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The Energy Islands: A Mars Mission for the Energy system

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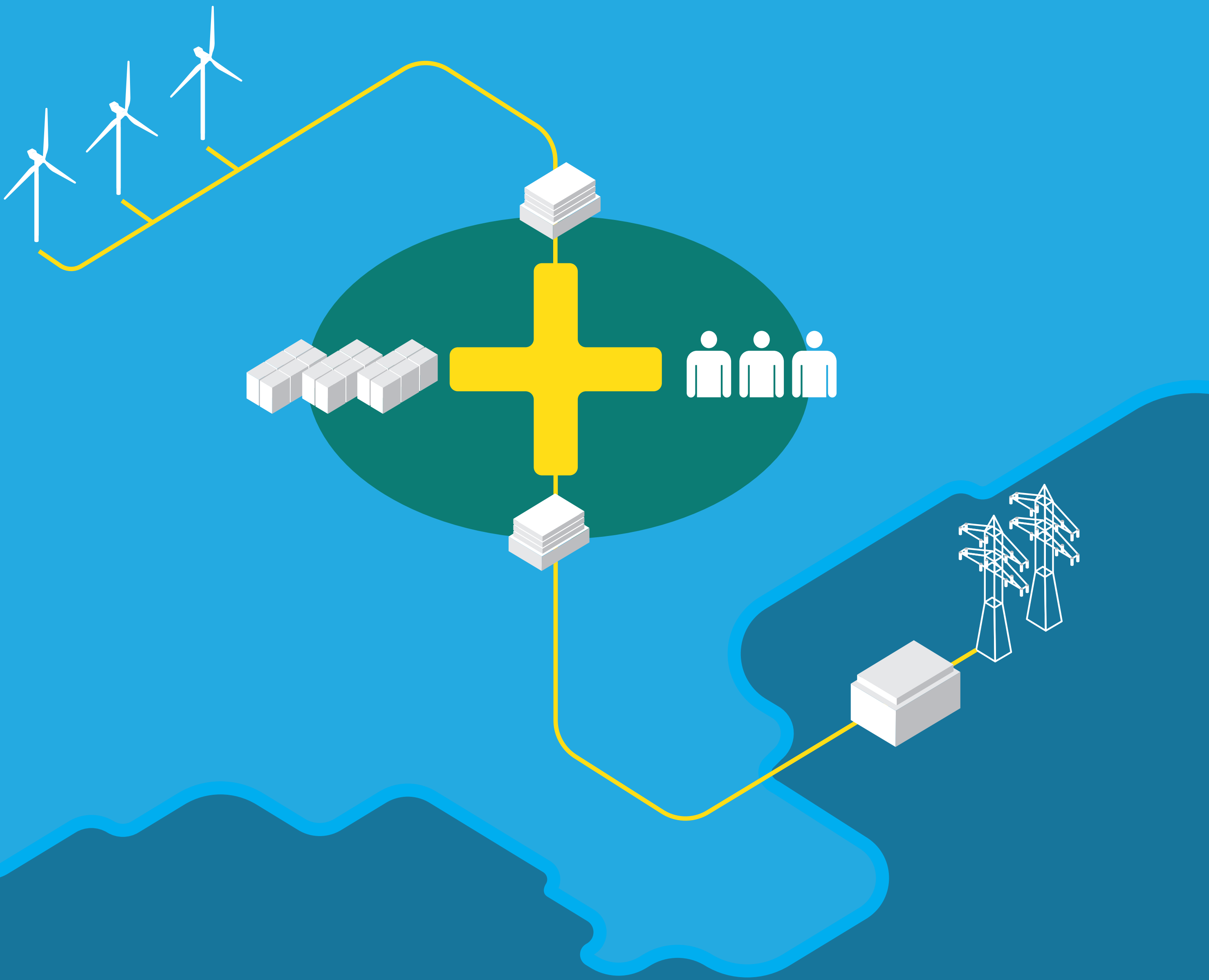
The Energy Islands



A Mars Mission for the Energy system

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A Mars mission for the Danish energy system

Denmark has set ambitious targets, to reduce emission with 70% by 2030 and become independent of fossil fuels by 2050. To achieve those targets, Denmark is planning to accelerate the de-carbonization of the power system, by replacing fossil fuel generation plants with renewable energy sources (RES). Offshore wind power will form the backbone of power generation in a decarbonized system. Already world leading in electric consumption share covered by wind power, Denmark plans to install an additional 6.8 GW of offshore wind by 2030, quadrupling the 1.7 GW already connected to the system.

