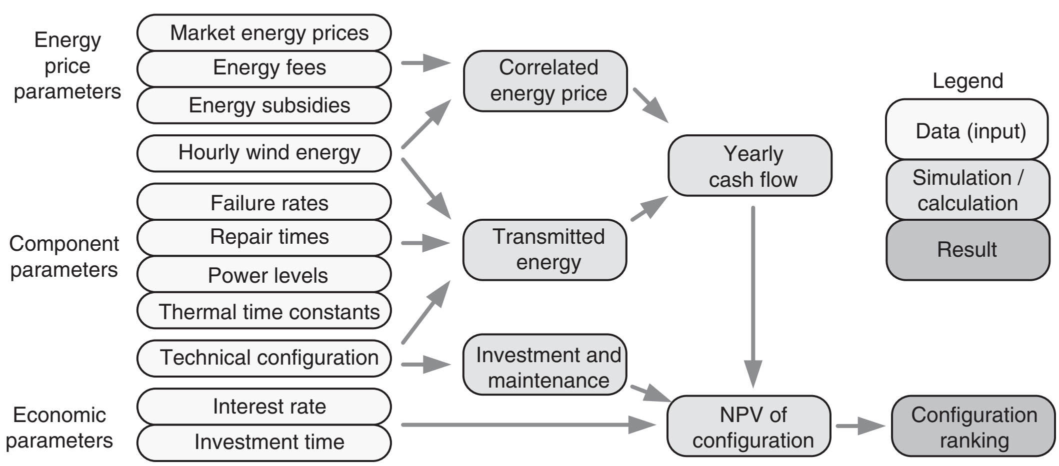

FIGURE 7 Overview of the net present value (NPV) method (Getreuer et al., 2016)

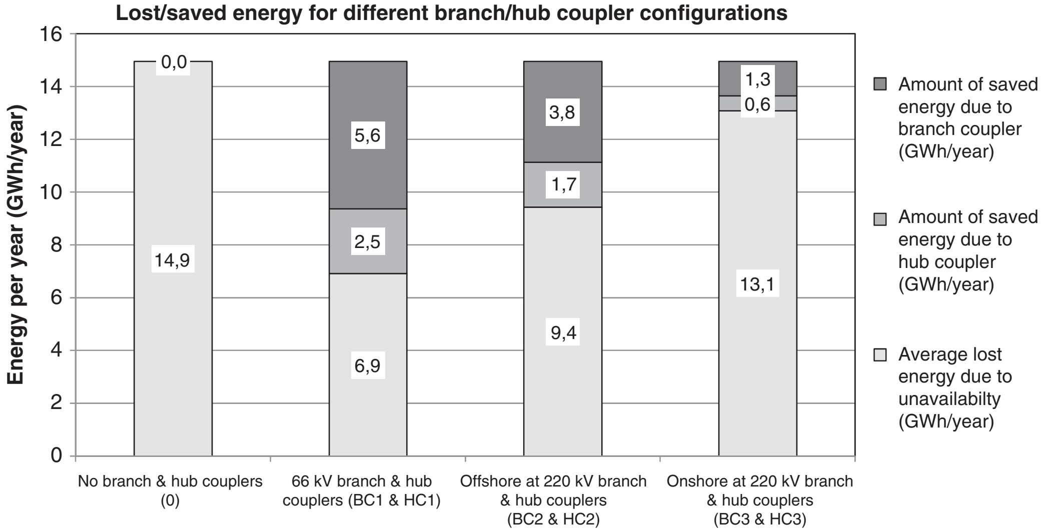

FIGURE 8 Lost and saved energy for different branch and hub coupler configurations (Getreuer et al., 2016)

