Bornholm as a test and demonstration site for energy island technologies

Nationalt Center for Grøn Energi
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1. Background

On the 22nd of June 2020 the Danish Parliament mandated the construction of world's two first energy islands – one in the North Sea and one on the island of Bornholm in the Baltic Sea - and has thereby set the path towards the integration of large amounts of offshore wind power in the future. The establishment of the first two energy island can be considered a Mars-mission for the energy system as most of the technologies and solutions will be applied for the first time in such an environment and scale. To harness the huge wind power potential in the North and Baltic Sea of 150 GW and 93 GW, respectively, many other energy islands might follow. Altogether these could provide the backbone of a future offshore energy system, which differs completely from any of the systems known today. While the initial energy islands are first and foremost aiming to make Denmark independent of fossil fuels it is also an opportunity to establish Denmark as a market leader in energy island technologies.

This document provides an initial assessment of the opportunities to progress the development of energy island technologies through test and demonstration that arise from constructing the first of the energy islands on Bornholm.

2. Energy islands

2.1 The energy island concept

The main concept of the energy islands is indicated in figure 1. Essentially, energy islands are hubs that provide a centralized infrastructure for the connection of multiple offshore wind parks and the transmission wind power to different locations in the onshore system. and thereby provide access to different electricity markets. Apart from merely providing new ways of integrating wind power, the transmission system of the energy island can also serve as an interconnector for the onshore systems and thereby increase the interconnection capacity between different countries. Additionally, energy storage and power-to-x facilities can be connected to the energy island to either store or convert excess electricity from wind power. The concept itself is often also referred to as the more general term offshore energy hub, as it serves as a hub for electricity generation and transmission and considering hydrogen production and transmission even as a multi-energy hub.

The main technology employed in the context of the energy islands are high voltage direct current (HVDC) transmission systems, that transmit power via direct current (DC), which is particularly suitable for the transmission of bulk power over long distances via subsea cables

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and allow to connect power systems that are part of the same synchronous area. Since both the onshore systems as well as the electrical infrastructure on the hub operate in alternating current (AC), HVDC converters are required in both locations. To allow the export of power to different locations onshore and the exchange of power between these areas, multiple HVDC converters need to be coupled together offshore.

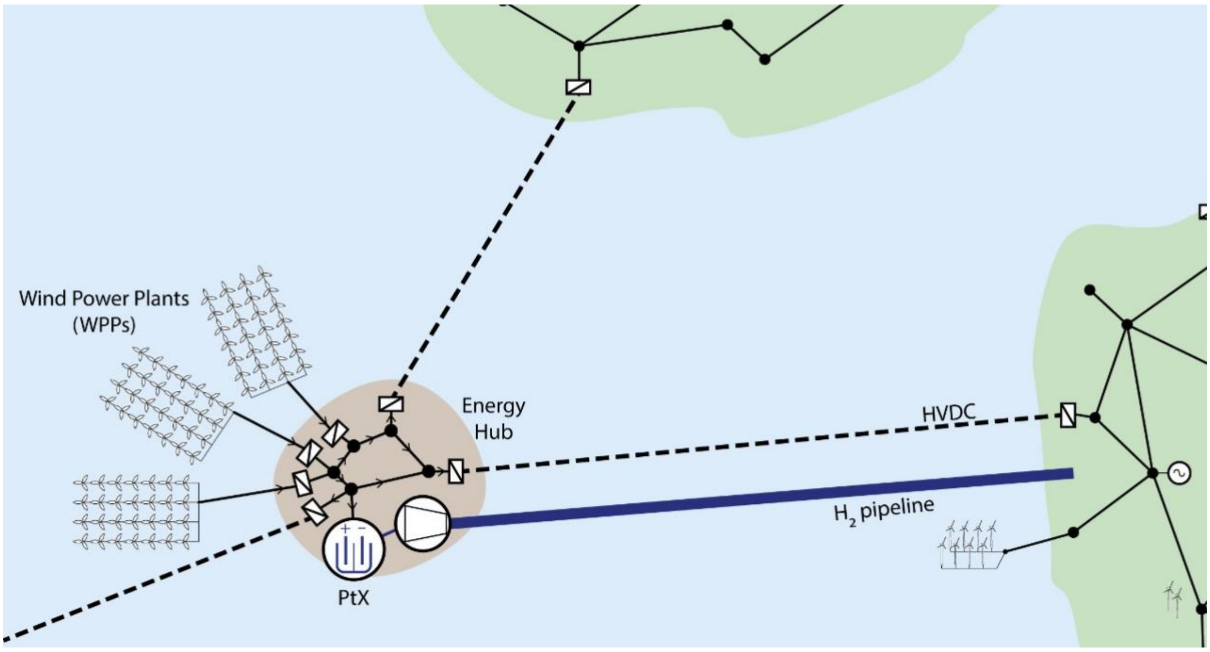

Figure 1: The energy island concept. Multiple wind farms are connected to a central hub with HVDC transmission systems and potentially energy storage and power-to-x infrastructure.

This innovative approach represents a paradigm shift from the currently employed point-to-point, single purpose, single vendor concept of integrating offshore wind power, where wind power is generated and directly transmitted to a single point onshore. With the energy island wind power integration is transformed into a multi-terminal, multi-purpose, multi-vendor, cross border, or multi-market system as indicated in figure 2.

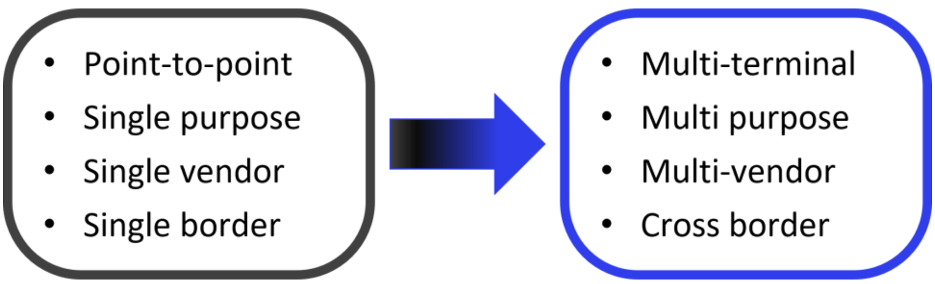

Figure 2: The paradigm shift in wind power integration enabled by the energy islands

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2.2 Energy island technologies

As an infrastructure project of such a massive scale the energy island touches upon many aspects in respect to technology as well as society as indicated in figure 3.

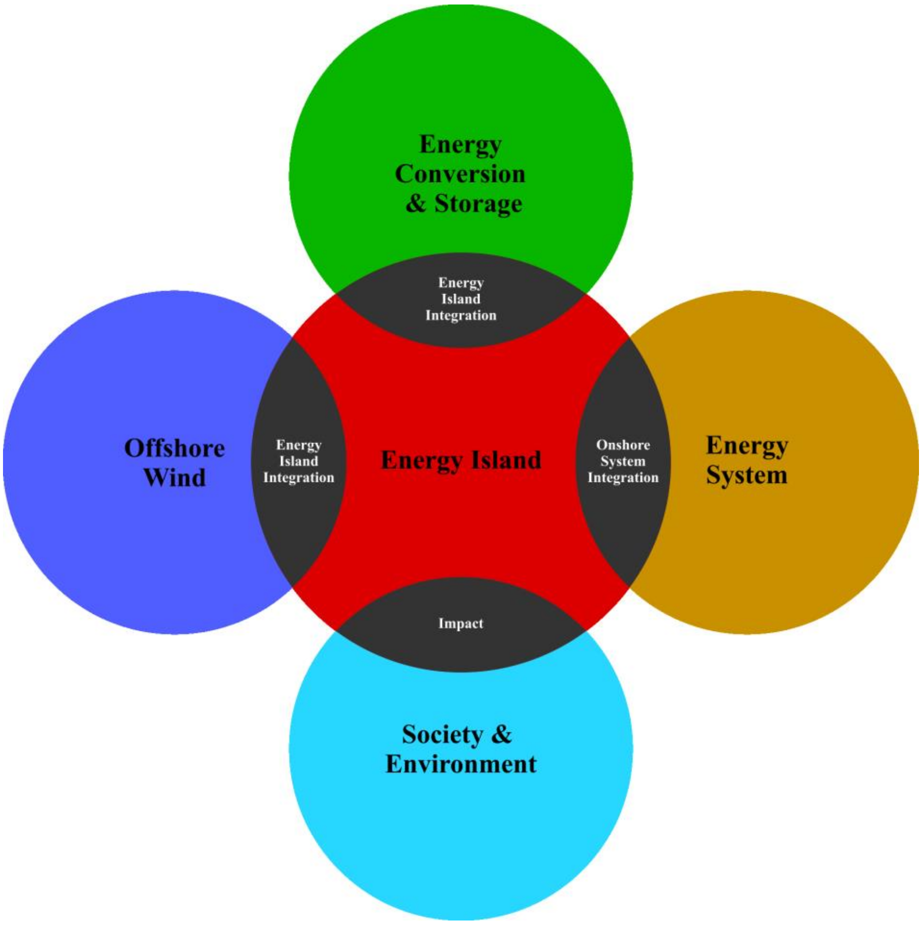

Figure 3: Energy island related research topics

Defining a boundary for what aspects of technology development should be classified as energy island technologies within these specific areas is a challenging prospect. An indicative solution for mapping technologies into energy island technologies, and those that are not considered as such, is presented in figure 4, where the societal and environmental impact has been neglected as it is considered outside of the scope of this document. Generally, key enabling technologies that can radically change the way energy islands can be designed and operated are considered as energy island technologies, while the more general technology developments that aim to improve existing solutions or involve the design of solutions not

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specifically targeting the application in the context of the energy islands are considered out of scope.

