NSON II: Next Steps in Economical Connection and International Integration of Offshore Wind Energy in the North Seas

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***Abstract*—The last two decades have been witness of a transformation on how electrical energy is supplied. This paper presents an overview of the North Seas Offshore Network II project investigating the required advancements to enable an effective deployment of further 30 GW of offshore wind to be installed in the German North Sea exclusive economic zone according to current grid development plans by 2035.**

Besides voltage source converter-based high-voltage direct current- (HVDC-) systems and alternative technologies such as line-commutated converters and diode-rectifier units, the parallel connection and operation of existing and new offshore wind farms (OWF) seem to be an effective way to optimize investments and increase operational flexibility. The offshore generation, connection and transmission capacities enable the possibility of creating an interconnected HVDC-grid. HVDC-grid structures introduce new opportunities for electricity trade but raise questions on the stability of the interconnected AC-grid.

Realizing HVDC-interconnected European grids requires thorough planning of short- and medium-term tasks to keep long-term goals technically feasible while at the same time minimizing todays' and future investments. New and efficient options for OWF connection as well as control structures for point-t-point and parallel HVDC-connection systems have to be developed. In order to efficiently realize medium to long-term grid structures, methods and procedures for their optimized planning and operation and efficient methods to reduce and solve resulting large (non)linear optimization problems are to be realized. These fields of research are seen as next steps on the path to an economic connection and international integration of offshore wind energy in the German exclusive economic zone.

Keywords—Multi-Terminal, Offshore Grid, Optimized Grid Operation, Plant and System Control, Transmission Expansion Planning, Scenario/model reduction

I. INTRODUCTION

Ambitious climate protection strategies in medium and long-term scenarios towards climate neutrality [1] represent major challenges for future electrical energy supply networks. Because of the great potential in the North Seas, ambitious network expansion projects for the integration of offshore wind energy are promoted. Against this background, Fig. 1 shows the offshore wind farms currently operating, under construction and further planned wind farm zones in the German North Sea. The integration of offshore wind energy with a recently updated goal of 30 GW until 2030 is a vital component for achieving current climate protection goals in Germany (confirmation pending, see [2]). The European Commission estimates between 240 and 450 GW of offshore wind power by 2050. Due to the large distances to the mainland, expansion of transmission capacities is in most cases only economically feasible in high-voltage direct current- (HVDC-) transmission [3, 4]. From an ecological point of view, an increased transmission capacity is favorable to reduce the number of cables laid in order to protect the unique environment of the coastline. In addition, there are plans and studies in scientific research, e.g. see [5–8], but also concrete projects of different commercial consortia to establish more complex offshore grid structures [9]. One major driver behind integrated offshore grid development is the stronger integration of European market areas towards the European Union's internal energy market via offshore links. Another driver is the more economic evacuation of offshore wind generation to more than one onshore power system by increasing the utilization of transmission assets, see e.g. [4]. Against this background, the work at hand describes next steps in economical connection and international integration of offshore wind energy in the North Sea as tackled within the research project North Seas Offshore Network II (NSON II).

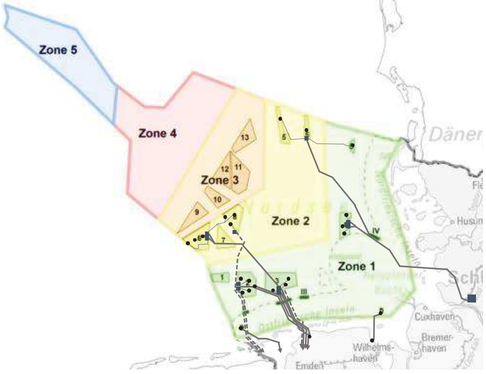

Fig. 1. Offshore wind farms and wind farm areas in the German North Sea (with input from TenneT adapted from [2]).

This research was supported by the German Federal Ministry of Economic Affairs and Energy within the framework of the project "North Seas Offshore Network II: Economical Connection and International Integration of Offshore Wind Energy in the North Sea" (German title: North Seas Offshore Network II: Kosteneffiziente Anbindung und internationale Integration von Offshore Windenergie in der Nordsee, FKZ: 03EI4009).

This paper was presented at the 19th Wind Integration Workshop and published in the workshop's proceedings.