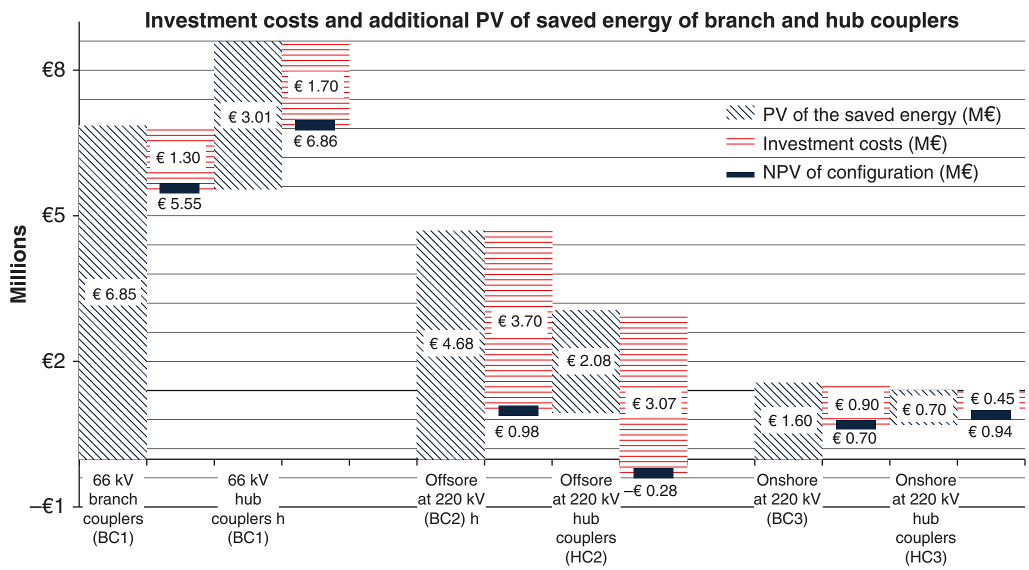

FIGURE 9 Net present value (NPV) of different configurations (per 350-MW connection; Getreuer et al., 2016)

of 6.86 million euro. From the figure, it can be concluded that this is the most economical solution, as the NPV of the other branch and hub couplers is smaller.

It must be mentioned that other combinations of branch and hub couplers were considered as well. However, these configurations were not realistic (e.g., installing a hub coupler without branch coupler at a certain location is not logical) or not economical (i.e., the NPV is smaller than the NPV of the options shown in Figure 9).

It was also studied what the most optimal capacity of the branch couplers is. The result is shown in Figure 10. As can be seen, the amount of wind energy that can be saved increases for branch couplers up to about 175 MW, which is half the capacity of one 220-kV cable. Installing couplers with a larger capacity does not lead to a larger amount of saved wind energy. This can be explained as follows. At 50% of the peak wind power, a 350-MW transformer or 220-kV cable has to process 175 MW from its own branch. In this case, the transformer could thus take up to 175 MW from another branch. At higher wind powers, the transformer can take less power from the other branch because it has to process more power from its own branch and at lower wind speeds, there is simply no need for a branch coupler capacity of more than 175 MW.

As the final NPV depends on many input parameters such as the distance to shore and the energy price, a study was performed to determine which combination of couplers BC1 and HC1 is the most economical in which case. The result is shown in Figure 11. As can be seen, for short distances to shore and low energy prices, it is the most economical to install no branch and hub couplers. For moderate energy prices and distances to shore, it is the most economical to only install BC1, and for high energy prices and long distances to shore, it is the most economical to install both BC1 and HC1.

