Do Energy Islands support the Green Transition?

Energy islands are an emerging concept in the Nordic countries and predominantly in Denmark. They represent the idea of constructing large wind farms far out in the sea and placing energy conversion and storage technology such as electrolysers, ammonia production, and batteries nearby. The concept is novel to the sector and delivers a perspective on post-fossil fuel large-scale energy supply. This article is based on Lüth (2022) and related research, and it reflects and highlights the insights that are of relevance for the development of the Danish energy islands.

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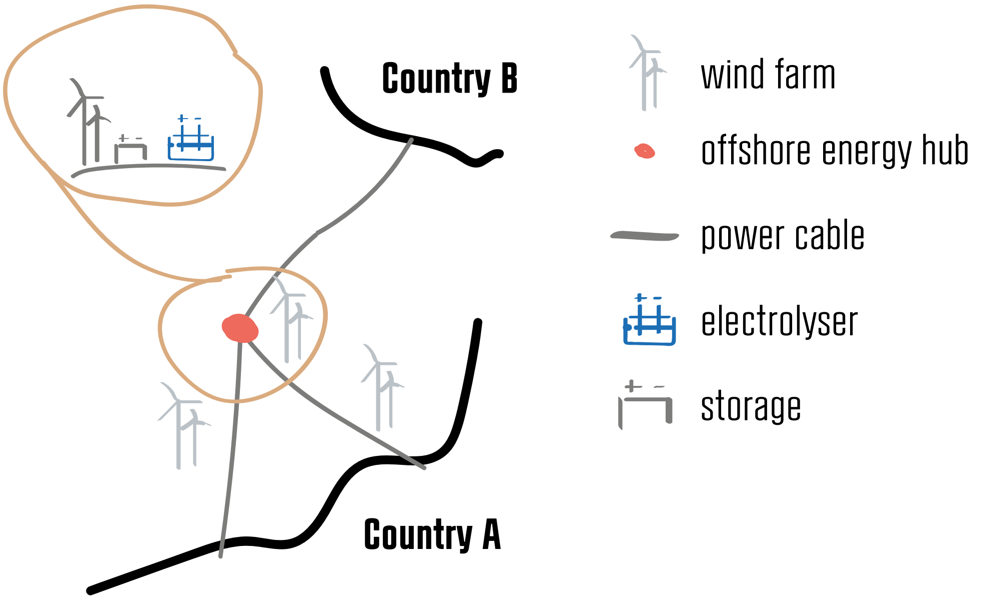
The green transition in Denmark is an ambitious process and goal. To achieve 70 pct. emission reduction by 2030 and mostly clean energy latest by 2050, large renewable energy supply capacities need to be built. As part of this plan, the Danish government announced in 2020 that it would support and require the development of two energy islands in the Danish waters of the North and Baltic Seas. These projects are envisioned as contributing with their large capacities to the expansion of renewable generation, bringing energy storage and stabilising market prices. With the current energy supply crisis and market price peaks, such large-scale projects seem a promising tool to stabilise future renewable energy-based systems with the hope to no longer rely as much on fossil resources and trade that may be subject to geopolitical challenges.

What are energy islands, and what can they deliver?

Traditionally, the energy system in Denmark was developed around large-scale coal or gas-fired power plants that can supply vast amounts of energy in the form of electricity or heat. With the goal to reduce greenhouse gas emissions, Denmark has started to transition its system into a wind- and solar-based system which is accompanied by biomass and biogas technology. This transition in technology started a paradigm shift in the Danish energy supply. Fossil fuel-based power plants operate from a centralised point at a large scale with certain production and variations in fuel prices. Wind and solar technology, however, are small in unit size, located far from demand, produce only when wind or sun are available, and have no fuel costs. Due to their volatility in supply, wind and solar technology must be accompanied by flexible technology. Such flexible technology in a renewable energy-based system will, in the Danish context, mostly be battery storage, thermal storage, hydrogen, demand-side management, interconnection to surrounding countries with hydropower, and power-to-x technology. The latter describes a concept that produces a variety of products from electricity and amongst others hydrogen. Hydrogen produced from electricity through so-called electrolysis is especially valuable when the electricity is purely from renewable sources because it then serves industry, maritime transport, and long-haul trucking as an alternative to fossil fuels.

Figure 1: A stylised illustration of an energy island. Source: Lüth (2022, p. 19).