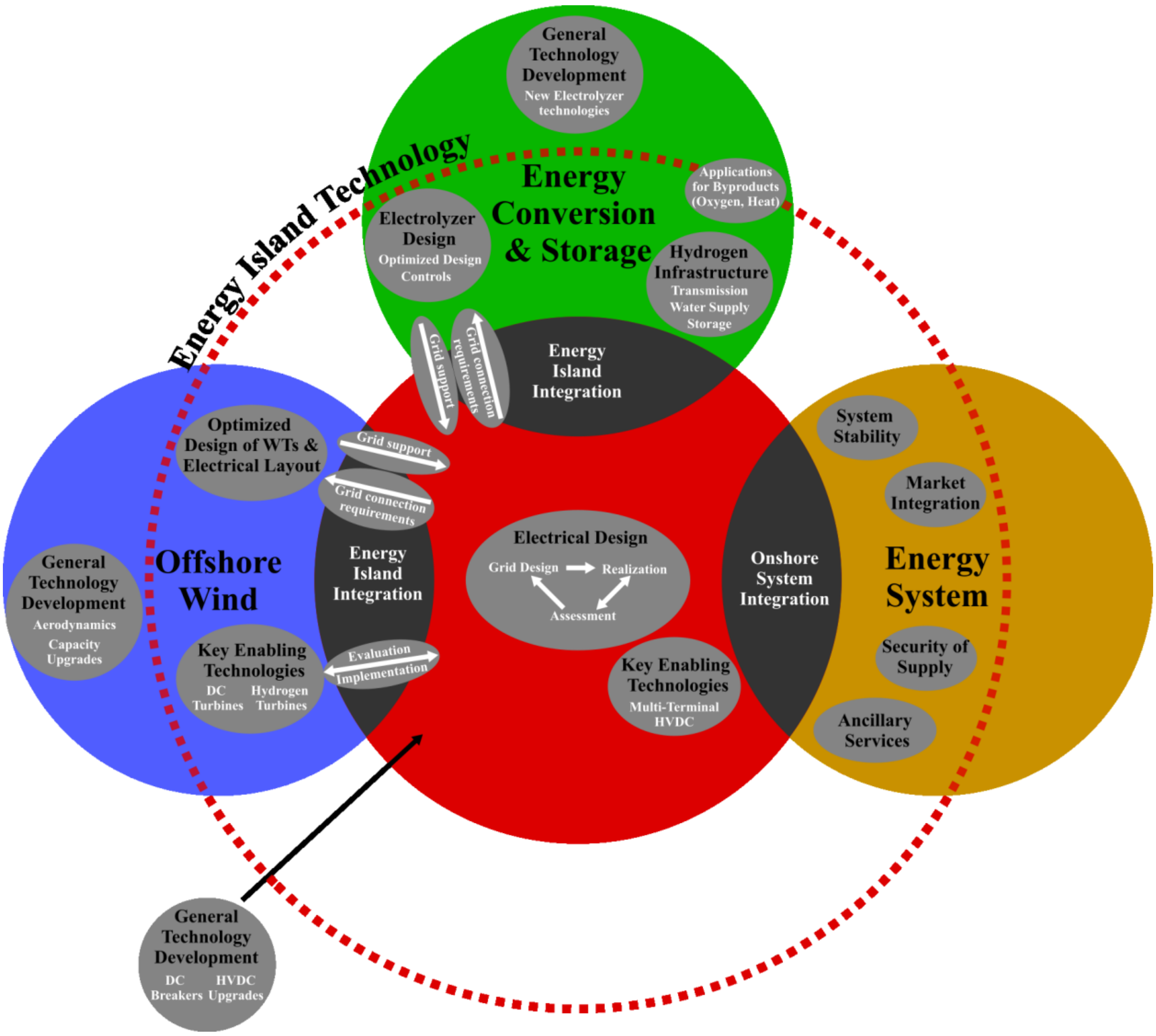

Figure 4: The scope of energy island technologies

In the center of the development is the design of the energy island itself, which is here considered as the main infrastructure for transmitting wind power to different locations onshore and routing electric power from one onshore location to others. In particular the design is related to the topology of electrical system, i.e., how the different components are connected. This applies primarily to the HVDC converters, which are the central component of the energy island infrastructure. Furthermore, the design relates to the way the individual components are operated. This involves the conceptual design and the realization of coordinated controls that make sure that the individual components can be interfaced with each other.

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Some of the major requirements for the electrical design of the energy islands are that they need to be expandable, cost-efficient, resilient and provide the necessary infrastructure for integrating offshore wind power, storage and power-to-gas technology. This includes, among others, choosing an optimal island topology in terms of cost, control and protection. The solution needs to allow modularity in order to enable a seamless expansion of the design by adding more wind power and additional interconnectors. Additionally, energy islands need to be integrated in the existing onshore systems, capable of being integrated in potential meshed systems including multiple islands and integrated into existing energy markets.
There exist two main concepts that facilitate the connection between the different HVDC converters, the AC and the DC solution. The DC hub topology is a hub design where the interconnection between the offshore power converters is made on the DC side, while in the AC hub topology the offshore HVDC power converters are connected on the AC side.

The AC hub topology shown in figure 5 is comparable to the standard point-to-point HVDC systems but all offshore HVDC power converters are connected to the same offshore AC network and operated under extremely weak network conditions. Additional challenges arise from the multi-vendor and multi-owner converter dominated environment that requires careful considerations to avoid potential adverse interactions.

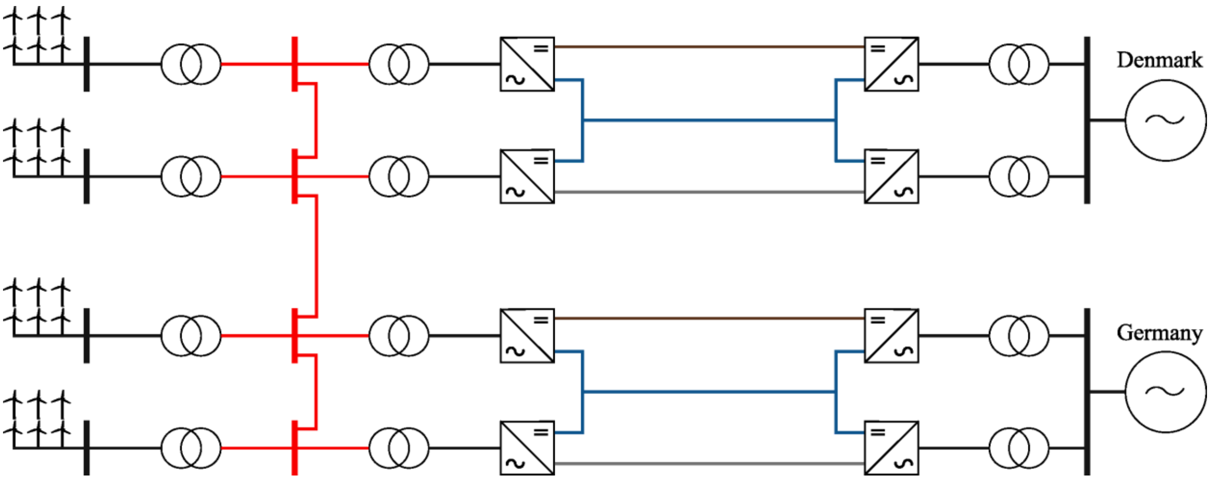

Figure 5: AC Side Interconnected Energy Hub Topology - AC Hub

The main advantage of this topology is the maturity of the technology and possibly higher levels of transmitted energy in cases of faults or maintenance on one of the converters. If one of the converters is out of operation, then the energy can be distributed among other converters

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if there is excess capacity. Some drawbacks of this solution are the higher risk of control and stability issues in the offshore AC network, amplified due to the multi-vendor environment and higher losses during operation as an interconnector.

The alternative is the coupling of the converters on the DC side as indicated in figure 6, we referred to this topology as a DC hub or a multi-terminal HVDC. The main benefits of the DC topology are that it reduces interconnection losses and reduces the AC side networks to the standard HVDC connected offshore wind systems, for which the technology is at high level of maturity. The main disadvantage of this solution is the maturity of multi-terminal HVDC systems in particular in terms of DC circuit breakers, where little to no operational experience exists today. An additional challenge stems from the control aspects of interconnected DC systems. The ENTSOE currently considers the technology readiness level (TRL) of meshed multi terminal DC systems to be on the level of TRL 4, which equates to laboratory testing of prototype component or process. Another aspect in the application of the DC solution is, that currently there are no specific functional requirements, i.e., grid codes, formulated that apply to interconnected DC systems.