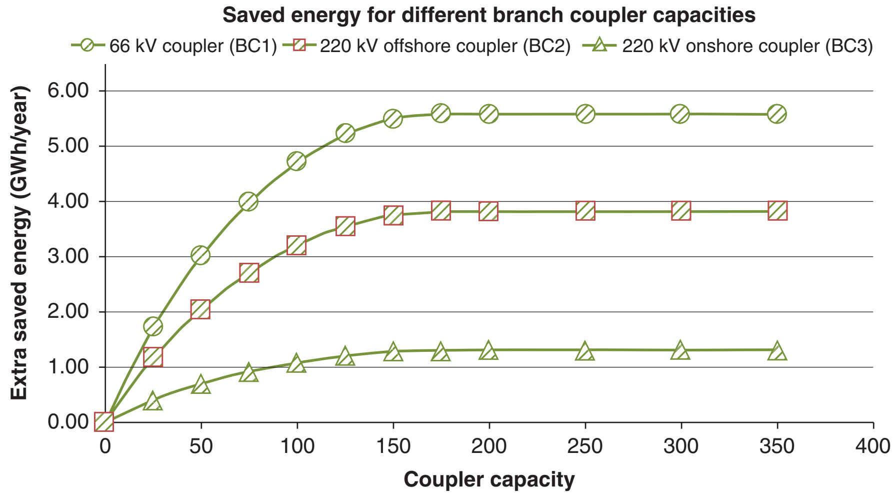

FIGURE 10 Amount of saved energy for different branch coupler capacities (Getreuer et al., 2016)

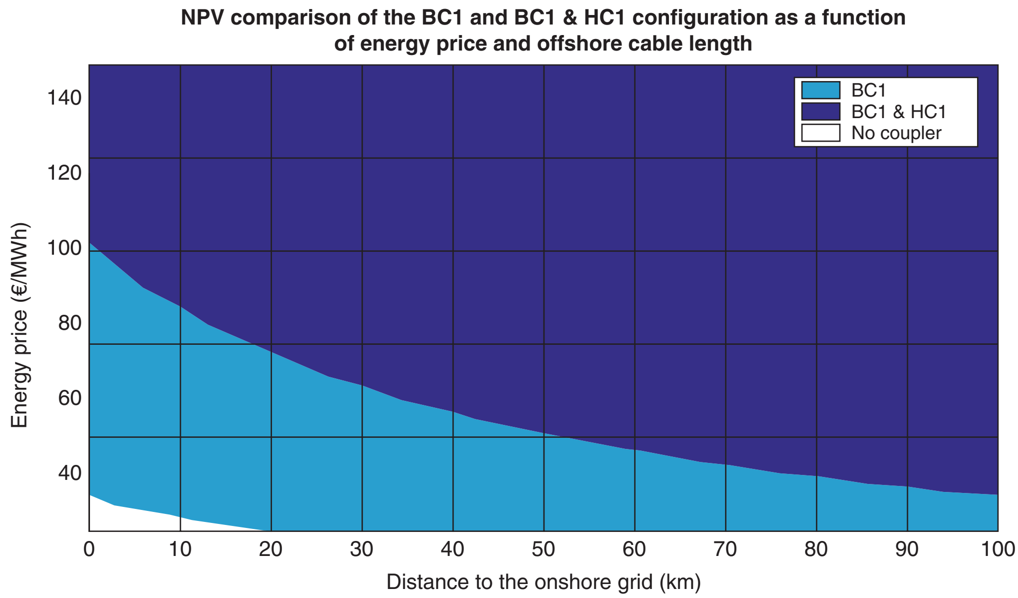

FIGURE 11 Net present value (NPV) comparison of the BC1 and BC1 & HC1 configuration as a function of energy price and offshore cable length (Getreuer et al., 2016)

This study shows that it can be economical to create some redundancy in offshore networks in specific situations. In the studied offshore network, both the availability of the offshore network and its NPV increased by installing some redundancy. However, creating more redundancy can become uneconomical and full *n*-1 redundancy is probably not economically feasible.

2.3 | Conclusions

In this section, the connection of near-shore wind farms was discussed. The concept of a hub-at-sea was introduced and it was explained how such an offshore substation can be used to improve the reliability of an offshore network. This was further illustrated by a practical case study of the connection of near-shore wind energy in the Netherlands.

In the studies described in this section, offshore network reliability is mainly seen from a wind farm owner's point of view. The analysis thereby becomes an economic study of the benefits of installing redundancy in an offshore network. The main conclusion is that full *n*-1 redundancy is probably not an economical solution, but some level of redundancy can be economical though. This conclusion is supported by the work described by Hennig, von Bonin, Rohrig, Stock, and Hofmann (2016). This work describes the (AC) interconnection of two offshore platforms connected by direct current (DC) to the shore and concludes that the interconnection of the two platforms can be economically attractive, also with smaller capacities of the interconnecting cable. In an older publication (Bresesti et al., 2007), the interconnection of two offshore platforms was also found to be an economical solution under certain conditions.