The remainder is structured as follows: Chapter II gives an overview of the state of the art and recent developments in the connection of offshore wind farms (OWF) and their integration into the existing power systems. The following chapter III then addresses concrete goals and objectives of current research approaches as defined for the NSON II project. Herein, different key tasks for the further integration of offshore wind power and the interconnection through an offshore system are addressed and projected solutions are drafted. The concluding chapter IV finally sums up the described challenges and tasks and gives an outlook on further works towards an economic connection of further offshore wind farms on the one hand side and possible developments towards an integrated offshore system on the other.

II. STATE OF THE ART AND RECENT DEVELOPMENTS

Offshore wind farms in Germany are traditionally connected via AC-strings to an offshore HVDC-converter station in voltage source converter- (VSC-) technology. The station is connected to the mainland via a point-to-point (P2P) HVDC-connection [10]. In particular, the operation of purely converter-based offshore AC-grids represents a complex technical task. For the European (and global) energy transition to succeed, it is of vital interest that the ongoing and mostly national connection of offshore wind energy continues in a robust manner, while, at the same time, a cost reduction is achieved.

In order to reach the long-term goals of interconnected offshore grid structures, different approaches are possible. Some of them are addressed in [6], especially concerning different basic approaches for the further connection of different market areas using the North Sea area as planning flexibility. Besides the therein focused scenarios in the meantime further concepts such as an artificial island-scenario are becoming more concrete (e.g. in the form of the so-called North Sea Wind Power Hub (NSWPH)). Not only the connection of large offshore wind farm areas to the onshore grid, but also enabling the conversion of electrical energy to hydrogen or methane are subject of this approach [9]. Therefore, on the path to an interconnected offshore system three stages have to be realized, wherein the offshore systems and offshore wind energy connection realizations are dependent on different system configurations:

- Standard connection of offshore windfarms realized by P2P-connections using different technologies.
- Increased transmission capacity and/or reduction of costs.
- Long-term vision of international multi-terminal systems.

While different types of technologies can be used to build P2P-connections, it is important to take into account different control capabilities and investment costs. TABLE I summarizes the main characteristics of P2P-connections by means of different technologies. Besides basic characteristics, non-controllable technologies like line-commutated converters (LCC) and diode-rectifier units (DRU) will not be able to meet the requirements of the future multi-terminal HVDC-grids [11]. Additionally, VSC-systems are to become the core technology of future HVDC meshed networks. One main advantage of VSC- over LCC/DRU-systems are not requiring the wind turbines to operate in a grid forming mode, to have black start capability, to provide reactive power and to change the direction of the active power flow without changing the polarity of the DC-link voltage [12, 13]. Since existing grid codes are mainly based on VSC, adaptions are necessary to cover the connection of OWF connected by DRU. Moreover, potential additional costs for enhanced OWF control need to be considered. Multi-terminal-HVDC-grids based on highly controllable technologies like VSC additionally are able to support the stable operation of interconnected AC-grids [14].

TABLE I. CHARACTERISTICS OF P2P-CONNECTIONS.

Criterion	**P2P-connection technology**			
	VSC monopole	***VSC bipole***	***LCC***	***DRU***
Investment	high	moderate	moderate	low
Losses	moderate	moderate	low	low
Black start	yes	yes	no	no
Reactive power control	yes	yes	no	no
Voltage/frequency control	yes	yes	no	no
Size	moderate	moderate	high	low
Multi-Terminal operation	yes	yes	no	no

TABLE II. CHARACTERISTICS OF PARALLEL SYSTEM-CONNECTIONS.

Criterion	**Paralleled system technology**			
	VSC-VSC	***VSC-LCC***	***VSC-DRU***	***HVAC-DRU***
Investment	high	moderate	moderate	low
Losses	high	moderate	moderate	low
Black start	yes	yes	yes	no
Reactive power control	yes	yes	yes	no
Voltage/frequency control	yes	yes	yes	yes
Size	moderate	high	low	low
Multi-Terminal operation	yes	moderate	moderate	moderate

Offshore wind farms can be connected in a parallel configuration with the aim to increase the reliability of the systems, and/or to reduce the losses of both, the OWF transmission system and the onshore AC grid [15]. The investment, as well as operation and maintenance costs associated with the offshore platform can also be positively affected [16]. Nevertheless, the extent to which these objectives can be achieved highly depend on the converter technology of those P2P-systems to be paralleled. TABLE II presents a comparison of parallel configurations based on different converter technologies. Due to the non-controllability of LCC and DRU, it is required that at least one of the P2P-links is equipped with either an offshore VSC- or an HVAC-connection to control voltage and frequency of the offshore AC-grid [16]. In these cases, active power control in a parallel operation has to be realized by the offshore VSC or has to be conducted by the wind turbines' converters [17].