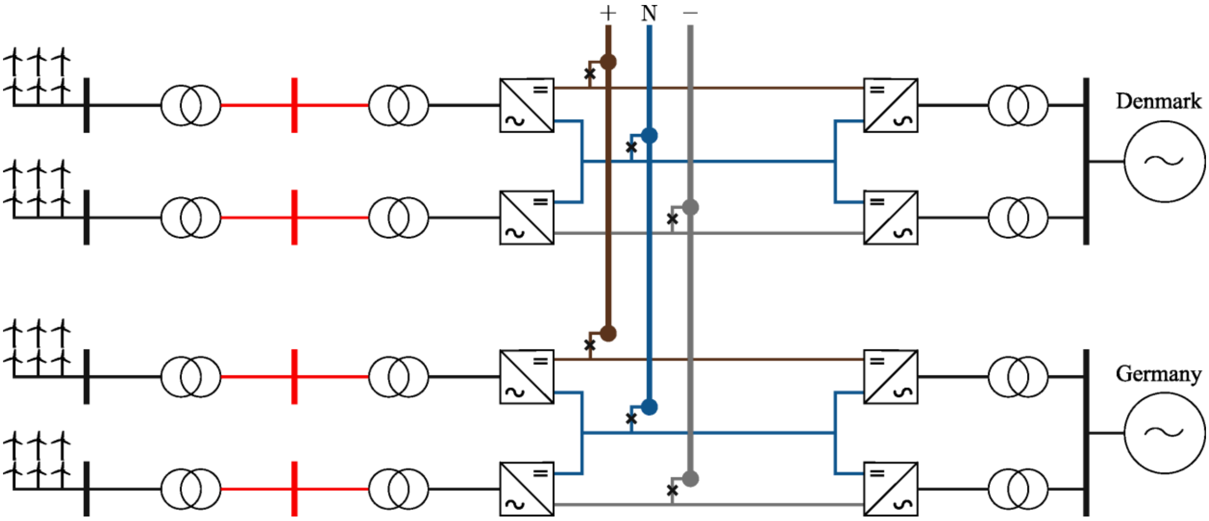

Figure 6: DC Side Interconnected Energy Hub Topology - DC Hub

In their business case for the energy island Bornholm the Danish transmission system operator Energinet came to the conclusion that overall, the DC solution is preferrable. However, due to the involved risks of the DC solution a hybrid solution should be applied to de-risk the overall project. The idea of the hybrid solution is, that the energy island can be operated either as AC or DC hub. This hybrid solution is indicated in figure 7. This solution allows to operate the hub as an AC hub when the DC connection cannot be established or is out of service. During normal

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operation the switches connecting the AC buses are open and the hub operates as a full DC hub. The AC hub topology is established by disconnecting the DC busbars providing a fall-back option in case of DC breaker failures or outage of one of the HVDC converters. Besides redundancy, the hybrid solution has the advantages and disadvantages of AC and DC hubs, depending on which mode the energy hub is operating in.

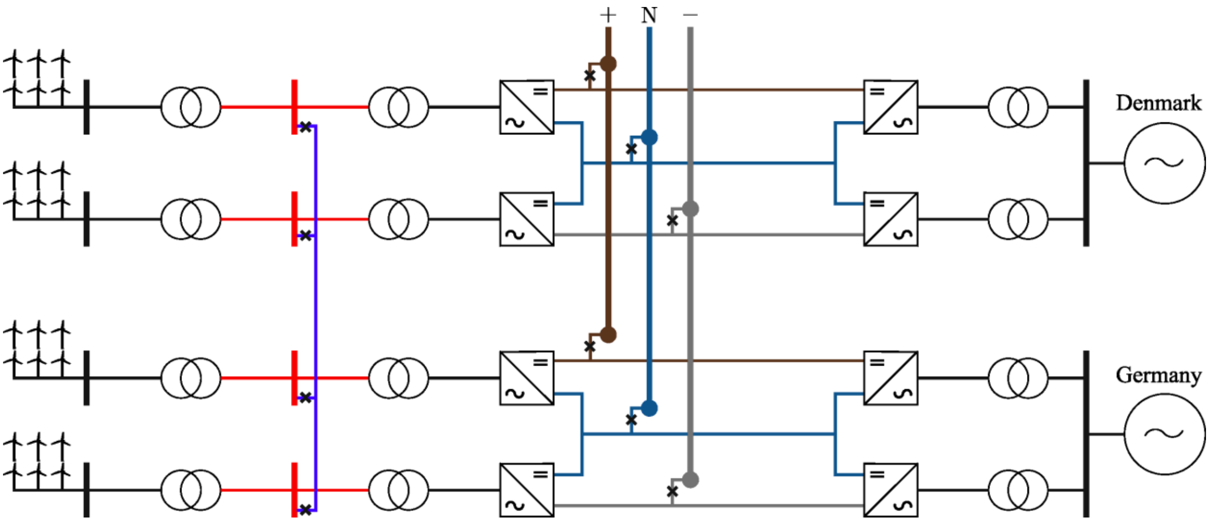

Figure 7: Hybrid Interconnected Energy Hub Topology - Hybrid Hub

In terms of the interlinked technologies that integrate with the energy island power-to-x currently has a particular focus. While not exclusively related to the energy islands the availability of potentially cheap electricity offshore can make the integration of electrolysers, that transform electric power into hydrogen, into the energy island attractive [1]. A secondary effect of having local demand on the island is, that its potential flexibility can be beneficial for the operation of the energy island, as it allows a means to balance power production and demand locally. The same applies to the integration of large-scale energy storage solutions.
From the energy island perspective, the main research questions are related to the integration of these components into the fully converter based, zero inertia power system and the services that can be provided by these components to improve the resiliency and efficiency of the offshore system.

While offshore wind power can generally be considered very mature the energy island concept has the potential of increasing the attractiveness of new offshore wind turbine designs. Namely, the development of hydrogen wind turbines, where electricity is converted to hydrogen within

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the individual turbines or DC turbines which could potentially be directly integrated with the offshore DC system.

The isolated offshore power system further allows for a potential revision of the status quo regarding the requirements imposed on offshore wind turbines. As the system is decoupled from the traditional onshore system and has a significantly different characteristics, potential cost savings can be achieved by reviewing and adapting the requirements that are currently defined in the existing grid codes. Whether new, different, requirements need to be imposed to address the specific characteristic of the energy island system is another aspect to consider.

3. Bornholm in the context of the energy island development

3.1 The island of Bornholm

Bornholm is an Island in the Baltic Sea and part of Denmark with an area of app. 588 km^2 and a population of app. 40000. As can be seen in figure 8, Bornholm is located app. 40 km south of Sweden, app. 145 km east of Zealand – Denmark, app. 90 km north-east from Germany, and app. 100 km north of Poland.

Figure 8: Geographic Location of Bornholm Island

The island of Bornholm was made part of a central energy strategy for energy research and development for Denmark in 2008, but has a tradition in renewable energy stretching back to the 1980's. Since 2008, the island of Bornholm has been a focal point of many research projects A few exemplary topics include solar PV integration, electricity market designs, active distribution networks, customer and demand flexibility, wind power integration, electric vehicle integration, microgrid operation and management, and many other topics within the energy research area. Additionally, there is a strong community engagement with Denmark's overall energy strategy and overwhelming support from the local businesses and population.

As Bornholm is an inhabited island it comes with existing transportation infrastructure, such as airport, roads and established marine and flight transportation routes. Additionally, the port of Rønne already serves as a pre-assembly port for wind turbines that can be further extended. Moreover, the area in the Baltic Sea around Bornholm offers an enormous potential for offshore wind power installation, which is yet unharnessed. Bornholm is therefore in the perfect spot to be in the center of the further development of the energy island concept and the related technologies as well as provide an outlook into a future in which energy islands and 100 % renewable energy provide the backbone of the energy system. Some of these potential opportunities are shown in figure 9 including the main aspects of the planned energy island.

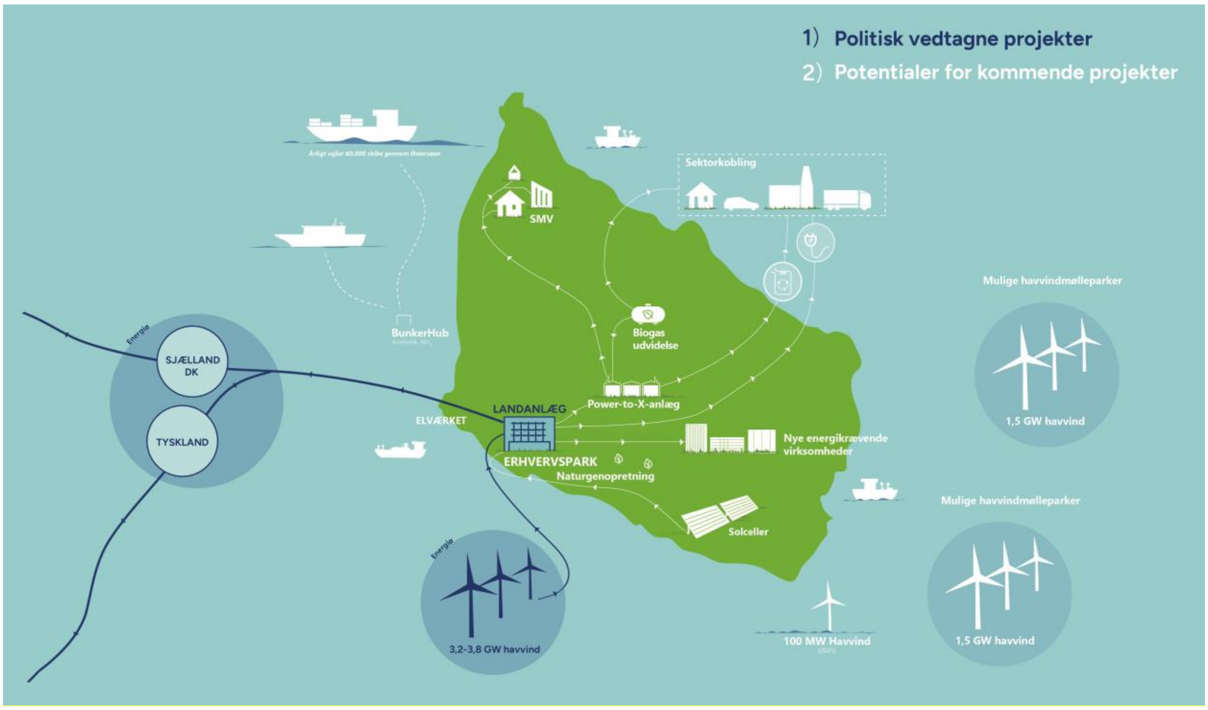

Figure 9: Potentials and perspectives for Bornholm Energy Island [2]