To facilitate a cost efficient connection of such massive amounts of offshore wind power, Denmark is revolutionizing the grid connection concept for offshore wind. In 2020, the Danish Parliament decided to develop and build two energy islands: one on the natural island of Bornholm in the Baltic Sea and a second as an artificial island in the North Sea. Both projects are very ambitious, but the North Sea Energy Island is particularly so. On completion it will become one of the largest energy hubs in Europe, with a target of 10 GW installed capacity in the long term (double the 5 GW power plants operating today).

The construction of two energy islands by 2033 is the equivalent of a Mars Mission for the Danish energy system. Firstly, because the gap between the cost-effective solutions we need and the solutions we have is still significant. Secondly, because it will require the combined innovation power of the public and private sector to design, plan, build and operate the islands in a cost efficient and reliable way. And thirdly, because the islands will be live test laboratories for the change that will shift the entire energy system in Denmark (and globally) in the coming decades as we head towards 100% independence from fossil fuels in 2050.

A particular challenge in the development of the energy islands is to design and build an electrical infrastructure that can operate with 100% renewable electricity. Each energy island will be an “electron metropolis” where electrons charged by offshore wind’s kinetic energy move through grid lines, will be traded on markets by multiple vendors, and eventually reach the mainland to directly power consumers or to separate molecules in power-to-X systems and green fuel technologies.
These electron metropolises will have to operate systems of generating, selling and transporting gigawatts of electricity with milliseconds of precision. Unlike traditional power systems, a 100% renewable system powered by wind does not have any system inertia to help balance the grid if energy supply suddenly drops.
New solutions will have to be developed and matured to enable this. The challenge this poses has not been widely recognized. This white paper provides an overview of the main technological challenges that we face to build energy islands and offers recommendations for how to address the challenges in a way that utilizes the unique learning opportunity of this “Mars mission” for the Danish energy system.

A unicorn of the fully decarbonized energy system

The challenge in building the North Sea energy island goes beyond its massive scale and the brick-and-mortar aspects of constructing the island itself. From an electrical perspective, the island is a unicorn of the fully decarbonized power system of the future. Its electrical infrastructure will consist solely of inverter-based resources (IBR), representing an electrical system with very little or even none directly connected mechanical masses. While the technology, to build such a system is largely available already today as individual components, combining them into a system of the scale of the energy island raises challenges at every step: how to design it, how to operate it, how to integrate it and how to expand it in a safe, seamless, robust and efficient manner?

Energy hub: *A geographically located system where production, conversion, storage and/or consumption of multiple energy-carriers (primarily electric energy in this case) is carried out and are characterized by some degree of local control.*

Inertia & inverter based generation: *Inertia (in power systems) is the energy stored in large (rotating) generators and which gives them the tendency to remain rotating for a period after the power is turned off. Inverted based generation, with their use of power electronic converters as interface between the rotating machine (e.g. wind turbine rotor) and the power grid, do not have the tendency to remain rotating. This removes the inertia, and hence takes away the energy buffer available in traditional power systems. Turning of power will consequently result in an immediate power drop.*

The stakes of operating a 10GW energy island are high: a failure that would cause 10GW of wind power in the North Sea to drop off the grid could potentially black out the entire European electricity system.

Many of the necessary solutions required to enable a cost efficient, stable, reliable and resilient operation of the energy islands have not yet been demonstrated at commercial scale. The standards and grid codes are not developed, and we see a series of potential 'chicken and egg' issues where the developer of the energy islands needs to know the potential solutions from suppliers while suppliers await further specification from the developer.

Embarking on this Mars mission is challenging, but also rewarding. It offers a unique opportunity to accelerate the development of clean power systems and provides us with a better understanding of how a decarbonized power system could look like in the future.