If the amount of offshore wind capacity increases significantly, the onshore power system will become more dependent on the reliability of the offshore network. This is especially the case if remote offshore wind farms are connected by HVDC connections with high capacity and when the offshore network interconnects power systems of several countries. Further reliability analysis of these international offshore networks and combined offshore–onshore power systems is needed.

3 | COMBINED OFFSHORE–ONSHORE POWER SYSTEMS

The studies described in the previous section showed that some level of offshore redundancy may be economical, seen from a producer point of view. Full n-1 redundancy like in the onshore transmission network is probably not economical. However, failures of the offshore network can have consequences for the reliability of the onshore power system. For example, the sudden loss of wind capacity could cause power imbalance in the system which can endanger the electricity supply. Therefore, the impact on the reliability of onshore power systems must be studied as well.

3.1 | Impact of offshore network topology on onshore reliability indices

In the work of Tuinema et al. (2010), the impact of various offshore network topologies on the reliability indices of the onshore network is analyzed. The approach followed is a generation adequacy analysis (Billinton & Allan, 1996; Li, 2005), in which the amount of available generation capacity is compared with the level of the system load. Four offshore topologies were considered in this work, as illustrated in Figure 12. In the first configuration, wind farms are connected individually by AC connections while in the second configuration, wind farms are connected in clusters of 1 GW by DC connections. In the third topology, two clusters of wind farms are formed and connected by DC connections to the shore, while the fourth configuration also includes an interconnection between the offshore substations. For the wind production, a year scenario with hourly values was used, while for the onshore conventional generators, the installed capacities were used.

In Table 1, the results of the analysis are shown. The expected energy not supplied (EENS) is the amount of offshore wind energy that cannot be transmitted to the shore because of offshore network failures. It can be seen that the individual AC connections give the smallest EENS, as DC connections require more critical system components like converter stations. If DC is preferred because of the high electrical losses in the connection of wind farms far from the shore, clustering the wind farms in offshore substations leads to a reduction in the EENS. Further analysis must be performed to decide whether this is an economical solution.

Table 1 also shows the values of some loss of load-related indicators: loss of load expectation (LOLE), which is an indication of how often the load cannot be supplied, and loss of energy expectation (LOEE), which is an indication of the energy that cannot be supplied to the load. Although there are slight differences between the values for the different topologies, the values are extremely small. This could lead to the conclusion that onshore loss of load indices are not affected by the offshore topology and offshore redundancy is only an economic decision seen from the wind farm owner's point of view, but reality is more complex. Loss of load indices are typically very small for generation adequacy analysis of power systems with much more installed generation capacity than the maximum system load. Basically, it is assumed that all generation capacity can be instantly available while (onshore) network failures are excluded from the analysis. It would therefore be more realistic to perform such a study considering only the spinning reserve generation that can be instantly available.