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3.2 Design of the energy island Bornholm

The energy island Bornholm is currently planned for an initial capacity of 3 GW of offshore wind power. Transmission links via HVDC systems will be provided to the Danish power system via the island of Zealand and the German system. The transmission capacity is intended to be 1.2 GW towards Denmark and 2 GW towards Germany. The topological concept of the Danish TSO Energinet as presented in a market dialogue for potentially interested parties is shown in figure 10. Each of the HVDC systems will be realized as a bipole with a dedicated metallic return, which means that each converter pole can operate as an individual unit increasing the security of supply in case of faults at individual converter poles. The planned topology concept is based on the hybrid solution, with the option of both, AC and DC coupling, as described in section 2.2. Wind power as well as potential power-to-x facilities and energy storage solutions are integrated via high voltage AC buses that can be separated in case of operation in DC mode.

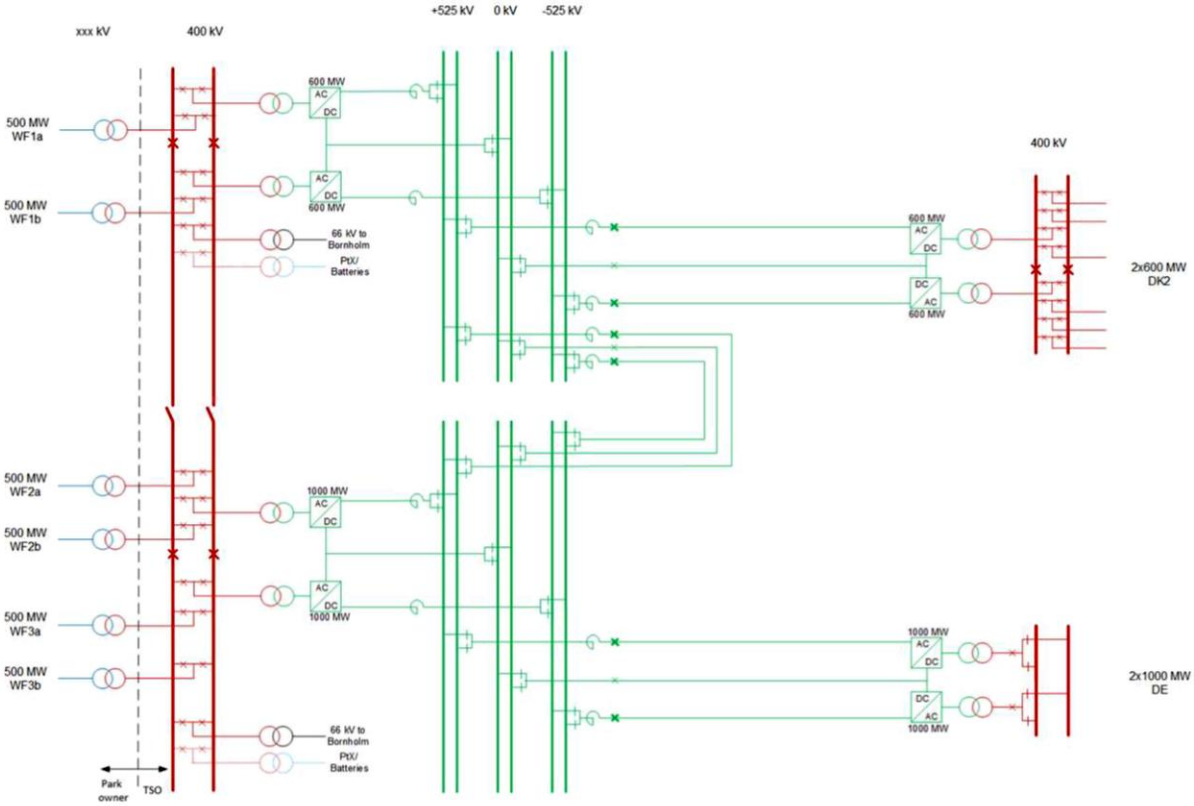

Figure 10: Topological Concept of the energy island Bornholm (Source: Energinet [5])

One particular challenge is the integration of the existing 66 kV system on Bornholm.

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Energinet is planning to establish a connection between the local system and the electrical system of the energy island [3] but how exactly the connection will be established technically is not yet clear [4].

3.3 Bornholms current energy system

Bornholm's power system is operated at three voltage levels: 60 kV, 10 kV and 0.4 kV. The island is connected to the mainland Sweden with 43 km undersea cable rated at 60 MVA. From time to time, the system operates in islanded mode in cases of maintenance or in case of faults on the interconnection cable or related substations. The distribution system operator on Bornholm is Bornholms Energi & Forsyning (BEOF). The minimum and maximum load in the system is 13 MW and 63 MW, respectively. The generation mix of Bornholm's power system consists of the following units:

- 16 MW biomass combined heat and power plant (CHP) with steam turbine. It has an inertia time constant $2H = 6.4$ s and apparent power $S = 46.8$ MVA. It has a primary frequency droop control at 2%, and automatic voltage regulator. The ramping rate of the generator is 0.2 MW/min (1.25% Pnom/min). This unit is termed generation block 6.
- There are two 1.5 MW CHP gas turbines with inertia time constant of $2H=5.6$ s, and they do not provide primary frequency control.
- 37 MW of installed wind capacity. 24 machines <100 kW; 16 machines between 100 and 1000 kW; 17 machines >1000 kW. The largest machines are three Siemens 2.3 MW wind turbines at the 60/10 kV substation in Hasle and three Vestas 2 MW units at Åkirkeby. Most of the small wind turbines are residential.
- 23 MW of installed PV capacity (8 MW distributed on rooftops at 0.4 kV; 2x7.5 MW PV plants at 10 kV at the secondary sides of the 60/10 kV substations in Åkirkeby and Bodilsker). There are plans in place to install additional 20 MW of PV capacity close to Østerlars.
- 1 MW / 1 MWh battery at Åkirkeby substation.

Besides the listed generation, the Bornholm power system consists of conventional units. They are utilized only in cases of emergency and when the system is operating in islanded mode, i.e. when it is not connected to the Nordic system with the sea cable. They provide 58 MW of power reserve. The ratings of the conventional units are provided in the list below:

- 25 MW oil-powered steam turbine, which is named Blok 5. It has an inertia of $2H = 8.6$ s and an apparent power of $S = 29.4$ MVA. It is equipped with primary frequency droop control at 2%, and an automatic voltage regulator. The ramping rate of the unit is 0.25 MW/min (1% Pnom/min).

- Four 4.5 MW diesel generators (block 4) with 2% frequency droop control and automatic voltage control. Each unit has inertia 2H = 8 s, two units are rated at S = 5.8 MVA, while the other two at S = 6.3 MVA.
- There are ten 1.5 MW diesel generators, which are named Block 7. Each unit has an inertia of 2H = 1.1 s and apparent power of S = 2 MVA. They do not provide primary frequency control and do not have automatic voltage control. The ramping rate of the units is 1 MW/min (66% P_{nom}/min).

The current situation on Bornholm requires the curtailment of renewable energy sources and using these conventional units to form the local grid in islanded mode

The layout of the current 60 kV system of Bornholm is displayed in figure 11.

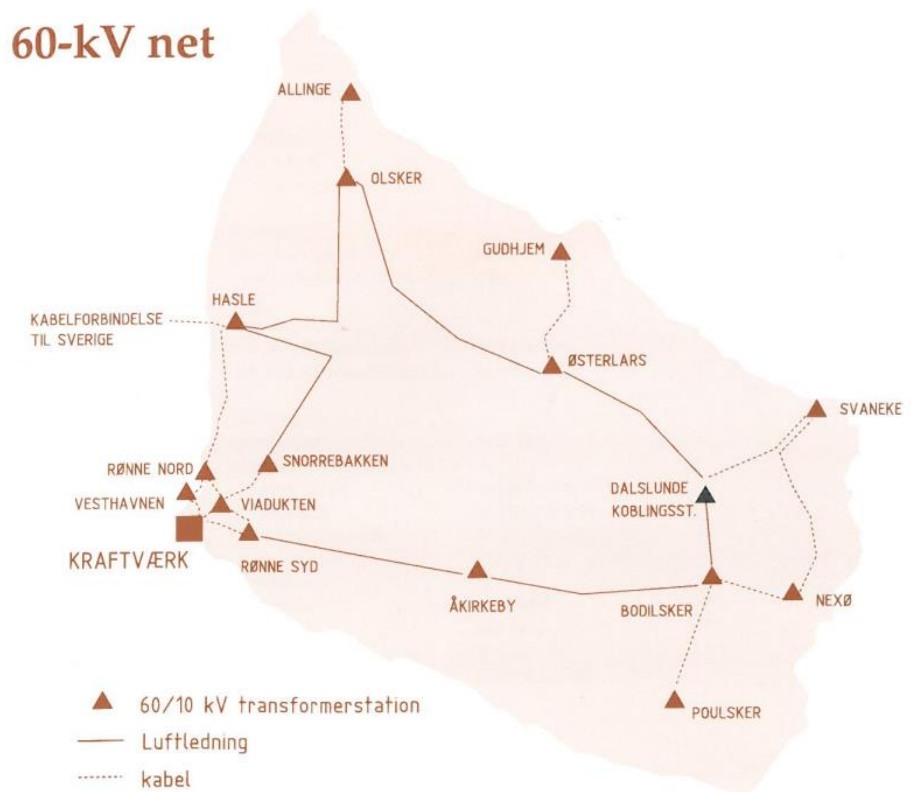

Figure 11: 60 kV System of the Bornholm Power System

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Bornholm district heating system (DHS), as shown in figure 12, consists of 5 district heating networks supplied by 8 district heating plants:

Figure 12: District Heating Systems of Bornholm. Not shown is the DHS of the city of Rønne in the southwest (source: Bornholms Energi & Forsyning)

- The district heating network in the northern part of the island is supplied by 3 district heating plants located in Muleby (3 MW rated plant using wood pellets burning boilers), Hasle (7 MW rated plant burning straw, wood chips and pellets), and Klemensker (burning straw). The northern network supplies hot water to Allinge, Sandwig, Tejn, Klemensker, Hasle, Sorthat, Nyker and Muleby.
- The network in the north-eastern part of the island is supplied by a single district heating plant located in Østerlars (3 MW rated straw and wood pellets burning boiler and three electric boilers rated at 2 MW in total). It provides hot water to 4 places, namely Gudhjem, Melsted, Østerlars, and Østermarie.
- The eastern network is supplied by a single district heating plant located in Nexø (12.5 MW rated straw burning boiler). It provides hot water to 6 towns: Listed, Svaneke, Årsdale, Nexø, Balka, and Snogebæk.
- The southern network is supplied by a single district heating plant located in Åkirkeby (6 MW rated wood chip burning boiler and two biogas units rated at 1 MW each). The

plant supplies 4 towns: Vestermarie, Åkirkeby, Lobbæk, and Nylars. There is also a plant in Lobbæk rated at 1.4 MW, burning wood pellets, but it is used only as a reserve.

- Finally, the network in Rønne, the capital city of the island, is supplied by a CPH plant located in the city. It uses wood chips burning boilers.

The annual heat power supplied by BEOF to the different district heating networks was 250 GWh in 2021 [6].

3.4 Energy island research and Bornholm:

The energy island Bornholm will be the first realization of the energy island concept and therefore provides a unique opportunity for demonstrating the feasibility of energy islands as a vital step towards a carbon free energy society. During the development of this first of its kind solution many challenges to make the solution secure, economically efficient as well as future proof will occur in the process. Realistically, the first solution will most likely not be perfect since many of the concepts will be applied for the first time and the energy island Bornholm will only represent a first, albeit very important, step towards a potential large-scale roll-out of offshore energy hubs worldwide. The island will be established based on the current state of the art with little time for the development of new energy island optimized technology concepts. Nevertheless, the experiences from establishing the energy island concept for the first time can provide valuable insights for developing new, innovative solutions specifically tailored towards an application within this new environment. This knowledge transfer from the development of the first energy island on Bornholm, towards the North Sea energy island and the general application of energy islands or offshore energy is illustrated in figure 13.

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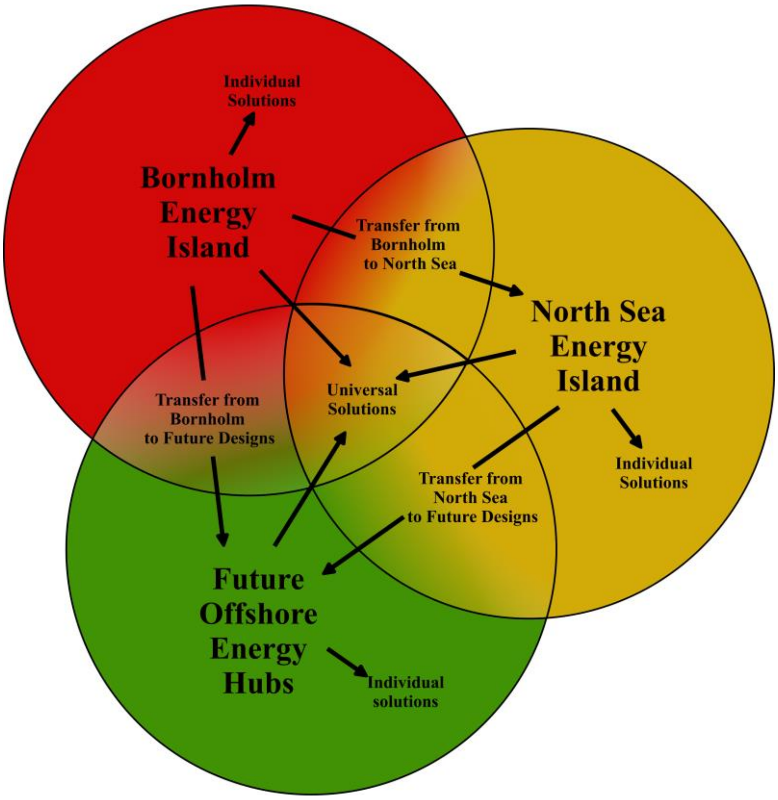

Figure 13: Bornholm in the context of the energy island development

Within this context it is considered that each realization of an energy island is unique in the sense that it is established in a particular, unique, environment and therefore needs some tailor-made solutions for that particular setting. There are, however, core elements in terms of design and operation that apply to all these solutions and each new realization contributes to this core with its own lessons learned, ultimately leading to more optimal designs. Additionally, some of the individual challenges might provide insights for solutions that are somewhat similar contributing to a pool of solutions for various specific settings.
Bornholm, as the first of its kind, will contribute quite significantly to this development and will provide the foundation for the energy islands to come.

From a technical point of view the development involves several different layers:

- Conceptually, based on a system level with the aim of introducing new potentially better topologies and operating modes
- On a component level, where the aim is to improve the individual components in terms of efficiency and performance within the given environment or to adapt them in order

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to integrate into a different operational environment. New technologies can enable or support the development on the system level.

- On an operational level, where the aim is to improve the operation of the energy island using the available equipment connected to the offshore system

An outlook, where and how the energy island Bornholm and test & demonstration projects associated with it can contribute to these different layers is presented in the following section.

4. Scenarios for test & demonstration on Bornholm

When referring to the opportunities for test and demonstration in connection to the energy island Bornholm it is important to keep in mind that the main test and demonstration is the establishment of the energy island itself, simply due to the fact that it is the first of its kind. Due to the uniqueness of the energy island concept, which includes several coupled HVDC converters, integrated wind farms and potentially electrolysers as local converter interfaced loads, thus forming an islanded zero inertia power system connected to different areas, it is conceivable that new solutions might be required. From a Danish perspective Bornholm is the ideal place for de-risking the application of these solutions where little to now operational experience exists today. It offers a well-established infrastructure, there is no need to place the equipment on platforms or artificial islands, and its geographical location allows to exploit a significant amount of wind potential making the location also attractive from a business perspective.

Figure 14 shows a conceptual drawing of Bornholm after the establishment of the energy island. The main elements of the energy island are located in the bottom half, containing the HVDC converters, the different offshore wind farms as well as the interconnections to Denmark and Germany. Additionally, potential power-to-x plants are indicated as part of the energy island as well as a potential hydrogen transmission towards Denmark, although details regarding location and size of hydrogen generation and transmission are not known yet. The upper half shows the energy system of Bornholm and its potential links to the energy island. Test & demonstration projects on the island of Bornholm can gain access to both the energy island infrastructure as well as the local energy system and allow to test solutions that can provide benefits to either one of them. The same reasons why Bornholm is the ideal candidate for establishing the first energy island also apply for test & demonstration of new innovative solutions that support the development of energy islands of the future. The location allows to directly integrate into the energy island system without some of the space restrictions & cost implications of energy islands placed on artificial islands or platforms.