In the process of developing joint solutions for emission reduction in the energy supply industries, renewable solutions that have characteristics of large-scale power plants emerged in the Northern European context as the concept of energy islands suggested by the North Sea Wind Power Hub consortium in 2016.[1] Figure 1 visualises such an energy island project in a stylised way. The energy island projects are planned to evolve in the centre of several offshore wind farms and include the construction of an island-like ground to host further technologies, such as electrolysers, storage, and fuel supply technology. The idea of energy islands describes assembling large-scale offshore wind farms around an artificial hub that hosts storage and power-to-x technology, or in other words is defined as,

> *"a fully renewable energy resource-based combination of assets that link at least two services, such as electricity generation, interconnection, and offshore storage. These services are relevant to energy system development and operation and foster decarbonisation of the energy sector while preserving the environment." (Lüth, 2022, p. 19)*

The current timeline for the Danish energy islands foresees energy supply starting in 2033. Tenders for wind parks and the construction of a potential artificial island in the North Sea and space on Bornholm will be announced in early autumn 2023.

Energy islands in their current vision and with the details outlined promise a large supply of renewable electricity and derived fuels. First and foremost, developers envision electrolysis to happen on energy islands. Electrolysers placed on the energy islands can benefit from a cheap and steady supply of electricity from the surrounding offshore wind farms to produce hydrogen. Renewable-based hydrogen is discussed as a suitable and required source of energy to decarbonise heavy industry, maritime transport, and long-haul trucking. Successful construction of large-scale electricity and hydrogen supply hubs, thus, can contribute to abating CO_2 emissions in hard-to-decarbonise sectors.

Secondly, with its suggested locations far out at sea, the wind farms around the islands benefit from stable winds offshore. Through cables connecting the islands to shore, they serve as a link and distributor of renewable energy and become an important asset in interconnecting wind resources as well as several countries. This facilitates market integration to stabilise the inner-European renewable energy supply. Market integration and better interconnection can deliver more stable prices (Li & Mulder, 2021) and help to balance renewable supply across Europe.

How can energy islands be integrated into energy systems and markets?

Energy islands out at sea need to be integrated into the energy system and there are various options to do so. Cable and pipeline connections to exchange electricity and renewable gases are the first to come to mind, but also shipping of renewable fuels produced offshore is a potential way of integration.

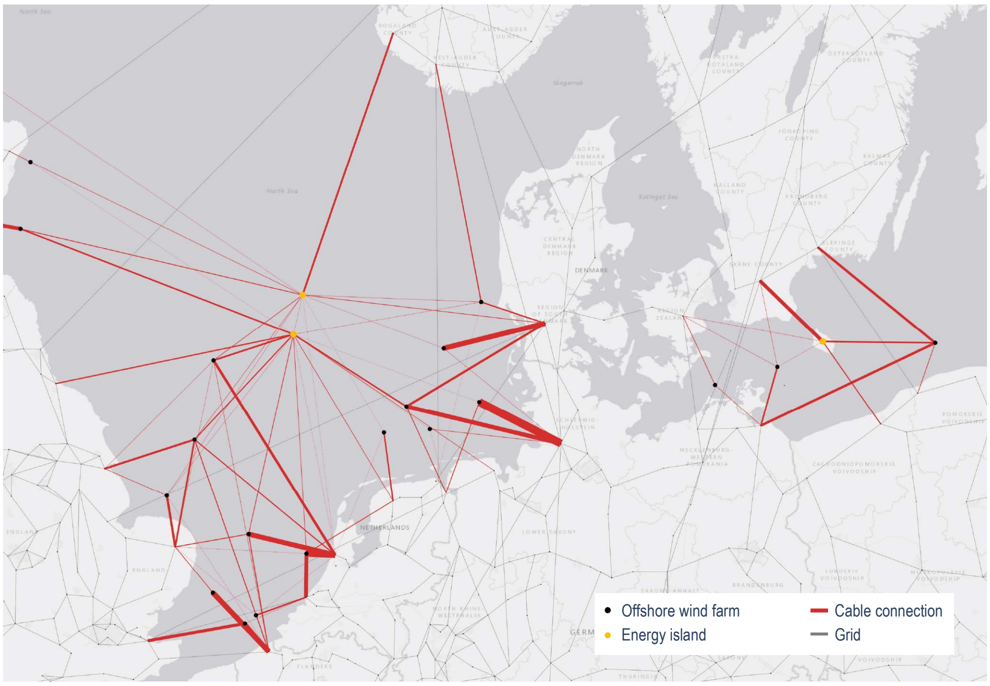
To provide initial insights, in Lüth et al. (2023) we suggest that the system is likely to integrate close-to-shore wind farms and to build electrolysers at small gigawatt sizes close to the links between onshore and offshore electricity cables (so-called landing points) to harvest excess electricity. We also show that energy islands can be integrated with onshore electricity systems via offshore wind farms rather than directly. In this way, they can become importers of offshore wind energy in periods of strong wind and still deliver electricity to onshore systems directly when close-to-shore production is low. This follows a body of literature analysing future connections of wind energy and concluding that combined grid solutions such as Kriegers Flak will become more relevant (see, e.g., Marten et al., 2018). In a further step, energy islands can become an integral part of an offshore grid. Offshore grids can support the efficient use of offshore renewable resources (Strbac et al., 2014) and lead to higher interconnection, which supports fully renewable systems (Schlachtberger et al., 2017; Spiecker et al., 2013).