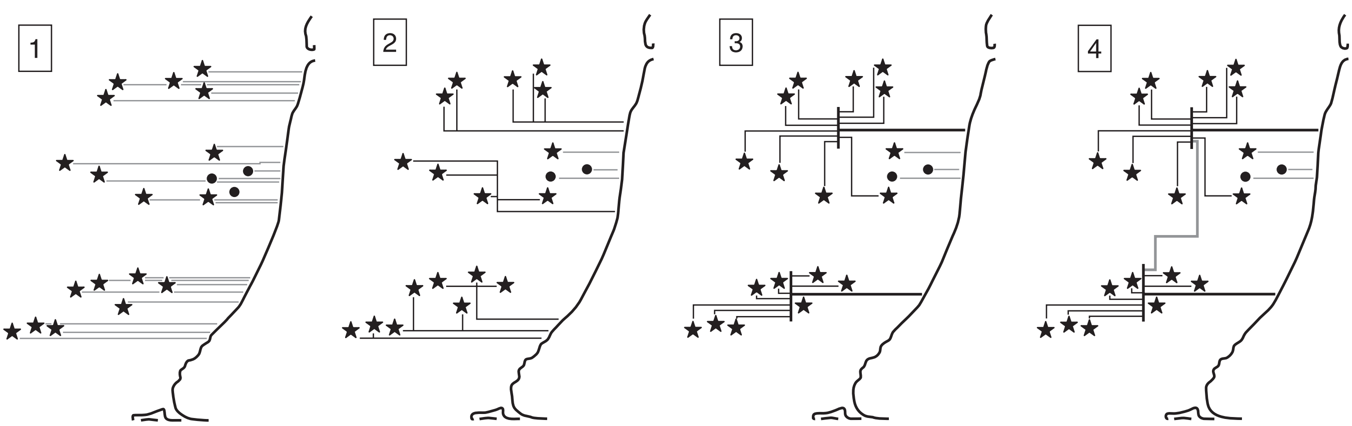

FIGURE 12 Offshore network configurations considered in the study by Tuinema et al. (2010)

TABLE 1 Reliability indicators for the offshore topologies shown in Figure 12

Topology	1	2	3	4
EENS (Expected energy not supplied) [GWh/year]	190	754	488	420
LOLE (Loss of load expectation) [hour/year]	4.94e-8	5.11e-8	5.02e-8	5.00e-8
LOEE (Loss of energy expectation) [MWh/year]	1.45e-5	1.50e-5	1.47e-5	1.47e-5

3.2 | Offshore redundancy versus onshore spinning reserve generation

In Tuinema, Rueda Torres, and van der Meijden (2015), an approach to determine and compare the severity of various causes of power imbalance in combined onshore–offshore power systems was presented. A power system with about the size of the Dutch system was considered. It was the objective to study whether *n*-1 redundancy should be required in offshore networks or whether the onshore power system is strong enough to cope with failures of the offshore network.

3.2.1 | General approach

In Figure 13, the general approach of the study is shown. In the study, the severity of various causes of power imbalance is determined. These causes are generator failures, load and wind forecast errors, failures of submarine interconnections, and failures of offshore networks for wind energy. The severity of the imbalance depends on the capacity of the components in the power system. For instance, if the capacity of the largest generator is 500 MW, it is possible to lose this 500 MW because of a generator failure. The power system must be able to withstand such power losses. Thus, the amount of spinning reserve generation is in the order of several GWs (the loss of a large generation center) in large interconnected power systems, such as the pan-European system. This is an example of a deterministic criterion, based on a worst case scenario. In reality, the failure probability of the system components and the actual power flow through the components are of importance as well, and were therefore taken into account in the study.

As can be seen in Figure 13, the different causes of power imbalance are first studied separately. Then, the results are compared. This study concentrates on the power imbalance from a security of supply point of view, in the sense of power imbalance for the system load. In practice, these power imbalances can be solved by remedial actions performed by the Transmission System Operator (TSO) to secure the electricity supply. Economic aspects, like whether it is better to invest in network redundancy or to invest in remedial actions and generation reserve, are not considered in this study.

3.2.2 | Case study

The numerical calculations in this study are based on a theoretical test power system with a comparable size as the Dutch power system, as illustrated in Figure 14. This theoretical test system has a peak load of 15 GW, about 17 GW installed generation capacity, 3 GW installed offshore wind capacity, and submarine interconnections with a total capacity of 3 GW. The offshore wind energy is collected by offshore substations. Each substation of 1 GW combines the power of four 250-MW wind farms and is connected by a DC cable to the shore. The reliability of the onshore transmission network is not included in this study.

3.2.3 | Comparison of causes of power imbalance

Figure 15 shows the comparison of the occurrence of power imbalance caused by various causes. It can be seen that forecast errors of the load and wind are the most frequent, which is logical as forecasts are never exactly right. Large load forecast errors (500–1,000 MW) are more likely than wind forecast errors of this size. However, considering that the peak load of the studied system is 15 GW while the installed wind capacity is 3 GW, it can be concluded that the predictability of wind is significantly worse than the predictability of the load.