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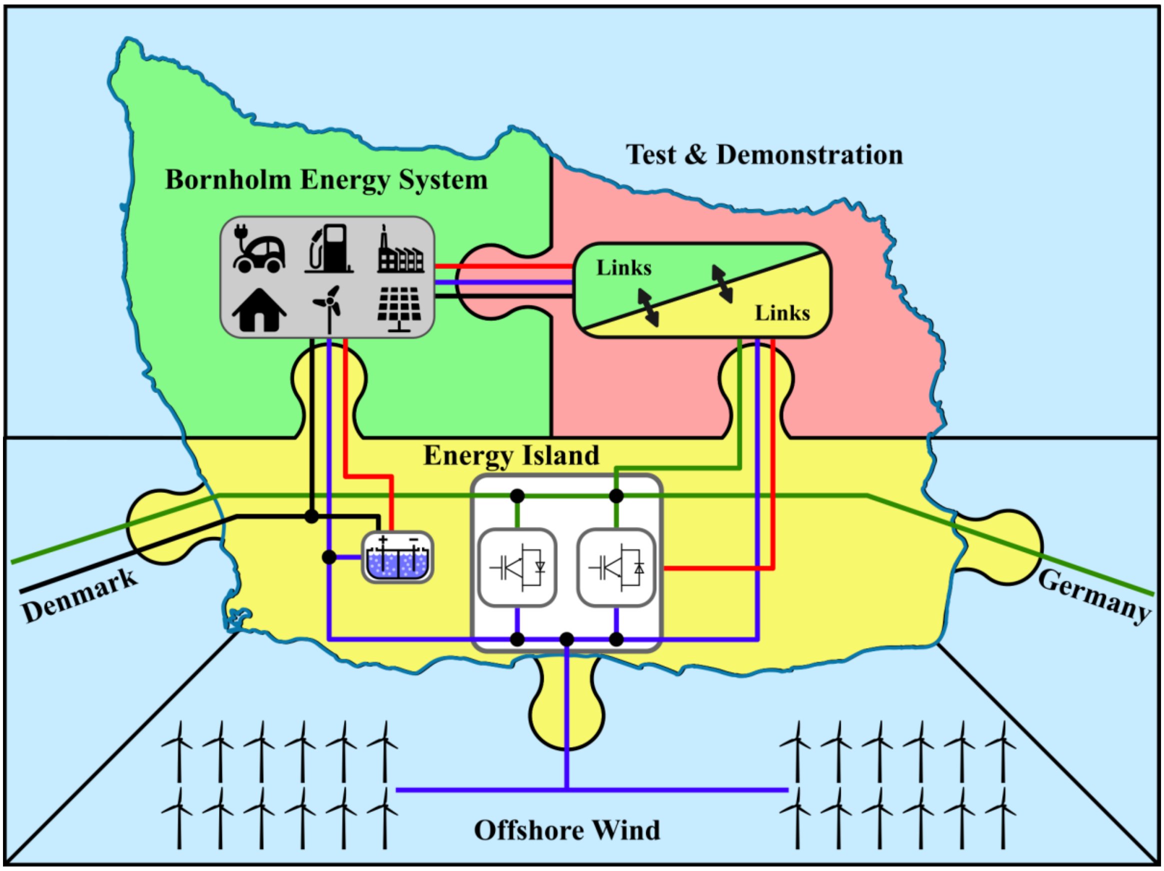

Figure 14: Conceptual drawing for the energy island Bornholm including the opportunity for test & demonstration

The HVDC converters are the main element of the energy island, since they are the elements that provide the connection between wind power and the electricity markets of Germany and Denmark, as well as provide an interconnection between the two markets. In terms of HVDC connected offshore wind, all existing projects in Europe are point-to-point, where a single HVDC is used to transmit power from the wind farm to the shore. A setup where converters, from different vendors, are utilized to transmit power to different locations and exchange power between each other is a completely new scenario. In their business case for the energy island Bornholm [7] Energinet evaluates the options of connecting the different HVDC systems on the AC or DC side. The report concludes, that, establishing a coupling on the DC side is considered as the preferred solution but the AC solution should nevertheless be applied as the initial and fallback solution. This hybrid solution is preferrable since there is not enough operational experience with multi-terminal HVDC systems and the DC solution therefore has an inherent risk that could threaten the reliability of the overall solution. This applies to both, the protection, as well as the control of such systems. To de-risk the application of such an innovative solution the AC solution is considered as a back-up.

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Nevertheless, the AC solution also requires some new approaches in design and control. Parallel operation of AC connected HVDC systems from multiple vendors has an inherent risk of adverse control interactions that need to be eliminated or minimized. This risk is further increased since parallel operation of HVDC systems in islanded systems requires a shared responsibility of the different converters to operate in the so called grid-forming mode. A structure for de-risking has been proposed in connection with the Johan Sverdrup project [8] and is also one of the scopes of the currently ongoing *interOPERA* project.

In terms of the DC solution the whole design, stretching from the busbar design, the protection using DC breakers and the active power and voltage control of interconnected DC systems are unknown territory thus far. Theoretical and analytical approaches for this design have been extensively discussed in the North Sea Wind Power Hub (*NSWPH)* project and are also in the scope of the recently started Offshore Energy Hubs (*OEH)* project, which also addresses the development of new requirements for wind farms connected to energy islands and the energy island optimized integration of power-to-x, both of which, to some extent, could also be envisioned to be experimentally rolled out in connection with the energy island Bornholm. It can be expected that the test and demonstration of the DC solution will provide valuable insights into the performance and reliability of such solution, which will be of great value for the design and operation of future energy islands.

In the following a number of potential test and demonstration opportunities in connection with the energy island Bornholm are discussed. Some of these applications involve physical testing on the island on Bornholm while others are based on data provided by the energy island or present digital solutions for planning, simulation and operation.

It should be noted that there are quite a number of uncertainties, which can highly impact the relevance and the specific design of the individual cases.

1. Some of the grid connection requirements and other functional requirements on the connected equipment are currently under development or review.
2. Technology development is a continuous process and certain technologies, such as power-to-x, currently progress on a fast pace. The state of the technologies at the point of time the energy island is established is therefore uncertain.
3. Currently planned is the establishment of an offshore bidding zone for the energy island Bornholm. The specific design of this market and which products it contains is not yet clear.

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4. It is not yet clear how the local energy system of Bornholm will be interconnected to the energy island.

4.1 Physical tests & demonstration

This section presents opportunities for performing physical testing on the island of Bornholm.

4.1.1 Power-to-x

Power-to-x is perhaps the largest variable in the development of the energy islands. Considering the current pace electrolyser technology is progressing it is difficult to foresee the status of the technology once the energy island is established. Due to its low to zero inertia characteristics the operating environment is substantially different from the current onshore systems which can have an influence on the design, particularly the converter design, of electrolysers. In terms of the energy island specific development of electrolyser solutions and hydrogen infrastructure there are a number of interesting applications to consider in the context of the energy island Bornholm. In the context of the energy island the main questions are:

- How can power-to-x benefit from the energy island? Are there any advantages compared to the placement onshore? If yes, should it be located centrally on the island or integrated in the wind turbines?
- How can the energy island system benefit from power-to-x? Can it offer ancillary services, in particular flexibility, that improve the resiliency and economic operation of the energy island system?
- Do the energy island require new electrolyser designs due to the particular operating environment (zero-inertia, offshore, space restricted)?
- Are there any applications for the byproducts of electrolysis, such as heat and oxygen, offshore?

4.1.1.1 Electrolyser dynamic performance and potential control interactions

The integration of large-scale power-to-x within the energy island electrical system requires the development of suitable models for electrolysers for stability and interaction studies. These models would need to accurately reflect the dynamics of the electrical control, and to a certain extent also the chemical processes involved. In this context it is important to investigate, whether electrolyser designs can be one to one applied in the energy island setting or the overall design and controls need to be adapted to the specific setting. Due to the zero inertia converter dominated system there is a particular risk of adverse control interactions between wind turbines, electrolysers and the HVDC system.

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Application of different electrolyser designs, potentially with new control modes, in a controlled testing environment embedded in the energy island electrical system can help to develop appropriate models and identify potential risks involved in power-to-x integration before roll-out on a large scale.

4.1.1.2 Energy island optimized power-to-x

While the development of power-to-x is also progressing independently of the energy islands there are a number of solutions that are particularly relevant for the offshore application of electrolysers.This involves particular space-optimized designs as the placement of electrolysers on an artificial island or even dedicated platforms limits the availability of space and leads to high costs per square meter occupied by the required equipment. There is an opportunity for Bornholm to position itself as a dedicated testing ground for energy island specific designs. In particular when the infrastructure for hydrogen production, such as storage, transmission or processing solution is already rolled out, as this would allow to reduce the cost of the individual tests.
Furthermore, the economic feasibility of the alternatives to onshore hydrogen production such as on-island and in-turbine electrolysis can be assessed in the real energy island market environment.

In terms of hydrogen transmission, a particularly interesting solution is the combined transmission of hydrogen and electricity and especially designed three phase cables. These cables currently under development make use of the particular space arrangement of three phase cables to fill up the remaining space with either one or multiple hydrogen pipelines, which has potential to reduce the cost of the overall infrastructure. These cables are aiming towards operation on medium voltage, e.g. 66 kV and are therefore ideal if electrolysers are integrated in the collection system of offshore wind farms. This is particularly relevant for future energy islands where hydrogen production might either be distributed on multiple platforms or integrated in multiple wind turbines with in-turbine hydrogen production.
The applications of these specific designs could benefit from the electrical installations and a hydrogen infrastructure on Bornholm.

4.1.1.3 Grid services from power-to-x:

Of particular interest for the operation of the energy island are the potential services that can be provided by electrolysers, especially in terms of balancing the active power on the island. Electrolysers have the capability of ramping power consumptions up or down. This capability can be differentiated between slow, manually activated responses, automated frequency response characteristics on different time scales and grid-forming capabilities that act on angle

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changes rather than frequency changes and thereby provide an immediate response. Which capabilities can ultimately provided by electrolysers depend on the limitations of the overall system stretching from the electrical converters to the chemical processes. While frequency response capabilities have already successfully been demonstrated in traditional onshore grids there is an opportunity to show that the same or even extended capabilities can be obtained in a zero inertia converter dominated system. Physical testing of such solutions is particular needed to assess the potential benefit for energy island operation and to assess the risk of potential stability issues caused by the individual control or control interactions of the different devices in the system.

The implementation of such services into the offshore bidding zone of the energy island would also need to be assessed to make the provision of these services attractive to the owners of the individual assets.