While technical system integration needs to stay feasible, the importance of integration with the existing energy system on market design is crucial. Once the technology is placed on the island, it should be used efficiently. Market design often invites investments in some technologies more than others and, thus, drives investment decisions. Currently, prices in Europe are set in zones, which in an ideal case would be designed to reflect bottlenecks as zonal boundaries. Recent debates shed light on the problem that the existing zones may not reflect network constraints well enough (ACER, 2022). With increasing activity offshore and the common approach of integrating wind farms into their home countries' or owner countries' market zones, we would move further from price zones set according to bottlenecks. For energy islands, this could lead to expensive measures to avoid congestion on power cables and impact the value of offshore hydrogen production (Lüth et al., 2022). The value of electrolysers offshore increases if an energy island constitutes its market zone, i.e., sets a separate electricity price for local production. In many hours, a separate price for the energy islands might lead to lower costs for electrolysis and thus cheaper production of hydrogen. The study by Lüth et al. (2022) also examined whether electrolysers as technology can contribute to stabilising volatile production from wind and sun by adjusting their level of production to the availability of renewable electricity. Technically, electrolysers can deliver such services to stabilise production, something they can also do when located on energy islands. However, the use of large-scale electrolysers solely for the purpose of reacting to the availability of wind energy is not yet a standalone business case.

Looking at the current planning for the European projects, there are notable differences between the industry projects and our recent study. The main difference is the envisioned way of connecting the islands to shore. Whereas we suggest a well-interconnected system with cable connections from the islands via offshore wind farms (Lüth et al., 2023), the current industry visions connect radially between islands and a few market zones that already integrate their offshore wind power. This neglects the possibility of supplying electrolysers on energy islands with offshore wind energy from sources other than wind farms directly connected to the hub as pictured in Figure 2. The stronger interconnection between offshore assets, energy islands, and shore exhibits a higher usage rate of offshore electrolysers.

Generally, the first studies show that integrating offshore wind via cable is predominant considering the vast demand for renewable electricity for direct consumption. Energy islands can contribute to this by supplying from the offshore wind but may not be needed if this was their sole purpose. Their envisioned location far out at sea invites some offshore electrolysers for hydrogen production. This can be further refined to supply ships with ammonia. Currently, projected costs make it reasonably attractive to use the island for such technology (Jansen et al., 2022; Lüth et al., 2023), but there are risks to it—especially due to the lack of mature offshore conversion and storage technology.

Figure 2: Possible integration of the energy islands into the onshore system by connecting offshore installations via wind farms to shore. The size of the line indicates the relative capacity with the largest one being about 6 GW. Source: Lüth et al. (2023, p. 6).



What are the risks connected to energy islands and integrated offshore systems?

The envisioned projects are very ambitious regarding both the timeline and the need for technical innovation. In Lüth (2022, pp. 59–94), I have identified the risks of technical, economic, environmental, and societal character that may drive the development[2]. Overall, there is an indication that immature technology and a lack of economic frameworks for the islands pose the most imminent risk.