Innovation opportunities

The challenges we face in constructing the electrical infrastructure of the energy islands are opportunities for innovation. The success of Danish wind power or district heating are examples to follow. The energy islands can be a platform for a range of stakeholders to learn and innovate. New solutions can be tested, competences build up, solutions and services matured and regulation and legislation adapted. In this chapter, we break down the multitude of potential innovations into four main categories: How to design, operate, expand and integrate the energy islands.

1. How to design the electrical systems of offshore energy islands

The energy islands will provide a significant share of Danish electricity generation and play a key role in the power system. It is therefo re essential to ensure that the islands can deliver stable and reliable power to the grid. Reliability and stability, however, are not enough. The system must also be resilient. It must be able to withstand extreme or rare events that can bring down the entire systems or part of it.

Advanced software models are essential tools for the design, construction and operation of electrical infrastructures at this scale. Due to the complexity of the energy islands, current software models lack the required details and validated accuracy, which may lead to large design errors. This inaccuracy can either result in excessive safety margins in the design and construction, which will increase the cost, or it can reduce the grid security. The latter may in the worst-case result in blackouts or force the disconnection of equipment for long periods in order to eliminate problems. Since the energy islands will be a critical part of the energy system, this could have severe effects on the entire Danish grid.

Important choices need to be made from the start, without the advantage of previous experiences and procedures. For example, the choice of the electrical topology and technology now will have a huge impact on the subsequent range of expansion options and decisions. Yet, these choices are supposed to be done using currently available models and simulation tools that are largely unable to provide accurate results. The design of such a complex infrastructure is highly multi-dimensional and multi-faceted, involving topics like:

Adequate simulation models: A range of simulation models are used to continuously assess different phenomena and scenarios. The novelty of the energy islands raises the question of we ensure the usefulness, validation and updating of these models over a period of several decades?

System resilience: Resiliency is assessed using three main parameters: damage prevention, system recovery and survivability. Standard metrics for such assessments are currently lacking. Combined with the uniqueness and novelty of the energy islands, this results in a difficult risk assessment of the system resilience.

Balancing system resilience and future development

The layout of the system and the choice of technology must be able to ensure a resilient grid while not limiting future expansion plans, the entrance of new vendors or the use of new technologies. The latter includes different types of cables, offshore masts instead of submarine cables or new HVDC controls that can reduce the cost and increasing system security.

Data confidentiality and cooperation. How do we approach confidential data in a project that requires cooperation with many different vendors and other stakeholders, considering the impossibility of referring to common procedures?

Power-to-gas plants operating either onshore or at the hub. There is little experience today with the operation of large-scale power-to-gas plants.

Last but not least, a variety of very complex phenomena that currently have not been considered or a simply unknown could occur at the energy islands. The unknown unknowns.

2. How to operate offshore energy islands

The Danish energy islands will be first of their kind, requiring a design from scratch of "extreme power system" that will have unprecedented characteristics. The 100% inverter-based generation will result in extremely low short circuit power and the system will have very low or even zero inertia. In addition, it will include multi-ter- minal, multi-vendor HVDC and a multi-owner construction that will gradually expand over time. Such a system will have many technically challenging characteristics, which require new solutions for ensuring stable and normal operation of the energy islands. New control strategies are needed to ensure the active power balance in the system and to provide needed resilience against disturbances when inertia is very low or even zero.

The fluctuating nature of wind power production implies that traditional offline approaches for ensuring a secure system operation will become insufficient. The dynamic nature of the system operation results in a need for approaches that provide real-time situational awareness and are able to trigger automatic reactions to ensure stability, and quantify the impact that possible contingencies would have on operational stability. A specific challenge here is the need to account for the limited knowledge about the detailed dynamic behavior of converters.

For the operation of the energy islands, it will also be essential to have the right methods for determining effective mitigations and countermeasures need to cope with critical operating conditions.