4.1.2 Battery storage systems & STATCOMs

Apart from the conversion of excess electricity to other energy carriers, the large-scale storage of electricity is an essential component of a fully renewable based energy system. The feasibility of large-scale battery storage, possibly in combination with energy conversion using power-to-x, can be evaluated using the test site. There are several major benefits of having battery systems integrated with offshore wind farms. Black start of an offshore wind farm is a complex and time extensive process. Conventional procedure involves energization from the grid side, where components are connected and energized in sequence and it might include auxiliary equipment to provide extra support (for example diesel generators). By employing battery energy storage systems (BESS), the wind farm system can be self-energized and operated as an island before being connected to the grid, thus reducing additional stress that wind farm black start can exert on the grid itself. Moreover, using battery system can reduce the time it takes to bring the system back in operation. As the offshore system is basically operating with net zero inertia, battery system can provide additional support in terms of stability of the system, namely concepts like synthetic inertia, active power balancing, oscillation damping, voltage support especially when battery is in standby mode during which it can provide full rated current as reactive current. Most of the aspects mentioned preclude that BESS would be operated in grid-forming mode, working together with HVDC converters to form, operate and maintain a stable offshore grid. Non-negligible advantage of having BESS connected to the offshore system is the capability of BESS to provide auxiliary power to wind turbines during down time in order to prevent damage to the equipment. For example, powering heating devices to prevent freezing of components at low temperatures, powering dehumidifiers to prevent moisture damage in the nacelle and tower, preventing unfavorable

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orientation of the turbine in high wind conditions, etc. Bornholm would provide a unique opportunity to test all of these concepts on a large scale.

The offshore system is a complex system with large reactive components such as cables and transformers, which requires significant reactive power regulation capability of active and passive components connected to that system. In that regard, static synchronous compensators (STATCOMs) are used for dynamic voltage/reactive power regulation. Besides the voltage and reactive power support, STATCOMs can be employed to provide synthetic inertia. This setup includes either super-capacitor or comparatively high-power and low energy battery system. Moreover, a grid-forming control strategy can be implemented in such a system, which in combination with other components in the systems, primarily HVDC converters, can serve as an additional step towards having a stable offshore system. STATCOM's can provide significant support during black start procedure in terms of reactive power (transformer and cable energizing current is primarily reactive) and suppress harmonics, which is a known phenomenon that occurs during black start procedure.

4.1.3 Integrated systems tests – multi-component tests

While most of the system scale concepts are developed and tested in simulations using dynamic models of the individual components there is still a potential for testing integrated solutions on a smaller scale on real hardware. The purpose of this kind of test would be to assess the performance and viability of the coordinated control solution of different assets. This could for instance include a single wind turbine, electrolyser and battery storage operating in grid-following, grid-supporting and grid-forming mode. An application example of such a solution would be the performance of such an integrated system in standalone mode in case of converter faults of the HVDC system, which during normal operation provides the grid-forming capability, i.e. provides the reference for voltage and frequency in the offshore system.

Currently applied reliability data suggests that non-scheduled outages of a single HVDC pole can be expected approximately twice a year [9]. It is expected that in DC operating mode the individual HVDC converter poles form their own islanded system. That means, that in case of a single converter fault the wind turbines and potentially electrolysers would need to be shutdown if they can only operate in grid-following mode. Auxiliary connections can be provided to other converter poles to reroute the power until the converter capacity limit is reached. However, without grid-forming capability the affected system would still need to be shut-down and black started though the healthy pole. A system that allows wind turbines and electrolysers, eventually supported by energy storage, to operate in standalone mode and facilitates the option to resynchronize with the electric system of another healthy pole could potentially reduce the downtime due to HVDC pole faults.

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Current plans suggest that the local energy system of Bornholm will be integrated in a similar fashion. That is, the system is connected to a single HVDC pole with a backup connection to another pole that can be established in case of faults. However, this would require the local system to be able to operate in islanded mode until the connection can be established. Considering the current situation, at least temporary outages can be expected in such situations and battery storage systems, eventually in cooperation with a STATCOM, could provide a solution for achieving operation without any downtime.

4.1.4 Bornholm – energy island synergies

Bornholm is a particular realization of the energy island concept with some very unique features. The presence of a local community and energy system allows to exploit some particular synergies between the energy island and the local community. In particular, large-scale integration of power-to-x has the potential to exploit some of these synergies, such as waste heat integration into the heating system, opportunities for industries processing or consuming hydrogen. However, these applications are rather unique for the special case of the Bornholm energy island and won't apply to energy islands located far offshore and are particularly addressed in a project dedicated to assessing the opportunities for power-to-x on Bornholm [10]. There are many other opportunities for Bornholm enabled by the energy island as indicated in figure 9, but most of these address the overall energy system and business opportunities that are not applicable in the more general context of offshore energy islands.
One particular solution that is enabled by the converter stations of the energy islands, on Bornholm, the onshore system or more generally wherever there is access to a local network, is the availability of waste heat generated by the electrical losses in the power converters and converter transformers. Converters and transformers generate relatively large amounts of waste heat due to electric losses, which can be partially recovered to either supply the local district heating system or be used in other processes which require heat. Concepts and regulations for harnessing these heat sources and integrating them into heat networks and markets would be beneficial for the establishment of future large-scale HVDC stations onshore.

4.2 Digital and data based solutions

4.2.1 Digital tools for energy islands & offshore DC grids

Each energy island will form their own small power system, in which the connected components need to be coordinated in a proper way in order to operate in a stable manner. Due to their unique characteristics new applications for monitoring, visualizing and assessing the operational state of the on-island network and the interconnections are needed. The primary purpose of such application is to provide a platform for supervision in the control room that

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supports the operators in their decision making but could as well contain automated procedures for assigning specific setpoints and control modes to the relevant equipment.

These control room applications could further contain stability assessment methods, providing stability boundaries and information of the current operating state within these boundaries. The stability assessment methods would need to consider both, the electrical system of the energy island itself, as well as its external interfaces onshore and offshore. This is particularly relevant in a future scenario, where many energy islands might be interconnected and form an entire offshore grid.

Apart from the security relevant operation there is also potential for developing solutions to optimize the operation of the on- and offshore system to achieve the most economical operation considering the security constraints.

First approaches for these solutions could be developed and demonstrated in the context of the energy island Bornholm. The main requirement is the availability of adequate models that accurately reflect the dynamic performance of the interconnected system. This in turn requires the availability of high resolution dynamic measurements that allow to validate the applied models against the real world performance. Further research is required to identify the most relevant stability issues in interconnected DC systems and the particular zero inertia AC systems of the energy islands and develop the methods and tools that provide an early warning and establish suitable countermeasures to prevent these issues.

4.2.2 Energy island model development and validation

Equipment models and simplified model representations of complex systems are used extensively in a number of applications ranging from stability analysis, system planning and optimization. An important step for the feasibility of these analytical approaches is the development of models that suite the desired applications and evaluate their adequacy by comparing the model representation against the real world performance. Operational data from the energy island Bornholm can facilitate the development of energy island specific models of different resolution. While high resolution dynamic measurements, particularly from disturbances, enables the development of dynamic models used for stability studies, long-term operational data can be used within economic models and system planning. This could stretch as far as developing a digital twin of the Bornholm energy island that can be used to test new operational concepts, digital tools and controls as well as optimize the economical operation.

4.2.3 Energy islands and markets:

The Bornholm energy island will form a separate offshore bidding zone. It is not yet clear how this market will be designed and if it will contain the same products as the traditional electricity market. It will be relevant to assess the potential benefits of different services, such as shortterm flexibility or other grid supporting services, for the stability and overall efficiency of the system. The specific cases would need to be designed based on an evaluation of the system needs and potential rewards.

Furthermore, it could be assessed if a joint operation of generation, load and storage has the potential to improve the overall efficiency compared to a decoupled market-based operation of the individual assets.

4.3 Bornholm as an example of the future energy system

Bornholm represents a unique case of an energy island due to the presence of a local energy system which will be integrated into the energy island infrastructure. On a small-scale the local energy system of Bornholm will thereby provide a glimpse of a future energy system relying on massive amounts of wind power, large scale power storage and conversion in form of power-to-x embedded in a system with close to zero inertia. While challenging to realize, there is also a unique opportunity to investigate the potential synergies between this large-scale infrastructure and the local community and industry. The local community can benefit from resources, such as cheap electricity, heat and hydrogen as well as hydrogen derived products provided by the energy island while there is also a large potential of using local resources, such as waste water or CO_2 within the power-to-x related processes. However, the development of solutions for this multi-energy system and the, in the best-case circular, processes that optimize the use of available resources, requires further research and is outside of scope in the context of this project.

5. Potential Setups for Test & Demonstration on Bornholm

In this section specific setups that allow physical test & demonstration in the context of the energy island Bornholm are discussed. Generally, the potential solutions can be distinguished in terms of a centralized and a distributed solution. Centralized testing would take place in a dedicated test site that is embedded in the energy island infrastructure. Distributed testing, on the other hand, assumes that test and demonstration projects are handled individually, meaning that the entire framework for testing, infrastructure, procedures, agreements, etc., are established on a per project basis. In principle, none of these solutions is exclusive and can be realized in coexistence.

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5.1 Distributed testing

Bornholm has a long history as test island for green energy solutions. Traditionally these projects have been distributed across the island and have been individually integrated into the existing infrastructure. The distributed testing scenario would therefore implicate a continuation of the business as usual under different circumstances, i.e. a focus on solutions that are either provided by the energy island and provide value for the local community or that can progress the development of solutions related to energy islands.