The currently envisioned **technology** for energy islands is too expensive to compete with other flexible sources and conventional hydrogen production, and that is mainly due to technological immaturity (Lüth, 2022). A usable technology mix would likely only materialise with higher CO_2 or hydrogen prices or lower technology costs. Offshore electrolysers and energy islands are a new, untested element to be integrated into energy systems, and this creates a risk. For offshore electrolysers, we suggest that they are built at moderate sizes and run at capacity factors of 50% (Lüth et al., 2023), whereas Gea-Bermúdez et al. (2023) find that offshore generation is likely to be of negligible importance. The technical infrastructure and cable connection also influence the mode of operation and the availability of electricity for hydrogen production. Besides offshore electrolyser technology, high-voltage direct current (HVDC) cables are a promising technology for offshore settings, but they are still expensive, need further testing, and are in early topology development stages (Fernández-Guillamón et al., 2019). The aformentioned energy island projects are, however, part of the first large-scale roll-out which makes them generally expensive and challenging. The progress of technology thus influences the system benefits and competitiveness, and in essence, there is a trade-off between electricity and hydrogen supply.

From an **economic** perspective, there are many possible hurdles to the development of energy islands. Although the offshore and hydrogen strategies used by the EU have set the first goals for a fossil-free energy system, there are not yet specific economic frameworks. Bidding zone configurations, an aspect of market design, are relevant for capturing the desired value of conversion, flexibility provision, or hydrogen (Lüth et al., 2022), but the bidding zones need to be set such that technology operators can ensure profitability and network operators cannot exploit congestion rents. Currently, it is assumed that the operation and ownership of offshore grids and assets will be feasible and attractive, but there is no consensus yet on how to successfully implement this in a fast manner. Combined interconnected solutions between different energy carriers are disconnected from the current planning procedures. Currently, the gas and electricity sectors work separately and so do the various national system operators. To achieve an integrated energy system across borders, coordinating efforts must be increased, as suggested by Dedecca et al. (2019), but their failure poses an immense risk.

On the **environmental** side, there is also a risk that energy islands will increase carbon emissions in the short run because of CO_2-intensive construction and the relocation of processes far from demand and existing infrastructure. Marine ecosystems will be exposed to intrusive construction processes if an entirely new infrastructure is built, and the long-term impact cannot be entirely assessed. Yet, the future electricity supply will be highly dependent on available offshore resources to reduce emissions and deliver electricity for clean fuels.

Succeeding in delivering emission reduction through the construction of energy islands can positively impact **society** through health improvements, job creation in renewable energy and around the maritime sector in the Nordics. Currently, the projects are also motivated by onshore acceptance issues and the prospect of more affordable electricity prices in the future. Long-term effects on equity cannot be evaluated at this point—there are indications of welfare-improving character for such international offshore projects (Schlachtberger et al., 2017), but it remains open whether this holds for energy islands, too.

Overall, offshore technology for energy islands must become more affordable and sustainable to satisfy society's desire for just access to cheap electricity. The current radial connections of offshore renewable energy sources and the use of onshore electrolysis may be part of the solution but must be combined with further conceptual novelties. When we pursue the expansion of offshore wind even farther from the coasts, cost-efficient network extension will develop into a meshed structure at sea. Eventually, offshore electrolysis can play a role in far-away electricity production to supply affordable and clean fuel for hard-to-decarbonise sectors. Yet, the economic framework and the viability of offshore electrolysis are uncertain.

Perspectives on the future role of energy islands

Energy islands are considered a significant milestone in the Danish transition to sustainable energy in the Nordic and Baltic regions. These islands are expected to harness the wind potential at sea to supply electricity, hydrogen, and sustainable fuels. However, the system design, technology mix, and market integration of these islands are not yet clearly defined. Current studies on energy islands have identified the need for further research as the value, benefits, and costs of the islands are influenced by various factors such as the regulatory and policy frameworks, and market integration.

The lack of comparative projects and the need for considering various innovative approaches to energy system transformation mean that it is too early to conclude on the overall benefits of energy islands. However, as projects move toward implementation, the aim is to develop a meshed offshore grid and a technology hub focused on hydrogen, and potentially other conversion technologies. It is preferable to avoid long-distance cables to far-offshore wind farms in favour of offshore hydrogen production. Incorporating large offshore generation facilities within existing market zones would require costly measures to adjust market outcomes to the physical constraints of the power system. Energy islands may facilitate market integration across countries and enhance the interconnection of the involved parties to construct the island. Interconnection has been shown to stabilise the energy systems and belongs to the priority corridors for the electricity grid (European Commission, 2020). The islands also allow for a more cost-efficient way of connection to shore: combined and bundled cables from central offshore locations provide an advantage over many parallel small connections. If the islands include energy storage and conversion, possibilities for energy system integration and emerging synergies can be exploited.