Stability: *The ability of an electric power system to regain a state of operating equilibrium after subjected to a physical disturbance. The electric transmission system needs to maintain the balance between production and consumption (keeping the frequency at 50Hz). If this balance is temporarily disturbed, i.e. a big load is connected/- disconnected, a stable electric power system will be able to restore it (bringing the frequency back to 50Hz) by increasing/decreasing the production accordingly.*

Resilience: *The ability of an electric power system to withstand, adapt and recover from low-probability, high-impact natural or artificial disasters. This could be a very strong storm that would shut down all wind production and potentially lead to a system black-out.*

Critical operating conditions will primarily be cause by three types of events that have a low probability but a high impact (LPHI). Firstly, power system stability issues coming from low inertial characteristics of wind systems and harmonic interactions will challenge the system security. Secondly, natural disasters will test the resilience of power systems. And lastly, cyber-attacks targeting wind plant control, or the energy island operations can jeopardize the operation. The failure occurrence at any component of such a complex system of wind plants can cause either low impact (local issues) or high impact (cascaded outages) which in turn deteriorate the overall reliability of the energy island.

The methodologies should address new power electronic technologies and their failure characteristics, stability issues, and LPHI events effect on overall system risk. Then, new approaches should be introduced to improve the system security in terms of sudden disturbances and cascaded outages under different operating conditions. Moreover, new software and hardware solutions are required for enhancing system resilience by improving system resistance, recovery capability and restoration.

3. How to expand offshore energy islands

At the moment a lot of efforts go into having the energy islands ready for operation by 2033. However, once constructed they will exist for much longer and will accommodate significantly larger shares of generation (offshore wind power) and, possibly, consumption (power-2-gas facilities). The North Sea energy island will be built for 3 GW but must be designed to expand to 10 GW.

The energy islands represent a significant change in the paradigm of how offshore connections have been built up until now. Current offshore connections are built between single production units (a wind farm or an oil/gas platform) and a power system entry point. There is consequently no experience of offshore connections having been reinforced or altered for system expansion once they are in operation.

The energy islands changes this. From the design phase, the electrical infrastructure needs to be modular, scalable and robust. Adding new components should be seamless, efficient and be friendly to existing infrastructure without introducing any adverse interactions.

The nature of this challenge becomes apparent when you consider the continuous pace of technology development in areas such as power electronics. The initial design should be scalable, i.e. be able to accom- modate more units with their own control without the need of a substantial retrofit or redesign. At all stages, the technology choices must allow a high degree of freedom and not limit future expansions with more intelligent solutions, while assuring a high resiliency.

Another critical challenge in enabling the expansion of the energy islands is to ensure that system compo- nents can "speak" to each other. This is called interoperability. Offshore energy islands will include a sizeable number of power electronic units, either as converters in the wind turbines or as large HVDC converters.

(HVDC) Converters: *A power converter processes and controls the flow of electrical energy. An HVDC converter is an active device converting electric power from high voltage alternating current (AC) to high voltage direct current (HVDC), or vice-versa.*

Multi-terminal: *A system that comprises three or more interconnected terminals, i.e. converters*

Multi-vendor: *HVDC converters from different manufacturers (vendors), each with proprietary control system.*

Power electronic converters are versatile and flexible units, with complex and sophisticated control algorithms. Operationally, they are (almost) fully defined by control (software) rather than physical characteristics (hardware), with the latter mostly defining their limitations. In their final form, the electrical system of the offshore energy islands will include multiple wind power plants and HVDC converters from multiple manufacturers, and their control systems are vendor-specific and confidential. Consequently, a system (wind power plant) or component (HVDC converter) needs to interoperate effectively with other systems and/or components from a different vendor.

The challenge here lies in developing a process for ensuring the interoperability without requiring full disclosure of the detailed converter control from the manufacturers while already acknowledging that converter control software (and even hardware technology) is likely to be significantly different in 2030 compared to today.

4. How to integrate offshore energy islands into the (Danish) energy system

The energy produced on the islands, either in form of electricity or other forms of energy, will be traded in the markets. Learnings from former projects in Denmark related to integrated energy systems, shows that it is crucial to develop proper coordination mechanisms among energy markets, including a market for electricity and hydrogen. Without such mechanisms, the power system will not be able to fully exploit the existing flexibility in other energy sectors, in particular the flexibility of power-to-gas assets.