Figure 15 also shows that imbalance due to generator failures is less common than the forecast errors. Large generator capacity outages of 500–700 MW are relatively frequent, about as frequent as wind forecast errors, but still less frequent than load forecast errors of this size. Enough reserve generation must be available to deal with these load/wind forecast errors and generator failures.

Failures of the submarine interconnection and the offshore wind energy network are significantly less frequent than the other failures. In the figure, these offshore network failures are still in the same range as the forecast errors. This suggests that if in a system of this size enough spinning reserve generation is available to cope with the wind and load variations, there is also enough spinning reserve generation available to cope with generator and offshore network failures. In this way, spinning reserve generation can be seen as a redundancy for the offshore network. Only the large capacity outages of submarine interconnections and offshore wind energy networks (−1,000 and 1,000 MW) are out of the range of the forecast errors. These large capacity outages are probably the most critical.

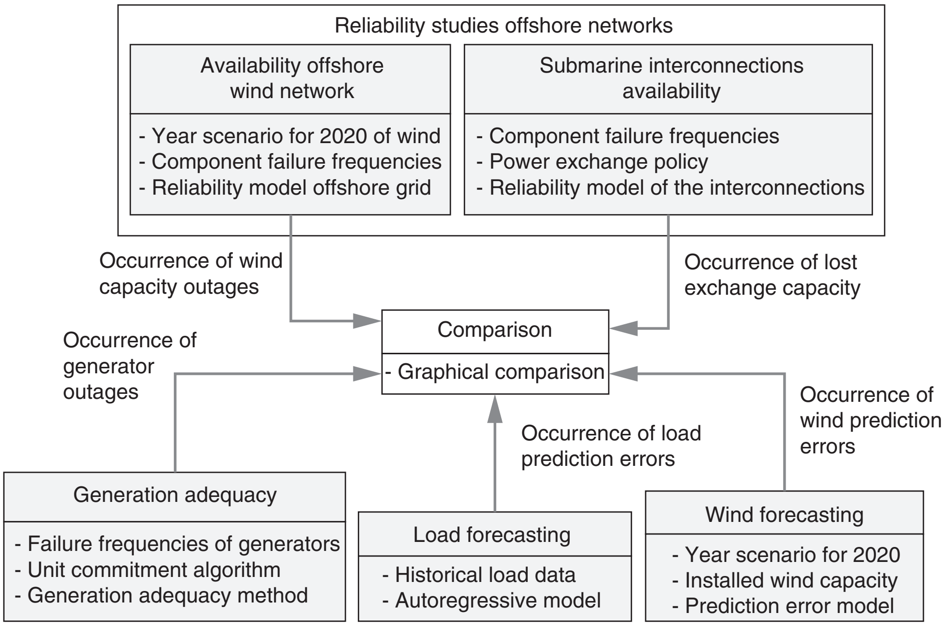

FIGURE 13 Schematic overview of the study approach (Tuinema et al., 2015)