Environmental benefits of energy islands remain unidentified

Moving a step beyond the available findings, there is a lack of sustainability research on the idea of implementing energy islands. The gains provided by large-scale offshore infrastructure for reducing greenhouse gas emissions are challenged by the visions entailing construction-related carbon emissions. Further analysis needs to shed light on the impact of energy islands beyond CO_2 emissions and intrusion through construction and investigate long-term impacts on the energy system and the environment.

Energy islands rely on coordinated planning among international consortia

Like offshore grids, achieving the optimal design of energy islands within an integrated grid structure may not be feasible in the desired shape. Integrated and coordinated planning over a long-time horizon carries uncertainties that are not addressed by any regulation. Projects that need cross-country coordination are difficult, and capabilities and guidance involved in bringing together players from across borders influence the outcome of the project. While an integrated system design that includes well-connected energy islands can offer significant benefits, achieving this ideal scenario requires coordinated planning and construction to ensure the gradual development of large-scale infrastructure and reaching several milestones to achieve the optimal layout. The first obstacle is identifying the ideal location for an energy island, which is a highly politicized issue and may face strong opposition. In addition to geopolitical considerations and interference with national plans, there is a lack of clear guidance on this topic. While some studies have examined offshore grids and market design with high shares of wind power, a smart approach to energy islands has not yet been explored.

There is high financial risk, and sunk investments cannot be precluded

So far, energy island projects are seen as an option without offshore competitors. Risks include financing strategies, the influence of interest rates and cost of capital on immature electrolysis and offshore technology, and uncertainty about the acceptability of supporting such large infrastructure projects. Their onshore counterpart does seem more intuitive: more mature technology, close to demand, and easier to access. To mitigate financial risks and ensure each module can exist if the whole does not materialise, a modular design can improve project outcomes. Tenders and their design are also relevant to the process. Energy islands seem an unattractive space for investments due to their distance to shore and undefined demand, risk of high maintenance cost, and uncertainty on frameworks for operation in coupled markets.

Energy islands suggest following a merely technological solution

Energy island projects are not solely technological but also involve considerations of nature, society, and the international community. However, the recent developments in energy and resource prices and inflation have led to increased costs for implementing energy islands. While many studies on energy islands use energy system modelling, they often fail to reflect or test the interplay among these developments, as well as the social and behavioural components, which is a commonly noted shortcoming (Süsser et al., 2022). The current energy price crisis highlights the need to transition to renewable energy and reduce resource dependence for energy security. However, energy islands are not a quick solution to achieving affordable and sustainable energy. In times of economic instability, public infrastructure projects like energy islands can either burden or benefit consumers, making it crucial to establish an adequate governance framework to allocate risks among involved actors. Overall, recent studies suggest the value of coordinated, large-scale exploitation of offshore resources but call for a careful reassessment of the role of energy islands under changing paradigms and societal challenges. Energy islands present a centralised, top-down and technology-driven approach. Others argue that concepts for empowering consumers at the household level need to drive the transition (Sousa et al., 2019) and they advocate for a stronger combination of bottom-up and top-down approaches for a successful transition.

A summary of considerations

These considerations arise in part due to the lack of studies and at the same time present research opportunities. There is a need to develop a common framework for the shared region of the North Sea so that everyone can collectively benefit and contribute to the islands, their fuel, and their energy. The main challenges in establishing energy islands relate to policy and regulation, such as determining subsidies, deciding on one or multiple operators for offshore electricity and hydrogen infrastructure, identifying who will pay for the power lines, and defining the offshore generation market. The design of policy and regulation will greatly affect costs, benefits, allocations, and long-term profitability as we enter uncharted territory. And lastly, there is large uncertainty about the future demand for hydrogen that may drive some energy island parts into sunk investments. That said, future research must address the characteristics and design features to identify cost-efficient and valuable characteristics of energy islands.

Notes

1. See North Sea Wind Power Hub: https://northseawindpowerhub.eu/
2. This reference contains a table with a more granular survey of the different criteria.

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