The multi-terminal operation of HVDC-links will bring together new challenges in the interaction of and differences of HVAC- and HVDC-systems, exemplarily the fact that the low impedance of HVDC grids makes the penetration of faults to be very fast [12]. Thus, the protection, fault currents and the coordination of such a HVDC-topologies still has to be researched. A large variety of topologies for multi-terminal HVDC-grids can be found in the literature [12, 18, 19], while e.g. [20] proposes a simplified classification into three groups: radial, meshed or ring and series-connected. It is important to remark that these topologies differ in terms of cable length, losses, cost, stability, number circuit breakers, VSC-converters and need of communication, and that the preference of one over the others is highly context-dependent. Against this background, [21] evaluated a future multi-terminal HVDC grid in the North Sea in the scenarios of a radial, ring, lightly meshed and densely meshed topology investigating overall system losses, transient fault currents, and post fault contingencies as shown in TABLE III.

TABLE III. CHARACTERISTICS OF MULTI-TERMINAL SYSTEMS.

Criterion	**Multi-terminal system topology**			
	radial	***ring***	***lightly meshed***	***densely meshed***
Investment	low	moderate	moderate	high
Losses	moderate	high	moderate	low
Transient fault current	high	low	high	high
Post-fault contingencies	low	moderate	moderate	high

One main advantage of HVDC- over HVAC-grids is the free controllability of power flows, which can be used for optimized power routing and therefore reduced losses, amongst others [22]. Thus, the topology of the multi-terminal grid is of great relevance since it will also determine the required control strategy [19]. Therefore, in a long term vision of international multi-terminal systems, a radial topology is recommended to be applied first. Subsequently, the grid can be gradually meshed while taking into account the development plans of each state member. Thus, the benefits in terms of costs reduction for the integration of new OWF, and the efficiency and the reliability of both, the multi-terminal HVDC- and the continental HVAC-grids, can be maximized.

III. GOALS AND OBJECTIVES OF CURRENT RESEARCH

From a German national perspective, the focus in the medium term is on further development and in short-term the connection of wind farms with existing technologies. Grid connection systems with up to 2 GW will already be used in zone 3 to connect offshore wind farms [23, 24]. In addition, any influences that may arise from the planned and still to be established connection systems of zones 1 and 2 should also be included in the area under consideration (see also Fig. 1).

Besides that, long-term market-driven international developments and opportunities in the planning, implementation and operation of connection systems for offshore wind energy should be included within the next steps. These aspects are intended to create a technical and scientific basis on which sustainable and efficient planning and efficient operation of offshore systems can be enabled. Considering the long-term prospects and the given short- to medium-term tasks, the overarching goals and next steps in the economical connection and international integration of offshore wind energy in the North Sea are:

- the development of new and efficient options for the short and medium-term connection of offshore systems in the German exclusive economic zone,
- the preparation of respective control structures and the preparation of the implementation of HVDC-connections systems of single and parallel connection systems,
- the development of methods and procedures for the optimized planning and operation of these systems, and
- the development and enhanced integration of mathematical methods for handling large linear and nonlinear optimization problems to efficiently represent and handle the problems at hand.

Fig. 2 gives an overview of research fields within short-term tasks and long term development, as well as derived scientific questions within the scope of NSON II by the partners authoring this works. The following sub-chapters give an insight in the works of the fields addressed above.

A. Robust Market-based Scenario Planning under Uncertainty

In order to provide robust decision-support for investors, traders, and policy-makers, a new type of quantitative analysis framework is required that can address the complexity and uncertainty of the transformation process towards net-neutral energy systems in Europe when determining offshore grid investment strategies. To that end, a modelling and optimization framework is to be developed to address the market-based scenario planning of offshore grids in the North Seas. Based on the knowledge gaps identified in [4, 6], the core contributions of this planning framework are characterized by three main pillars which are discussed below.

Path-dependent investment strategies: Being able to identify multi-period investment decisions in the planning framework is required to model realistic transitions from the current system towards medium- to long-term scenarios. Static (or myopic) planning approaches can be helpful, but fail to recognize the implications of path-dependencies that are particularly inherent to transmission network investments. Planning approaches that incorporate dynamic investment strategies help to avoid stranded assets and provide gradual and coherent offshore grid development stages.