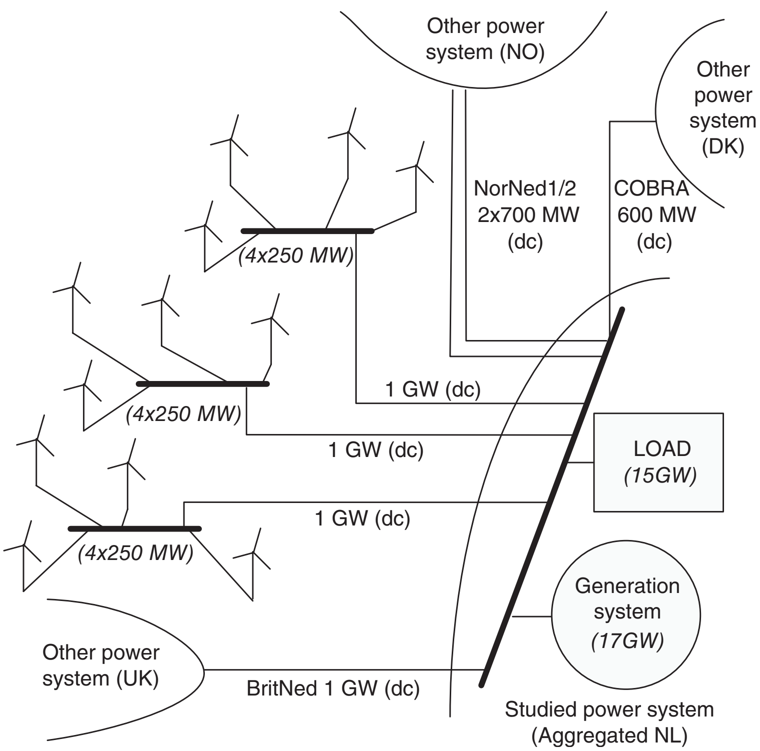

FIGURE 14 Schematic overview of the studied system (Tuinema et al., 2015)

3.3 | Conclusions

In this section, the impact of offshore networks on the reliability of onshore power systems was discussed. A first, rather simplified, analysis showed that onshore loss of load reliability indicators are hardly affected by the topology of the offshore network. In a second study, the severity of several causes of power imbalance was compared. In the theoretical test system, the severity of power imbalances caused by failures of the offshore network was not significantly more critical than load/wind forecast errors and generator outages. This suggests that if a power system is strong enough to cope with load/wind forecast errors and generator outages, it is also strong enough to cope with failures of the offshore network.

This conclusion, however, strongly depends on the capacity of the offshore network and the amount of spinning generation in the onshore power system. One can easily imagine that if the capacity of offshore wind increases significantly while the onshore system will contain less spinning conventional generation, the onshore power system will become more dependent on the reliability of the offshore grid and its international connections. The main conclusion here remains, however, that the

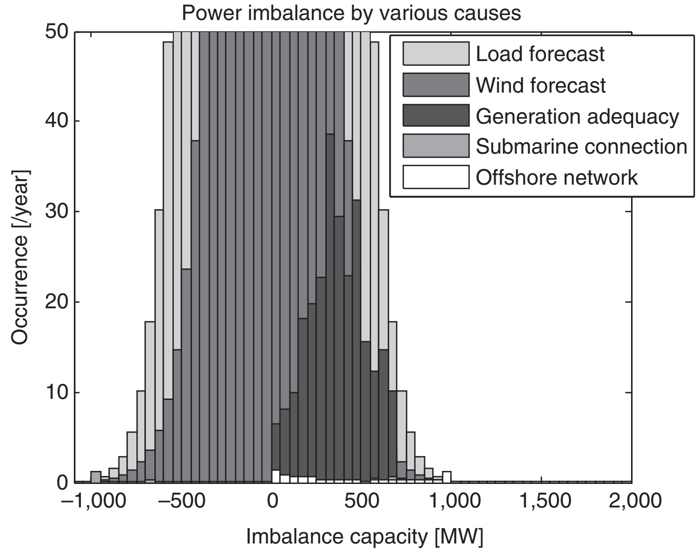

FIGURE 15 Overview of the causes of power imbalance (1-hr time frame, 3-GW installed wind capacity; Tuinema et al., 2015)

reliability of combined offshore–onshore power systems must be considered in a broader sense, that is, not only the offshore wind farm owner economics and not only the offshore network topology versus onshore loss of load indices. As mentioned in the work by Khuntia, Tuinema, Rueda Torres, & van der Meijden (2016), reliability analysis of power systems will move more toward an interacted approach in the future, where different processes (i.e., grid development, asset management, and system operation) are considered together to obtain the most optimal solution. As a practical example for offshore networks, reliability of offshore networks could be arranged onshore, for example, by spinning reserve, demand side response, or energy storage.