It is of importance to develop proper "market-based" coordination mechanisms among energy sectors (electricity, heating, gas/hydrogen), which can be obtained by defining new market products, and/or introducing new market players at the interface of energy systems and/or defining new bidding formats. In addition, the physics of integrated energy system including power-to-gas assets need to be properly represented in the market-clearing problem, while keeping such a problem mathematically straightforward for deriving efficient prices.

Both energy islands will become the largest single generation units in the Danish power system. Combined with the inherent variability of their wind power production, they will single-handedly challenge the supply-demand balance of the Danish power system. Current power system mechanisms for redundancy and security of supply dealing with failure of largest single unit(s) are not able to deal with the scale of the energy islands. While some of the challenge can be addressed by incorporating redundancy in the design of the electrical infrastructure, it is likely that these mechanisms will need to be reconsidered and adapted.

With the abundance of cheap, green electricity production from (among others) offshore wind power, electrifi- cation is the obvious and natural step to be taken in the transition to de-carbonized energy systems. Electrifi -cation alone will not be enough. That is why hydrogen is currently viewed as a future cornerstone to a fully integrated energy system, connec ting renewable electricity to green fuels for sectors such as heavy-duty vehicle transport, aviation, shipping, and the steel industry, still dependent on fossil fuels and for which equally energy-dense green fuels are required. The production of these fuels could be an integrated part of energy islands.

Interoperability: *The ability of a transmission system, its subsystems, and components to work together seamlessly, enabling the transmission of electrical energy with the required quality and required security of supply. The electricity system is constantly evolving due to innovations and grid requirements and enabling a system that can adapt to future innovations is therefore important.*

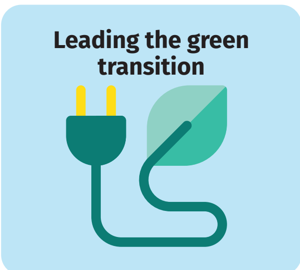
A unique opportunity to learn, to grown and to show the way towards a 100% decarbonized energy system

12 years from now, in 2033, a Danish minister will cut the red ribbon and declare the opening of the North Sea energy island. We have 12 years from now to close the gap between the solutions we have and the solutions we need to ensure a safe and reliable 'touch down' in 2033 for this Mars mission for the Danish energy system. Offshore energy islands can teach us how to design and operate the de-carbonized global energy system. This offers Denmark a unique opportunity, but three actions are needed to benefit from this:

We need a discussion in the broader stakeholder community to increase awareness and understanding of what the upcoming challenges are. How do we address them both at the energy islands and more general at Danish energy system level, as we move towards decarbonization?
The discussion should be centered on the importance of this for society at large. The energy islands are concrete, easy to visualize examples of the energy transitions. We can use that to communicate the green transition to the public. The islands also represent an extreme version of the power system – what we called the electron metropolis in the introduction – which helps clarify why solutions for resilience and reliability, interoperability and modularity are important.

This decade of designing, planning and building the energy islands is a unique opportunity to learn and build capacity. We can attract and train engineers, technicians, regulators, and businesspeople in how to create a decarbonized energy system.

We should do so through research and demonstration both at lab scale and in demonstration projects supporting the technology and service development. Education will also be key. The lessons we learn should benefit students in all fields from engineering and digitalization to regulations and environmental studies, but also students in vocational training who will eventually be working in the day-to-day construction and operation of the islands. Training and education should also extend to training activities for company employees as well as those who wish to make a career in the green sector.