Robust planning decisions: Incorporating the endogenous consideration of uncertainty in the planning frameworks has become a vital challenge for modelling energy systems. Growing shares of variable renewable generation, technology developments, the availability of centralized and decentralized cross-sectoral flexibility, climate change impacts on weather patterns, climate and energy policy instruments are

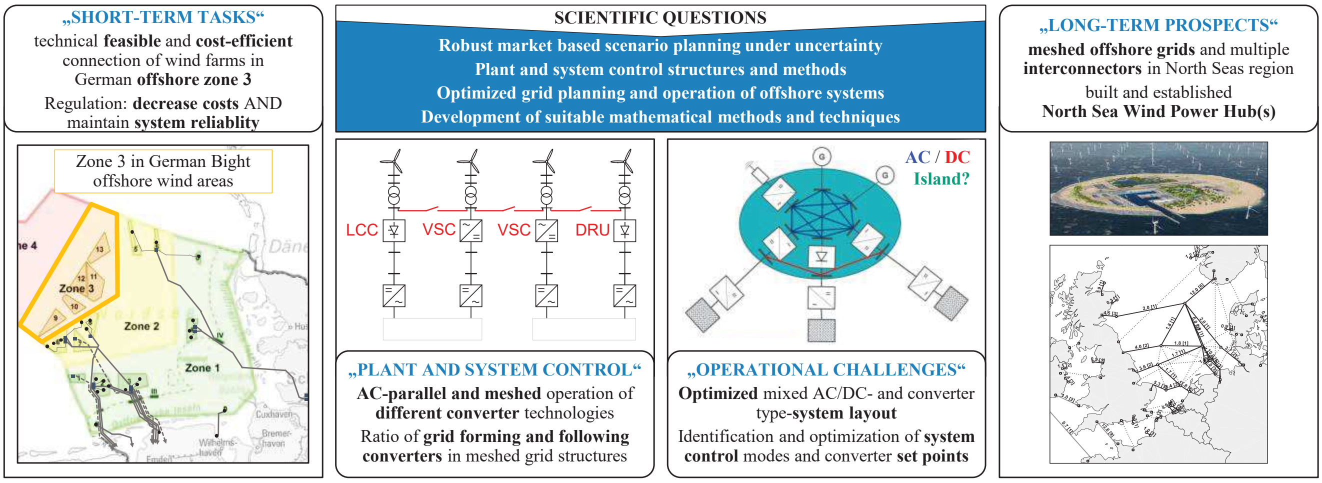

Fig. 2. Overview of research fields within short-term tasks and long term development as well as derived scientific question (with input from TenneT).

only a few exemplary sources of operational and strategic uncertainty. Hence, forward-looking investor behavior requires modern planning frameworks for offshore grid expansion studies to deal with short- to long-term uncertainty and come up with robust results, also see [25].

Integrated coordination of investment decisions: Coordinating transmission and other capacity expansion decisions in the future energy sectors requires a proactive planning approach that capture all relevant interdependencies when identifying optimized offshore network layouts. Extending the idea of generation and transmission expansion planning (GTEP), the modelling framework is to simultaneously determine optimal trade-offs between transmission, generation, storage, and cross-sectoral demand capacity expansion planning (CEP) decisions. Due to the low-carbon development trajectories of future energy systems, the complexity of representing the system increases substantially in different domains, i.e., spatial, temporal, technology, markets, energy carriers. Capturing the potential advantages of inter-sectoral coupling involves the flexibilities coming from demand response, multi-energy systems (e.g. gas, hydrogen, heat), and enhancing electricity uses (e.g. mobility, heating, feedstock for industrial processes). For instance, in [26], it is shown that hybrid technologies at the cross-sectoral interfaces might become crucial for the price formation effects in low-carbon power systems.

To address all requirements in the new offshore grid planning framework, the "Multi-stage Stochastic Cross-sectoral Investment Planning" (MSCIP) is under development. In a first approach, this new CEP framework is implemented as a linear program (LP) with the objective to minimize total system costs, i.e. investment and system operation costs. It is also possible to implement the modelling framework as a mixed-integer linear program (MILP) in order to include fixed cost components of offshore platforms, converters or artificial islands. The modelling framework includes all European energy sectors in a one-node-per-country granularity, each representing the national building, transport and industrial sectors with relevant direct and indirect electrification options. Explicit representations of hybrid technology options capture the additional electricity demand as well as new flexibility options in low-carbon power markets. The new CEP framework largely builds on previous work conducted for the static deterministic cross-sectoral CEP framework SCOPE SD [26–29].