The main risk of such an approach is the possibility to directly interface with the electrical infrastructure of the energy island. As the initial setup does not contain a distributed network on the island individual projects would need to establish eventually costly solutions to obtain a connection to the high or medium voltage network of the energy island. Furthermore, additional interconnections, for example to the heating system or hydrogen storage and transmission networks might be required. Additionally, individual agreements regarding the tests to be performed need to be negotiated with the relevant parties, such as Energinet as the operator of the energy island infrastructure and potentially the operators of the local heat & electricity networks.

For these reasons, this kind of setup is mostly suited for projects, which are already intended to continue commercial operation when the test and demonstration is successful. This kind of approach also allows to dimension the interfaces of the demonstration projects specifically to the project needs and avoids the congestion of testing capacity by commercially operating projects. Whether the latter could be an issue depends on the possibility of extending the capacity of a potential dedicated test site at a later stage.

5.2 Centralized testing

In this scenario a dedicated test site in close vicinity to Energinet's converter station is considered and the interface between the test and the electrical infrastructure of the energy island would be established by Energinet, which allows the allocation of a guaranteed connection capacity that can be used for testing. Indicative numbers for the capacity of a first dedicated test site suggest that a total capacity of the connection up to 100 MW with a flexible consumption in the range of multiple tens of MW can be realistically achieved. This would allow sufficient capacity to accommodate multiple electrolysers and wind turbines in the range of 10-15 MW as well as BESS and other assets in a similar power range. The specific details on the arrangement and technical layout, however, would need to be further discussed with Energinet. Testing would have to follow a code of conduct to be agreed upon with Energinet,

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but a relatively high degree of flexibility can be expected in that regard due to the large capacity of the system at the point of connection.

The clear benefit of the centralized solution is, that a connection to the energy island infrastructure could be established already in connection with the construction of the converter station and operation could commence as early as the HVDC system is operational. The dedicated test site concept further allows to construct a centralized interface with a potential hydrogen network and provide access to one or more of the district heating systems. This centralized approach would reduce the cost compared to the single purpose individual infrastructure of the distributed testing approach. Additionally, the clearly outlined specifications within the code of conduct allow a fast-track from project idea to realization as no lengthy negotiations regarding allowed testing procedures are necessary.

Two particular realizations of such a dedicated test site are indicated in figures 15 and 16. The simple approach in figure 15 illustrates a direct connection of the test site to the high voltage bus of the energy island through a transformer. The voltage level of 66 kV of the test site system is deliberately chosen as it is assumed to be the standard voltage of medium voltage collection system for offshore wind farms in the near future and allows to integrate a standard solution for components designed to operate in an energy island environment. However, if other voltage levels are deemed to be more reasonable there will not be any impact on the overall concept.
The direct connection implies that the conditions at the interface always represent the current operating condition of the energy island systems. This kind of solution is advantageous if the scope of the test is to assess the performance of components in the regular operation environment.

For testing advanced control concepts it might, however, be beneficial to be able to artificially provoke certain operating conditions. This is particularly the case when equipment is specifically designed to support the system under stressed or otherwise abnormal conditions. For these kind of tests the system presented in figure 16 could prove more beneficial. A back-to-back converter allows to decouple the operating conditions of the energy island and create artificial conditions that can reflect any kind of intended operating point at the interface of the components. An application example for this approach could be the test of automatic frequency activated active power balancing services that could be triggered by operating the back-to-back converter in grid-forming mode with the desired frequency characteristics, for example a fast ramp-up reflecting a sudden loss of transmission capacity. Furthermore, this setup is suitable for performing tests of multiple components meant to operate in a coordinated manner, where the back-to-back connection would reflect the intended operating conditions of

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the external interface of the subsystem in this particular test case. For example the response of a combined wind turbine, electrolyser and battery setup with either one or multiple of them operating in grid-forming mode subject to a sudden change in voltage angle.

While the converter solution clearly comes with a higher investment cost due to the additional infrastructure needed it allows to perform significantly more advanced tests and is the only solution to purposefully test the performance of components or small integrated systems under stressed conditions. Which of these solutions can finally be applied is largely dependent on the setup, regarding ownership and funding of the test facilities, which will ultimately define the available budget for the realization. There is, however, nothing that would restrict a modular development of the test site. Starting from the simple directly-connected setup in figure 15 focusing solely on integration in the electrical and later extend towards a converter-connected solution similar to the system indicated in figure 16 and providing access to hydrogen and heat infrastructure.

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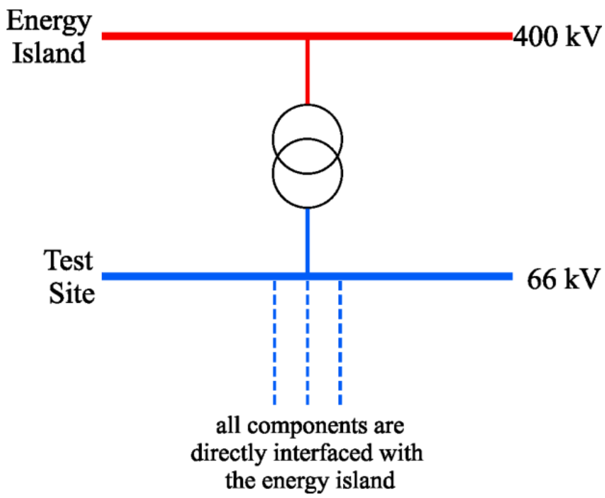

Figure 15: Test site connection without the converter option

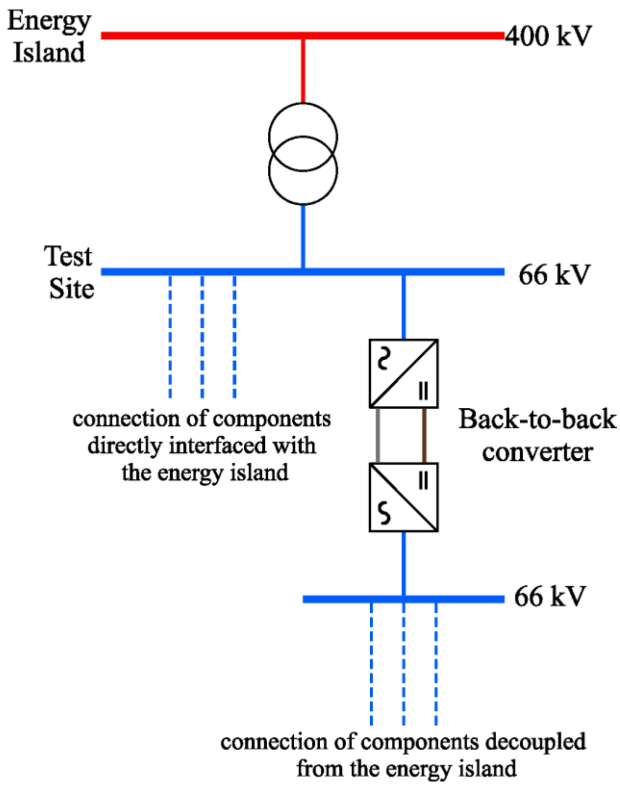

Figure 16: Test site connection with additional back-to-back converter

6. The road to 2030

The energy island of Bornholm is expected to be fully functional by the end of 2030, when the commissioning of the offshore wind farms is finalized. However, some form of testing might already be commenced as soon as the point of connection of the electrical infrastructure is established, which is currently estimated for Q1 2029. Until then small-scale solutions can already be tested on Bornholm. Small electrolyser solutions in the range of a few megawatts can be integrated in the current energy system and grid services such as frequency support can be tested in the current operating environment.

Of particular interest, both for the current situation, as well as looking ahead, would be a solution that would allow Bornholm to operate in islanded mode without having to rely on the conventional units currently needed to stabilize the grid in such situations. One of the promising solutions is the deployment of a large battery storage system that can provide grid-forming functionality that could potentially allow Bornholm to operate in islanded mode, solely relying on renewable energy sources. If such a solution is successfully demonstrated it could

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increase the security of supply for of the local energy system, both currently, as well as solve a part of the challenge of integrating Bornholm into the energy island infrastructure.

7. Conclusion

This documents provides an outlook into the potential future of Bornholm as a test and demonstration site for energy island technologies. Starting from the demonstration of the first ever Danish energy island, involving a new, innovative design from scratch that already pushes ahead the technology readiness level of several of the involved technology solutions to the opportunities of further progressing technology solutions that will enable even further innovation in the future.

An initial assessment of the aspects of energy island technologies where the energy island Bornholm has potential to provide a significant contribution through test and demonstration of new concepts, tools and components is provided. The focus is here dedicated towards energy island solutions that advance energy island technologies in general rather than the individual solutions of the specific case of the energy island Bornholm.

Finally, potential setups how testing and demonstration on the island of Bornholm can be facilitated are discussed. The distributed option, where testing occurs in suitable locations distributed throughout the island. The alternative is the centralized approach, where a dedicated test site provides direct access to the energy island infrastructure through a transformer and the most flexible option consisting of the direct connection but with the option to decouple the test system from the main system by means of a back-to-back converter, allowing to emulate a wide range of possible operating conditions.

There are many opportunities for testing but at the same time there is still a large uncertainty in multiple layers of the energy island design and operation. The specific requirements on the integrated components are not yet fully developed and an assessment of the potential merits of advanced concepts on the component level that go beyond the current state of the art requires further research. Ultimately, the decision how to facilitate test and demonstration on Bornholm comes down to the scope of the test and demonstration to be performed, the available funding and a strategic decision which aspects in the development should be prioritized.

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