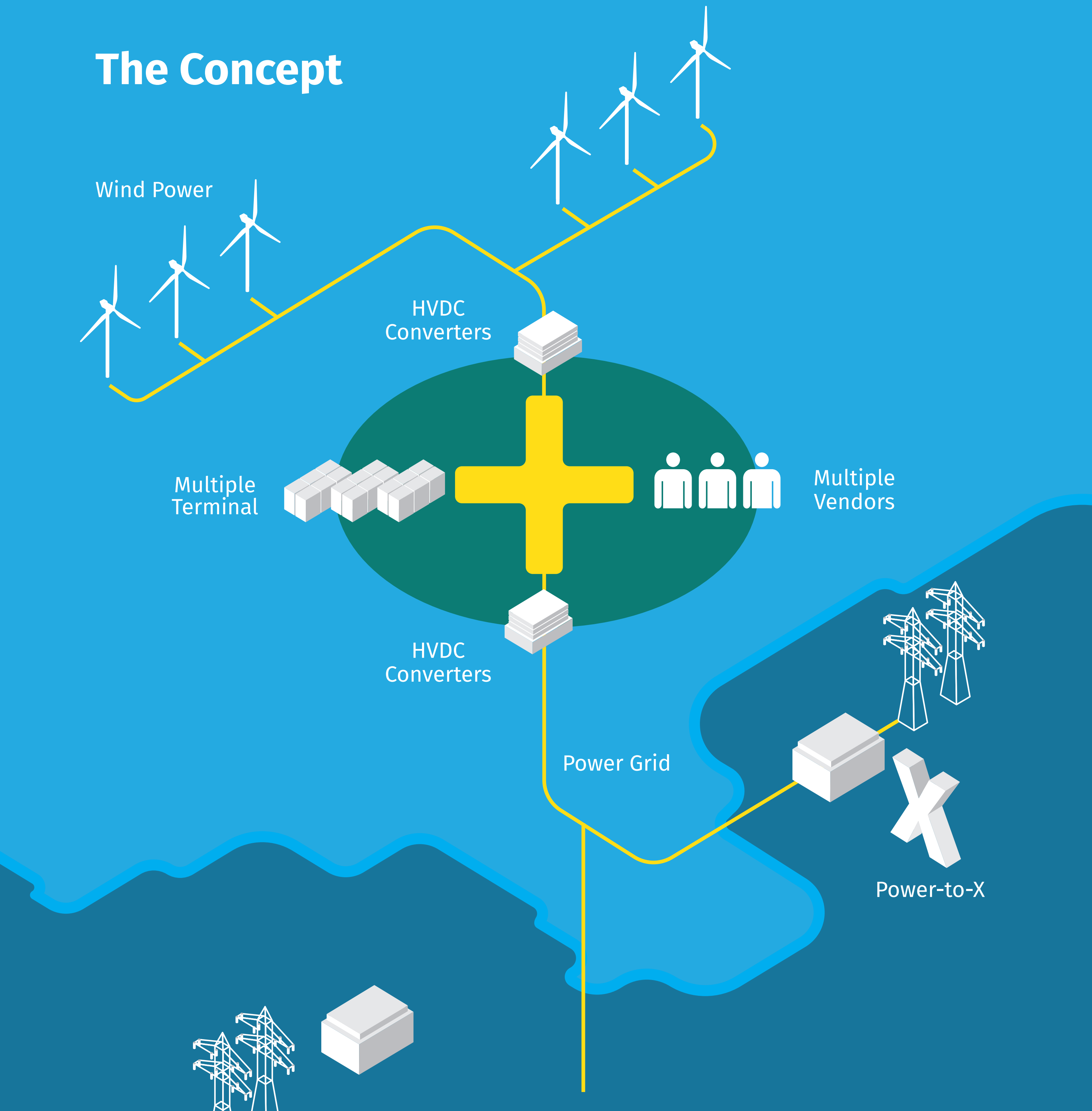
Offshore energy islands represent an opportunity for re-affirming Danish leadership in the green energy transition. Once again, Denmark can lead the way into a new era of offshore wind development and use the experience to assist other countries leapfrog the development.

Today, Denmark is the destination for international delegations who want to learn from our experience in wind energy, district heating and system integration to mention a few areas. As we develop the energy islands, this will extend to visitors who want to learn from our experience of building the energy islands and how to operate these electron metropolises.

Successful deployment of the offshore energy islands will consequently also enhance Danish competitiveness and exports. While the energy system itself is not an export product, many of the components and services will be.

Combined, the energy islands offer a unique opportunity for companies to develop innovation technologies and services, for politicians, regulators and TSOs to develop the framework required to run the energy islands and for universities and research organizations to research and develop new solutions to be used for the energy islands and beyond, educate the engineers to implement them and share knowledge with the world to advance the green transition around the globe.

The Concept



Energy islands are hubs connecting multiple offshore wind power plants to the power grid using multiple HVDC converters from different vendors. They may also host storage and power-to-gas conversion units.

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