Regarding the endogenous representation of uncertainty, the MSCIP framework relies on a stochastic programming approach. Fig. 3 illustrates a multi-stage configuration of the scenario tree including uncertain operational and strategic information. The investment decisions made in the first stage are robust against the uncertainty revealed in the later stages.

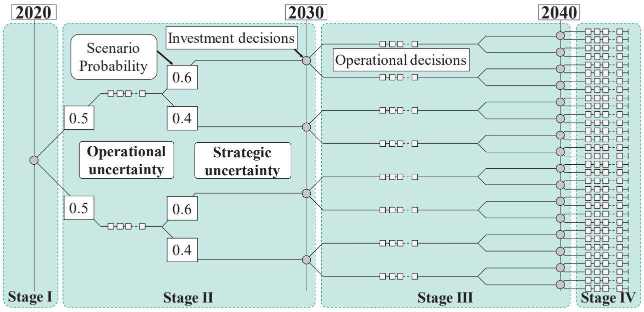

Fig. 3. Exemplary scenario tree in the Multi-stage Stochastic Cross-sectoral Investment Planning (MSCIP) modelling and optimization framework.

Note that each of the branch instances is a considerable optimization problem in itself. Hence, a monolithic solution approach is not viable, especially for full-scale instances of the multi-stage stochastic configuration. To maintain the computational tractability, the MSCIP modelling and optimization framework relies on advanced aggregation and solution methods. The implemented solution strategy uses a scenario decomposition technique together with a progressive hedging algorithm [30]. Moreover, employing time series reduction techniques lower the complexity in the temporal domain of the problem instances.

B. Plant and System Control

Currently available control concepts for HVDC-connections do not allow parallel or even meshed operation with their offshore AC-sides being connected. However, in order to connect the growing amount of offshore wind energy together with its inherently evolving offshore grid structure by means of HVDC-connections in a modular manner, such control concepts are absolute prerequisite. In addition, parallel operation with different onshore points of common coupling allows a flexible integration of the power generated into the onshore grid. One main aim of the NSON II project is the development of aforementioned control structures, being pursued in the work package "Plant and System Control", for which both proven and emerging HVDC converter technologies are to be considered.

Besides, meshed offshore grid structures offer potential for international active power trading, which contributes to relieving existing grid bottlenecks in the onshore grid by regulating the offshore grid connection systems accordingly. In the future, the question of offshore systems contributing to the transmission of control power within the framework of the international grid control system [31] will arise in terms of how offshore grids can optimally be utilized. Finally, the possibility of transmitting control power via a meshed offshore grid is examined. The NSON II project will therefore provide a technical base for three-phase intermeshing of existing HVDC transmission technologies in the North Sea performed in the short term. The knowledge gained will also actively be integrated into the next revision of the offshore grid connection regulations.

As a first step within this work package, currently available HVDC converter technologies were analyzed. As possible economically advantageous alternatives to the parallel operation of two HVDC-connections consisting of VSCs each, the application of either LCCs or an offshore DRU in combination with an onshore VSC in one of the two parallel HVDC-connections was identified [32–34]. Due to the technological development, losses of VSCs in practical operation nowadays are down to roughly 0.7 %, a value previously only achieved by LCCs, having been one of their main benefits. Together with modular multilevel converter (MMC) VSCs emerging in the market, allowing for omission of both offshore filters and reactive power compensation [35], and the power transmission capability of offshore HVDC-connections being restrained rather by the 2 K criterion's than the converter technology's current limitation, LCC HVDC-connections are no longer expected to be used in this field of application. Instead, the utilization- of an offshore DRU for rectification seems more promising, as of its main beneficialities being space saving, transmission-powerwise modularly as well as having lower losses and requiring fewer reactive power compensation than comparable LCCs [33].

In consequence, the control concepts to be developed and studied within the NSON II project are going to consider both the parallel offshore operation of VSC and VSC as well as VSC and DRU converter technologies. It is worth mentioning that especially the implementation of active power flow control for the basically uncontrolled DRU, exemplarily viable by means of controlling the offshore AC voltage magnitude, represents a special challenge of this work package.

C. *Optimized Transmission expansion Planning and Grid Operation of Offshore-Systems*

By the development of control-concepts that enable an interconnected parallel operation of converters on the AC-side or the application of new cost-efficient line-commutated converters new degrees of freedom in terms of grid operation and transmission expansion planning (TEP) are offered. These new degrees of freedom need to be modelled in a suitable way to implement them in an optimization-tool for mathematical optimization. This tool is intended to support the grid expansion planning process as well as the operation of newly installed offshore HVDC-systems or offshore grids, prospectively.