4 | CONCLUSIONS AND FUTURE WORK

In this paper, the reliability of offshore transmission networks was described. First, the development of offshore grids was roughly sketched. Then, two topics concerning offshore networks were discussed in detail, that is, the connection of near-shore wind farms and the reliability of combined onshore–offshore power systems. For offshore wind farms, it can be beneficial to collect the offshore wind energy in offshore substations (hubs-at-sea), which offers the possibility to increase the availability of connection. Although the expected amount of lost wind energy can be reduced by using a hub-at-sea, the economic improvement is limited. This is because the wind farms are within the same area and it is likely that all wind farms produce maximum capacity at the same time. In a study on possible network configurations for near-shore wind farms, the collection of wind energy by two platforms connected by AC cables was considered. It was shown that some redundancy in the network can be economical. It was also shown that the capacity of the optional (redundant) cables does not need to be larger than half the capacity of the AC cables that connect the platforms to the shore. Full offshore *n*-1 redundancy is not economical in this case.

When the total offshore wind capacity increases, it becomes more likely to lose a large amount of wind production at a time. In a study, various causes of power imbalance were compared. It was found that in a system of about the size of the Dutch power system, wind forecast errors are probably the most severe cause of power imbalance. Generator failures are also common, while failures of submarine interconnections and offshore wind energy networks are less frequent. The onshore system must be strong enough to deal with this. It seems that if there is enough spinning reserve to deal with forecast errors and generator failures, there is also enough spinning reserve to cope with failures of the offshore network. Onshore generation reserve can serve as redundancy for the offshore network in this way. Large capacity outages of offshore networks can, however, become more critical for larger-scale offshore networks. If the capacity of a submarine connection or the offshore wind network is 1 GW, it is possible to lose this 1 GW at a time. This can occur more frequently than forecast errors and generation failures, depending on the system size. It is of interest to study in the near future to what extent onshore generation reserve can serve as redundancy for the offshore network and under what conditions.

In general, the studies described in this paper showed that offshore network redundancy is probably not an economical solution seen from an offshore wind farm owner point of view. Reliability analysis of smaller offshore networks thereby concentrates on economic aspects for the wind farm owner. However, as the capacity of offshore wind energy and the offshore network increases, the impact on the reliability of the onshore power system becomes stronger. Measures might be needed to reduce the impact on the security of supply onshore. It is therefore proposed to analyze the reliability of combined offshore–

onshore networks in an integrated approach and to look at power system reliability in a broader sense. For example, onshore reserve generation, energy storage, and demand side response can act as redundancy for failures of the offshore network. In this way, various (offshore and onshore) measures are considered and compared to find the most economical solution to maintain a high level of security of supply.

As the capacity of offshore wind will increase in the future, onshore power systems will become more dependent on the reliability of offshore networks. It is therefore of importance to perform further research on integrated offshore–onshore power system reliability. Currently, the research on the reliability of offshore networks is limited and mainly concentrates on the optimal connection of a wind farm. Several research works consider the most optimal development of larger offshore networks, but probabilistic reliability aspects are generally not considered. Continued research on probabilistic reliability analysis of large offshore networks is therefore needed.

Another aspect is the accuracy of the reliability analysis and the question in how far it approaches reality. In power system reliability analysis, like in any other analysis, assumptions are made. In reliability analysis, these assumptions regard issues such as failure frequencies and repair times of components, fault behavior, and switching possibilities. While onshore, these are generally well defined and known, in offshore networks, these can cause more uncertainties. For example, for most onshore components, repair times are well-defined, while offshore, the repair times strongly depend on the (weather-dependent) accessibility of the fault location, thereby increasing the degree of uncertainty. Another topic is the switching possibility, which depends on the protection system and the location of DC circuit breakers in the network. An example of a study in which these topics are considered is MacIver, Bell, and Nedić (2016). A third topic is the dynamic behavior of the offshore network. Different kinds of faults can result in different effects. Reliability analysis can be made more realistic if this dynamic behavior is included in the analysis. In general, one can conclude that the accuracy of reliability analysis of offshore networks can be improved by making the analysis more realistic.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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FURTHER READING

Tuinema, B. W. (2017). *Reliability of transmission networks—Impact of EHV underground cables & interaction of offshore-onshore networks.* (PhD Dissertation). Delft University of Technology.

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