The transmission expansion planning differs in this step by the time horizon and in the level of detail in comparison to the robust market based scenario planning described in section III.A. Therein, long-term and basic structural factors of influence are investigated, whereas practical technical questions and the optimized design with subject to the technical constraints in such a system are answered within the optimized TEP and grid operation described here. The basis of current works in TEP and operation was laid in [36] and detailed in [37]. The results of the planned enhancements of this tool are an economically optimized technical arrangement of the offshore-system as well as fitting optimized concepts for the operations of such an interconnected offshore-system. In order to reach this goal in a first step technical solutions for the connection of offshore systems are analyzed as presented in chapter II. The therein shown stages I to III for an ongoing connection and international interconnection of offshore systems are to be modelled together with (parts of) the surrounding AC-systems. Starting from a modelling for power flow calculations of existing offshore systems in the German Bight the already planned and confirmed (according to [23]) connection systems are modelled as standardized point-to-point connections as given in [3].

Within the process of the modelling open questions and decisions are to be identified and analyzed whether or not being relevant for an optimized planning and operation of these systems. These derived questions later have to be translated into mathematical models in order to implement them in the optimization environment. Within the next steps, then alternative and possible future connection systems as well as the possibility of parallel and multi-terminal connection systems for the already sketched offshore wind fields are to be modelled accordingly and possibilities for a further optimization are checked. Also further possibilities of an international integration in neighboring offshore systems or the combination with interconnectors will be analyzed and investigated.

D. *Mathematical Methods and Techniques*

The optimization models arising from the enhanced cross-sectoral investment and grid operation planning problems are extremely large and complex. In order to solve these models efficiently, special mathematical techniques are developed and integrated within the existing tools.

One main goal is to develop methods to identify extremal time points and (short) time periods in time-series data using techniques from data analytics (PCA) to detect the most important directions of variation within the data and techniques from convex geometry to identify extremal points in the lower dimensional space(s) of these directions. This complements other approaches, such as clustering and scenario tree reduction techniques, which seek for characteristic (but not extremal) representatives and hopefully leads to more accurate model reduction and decomposition approaches for time-series based optimization models.

A second goal is to develop computationally efficient methods to integrate resilience requirements into power flow models and grid operation planning. For this, we propose decomposition approaches that use less accurate but computationally easier sub models for the power flows in failure scenarios as long as the accuracy of these sub models is sufficient and retreat to more accurate but harder models only when necessary.

IV. EXPECTED RESULTS AND OUTLOOK

The new modelling and optimization framework MSCIP allows for the analysis of several research questions arising for offshore grids in low-carbon energy systems. For instance, it can determine incremental expansion plans involving innovative offshore transmission technologies and path-dependent interactions as well as additionally assess the influence of long-term uncertainties on investment decisions for offshore networks in the North Seas. It can further quantify the contributions of offshore grid infrastructure to implementing direct and indirect electrification strategies for realizing the European Green Deal. Ultimately, the explicit modelling approaches allow for the detailed assessment of cost-benefit allocations, including new market participants from other energy sectors when comparing different offshore grid solutions.

With the developed control concepts at hand, the parallel operation of VSC and VSC as well as the emerging combination of VSC and DRU converter technologies is feasible, allowing to modularly connect future wind parks based on the aforementioned optimization results. In combination with meshed offshore grid structures including different onshore points of common coupling a more flexible integration into the onshore grid is yielded, for which the HVDC-system's possible contribution to control power transmission are identified and evaluated.

Mathematical models representing control and operational constraints allow the optimized planning and operation of newly installed offshore systems. Modelling and application of concepts and procedures for optimized planning and operation of offshore connection systems and grids can help to find favorable solutions regarding technical as well as economical aspects on the way to an integrated and interconnected offshore system. For network design and investment planning problems involving time-series demands or many scenarios, faster or more accurate solutions are expected using the developed techniques to detect extremal scenarios in the data and the corresponding model reductions. First results for pure robust network design problems show speedup-factors of several orders of magnitude with only minimal loss in accuracy compared to the complete model. Also, for problems involving power flows in many different network failure states, reduced overall computation times are expected with methods using the proposed adaptive refinement of the sub models' accuracies.

All these will enable and allow for the next steps on OWF connection on the short hand while keeping long-term visions in mind paving the way towards technically and economically feasible meshed and interconnected offshore grids.

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