DTU Library

Denmark as the Energy Island Pioneer

Østergaard, Jacob; Christensen, Erik Damgaard; Halsnæs, Kirsten; Riisager-Simonsen, Christian; Lisbjerg, Dennis; Jensen, Anker Degn; Duus, Jens Øllgaard; Madsen, Henrik; Frandsen, Henrik Lund; Savaghebi, Mehdi

Total number of authors:
31

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

DTU

DTU Sector Development Project

Denmark as the Energy Island Pioneer

The Danish parliament has mandated the largest ever infrastructure project in the history of our country. Let us make sure to take the optimal direction for the energy islands initiative from day one.

Contents

A solid foundation for energy islands

Rumor has it that all technologies needed to build energy islands are ready. Wind turbines are spinning in many large offshore parks, while combinations of sand and concrete have given birth to several entirely new islands. However, not all rumors are true. Not only has the Danish parliament mandated the largest ever infrastructure project in the history of our country. The first Danish artificial island built for energy production will also become the world's largest renewable energy project. On top of the technical and logistical challenges associated with building something of an unprecedented scale and nature come new concerns. The energy islands are an extreme version of the power system we know today, and therefore represent a Mars mission for the energy system.

More than once have large infrastructure projects been plagued by delays and significant additional costs. Often such problems have been rooted in overly optimistic planning, limited knowledge regarding the complexity and inter-dependencies involved, and not giving enough attention to the development phase relative to the construction phase.

For many reasons, it is highly desirable for the energy island projects to perform well. Therefore, we have teamed up to map the key challenges and suggest R&D initiatives to address them. Importantly, these initiatives are not intended as an inserted step before construction. Given the urgency in green transition and ending the reliance on fossil fuels, research and construction must be conducted in parallel.

On the following pages we invite you to delve into the complexity of constructing and operating offshore hubs for renewable energy. As you will hopefully agree, we are by no means saying that it cannot be done. It can. But only if decisions are based on a solid foundation of knowledge.

Enjoy your reading,

Anders Stouge
CEO The Danish Construction Federation
(DI Byggeri)

Jørgen S. Christensen
CTO Green Power Denmark

Marianne Thellersen
Senior Vice President–
Innovation and Entrepreneurship DTU

Members of the working group

Professor Jacob Østergaard
DTU Wind and Energy Systems (lead professor)

Professor Erik Damgaard Christensen
DTU Construct (lead professor)

Professor Kirsten Halsnæs
DTU Management (lead professor)

Academic Employee Christian Riisager-Simonsen
DTU Aqua

Senior Advisor Dennis Lisbjerg
DTU Aqua

Professor Anker Degn Jensen
DTU Chemical Engineering

Professor Jens Øllgaard Duus
DTU Chemistry

Professor Henrik Madsen
DTU Compute

Professor Henrik Lund Frandsen
DTU Energy

Associate Professor Mehdi Savaghebi
DTU Engineering Technology

Associate Professor Wenjing (Angela) Zhang
DTU Sustain

Professor Dogan Keles
DTU Management

Professor Jacob Ladenburg
DTU Management

Programme Director Malene Rod Vest
Danish Offshore Technology Centre

Professor Brian Seger
DTU Physics

Professor Niels Henrik Mortensen
DTU Construct

Professor Gürkan Sin
DTU Chemical Engineering

Associate Professor Lena Kitzing
DTU Wind and Energy Systems

Professor Athanasios Kolios
DTU Wind and Energy Systems

Head of Division Kenneth Thomsen
DTU Wind and Energy Systems

Senior Researcher Dominik Franjo Dominkovic
DTU Compute

Associate Professor Evangelos Katsanos
DTU Construct

Associate Professor Varvara Zania
DTU Sustain

Professor Anders Riisager
DTU Chemistry

Professor Thomas Fruergaard Astrup
DTU Sustain

Associate Professor Ashraf Fathi Khalil Sulayman
DTU Engineering Technology

Programme Manager Ulla Hoffman
Danish Offshore Technology Centre

Head of Section Ditte Kirstine Andersen
DTU Policy and Relations

Senior Executive Officer Lars Brückner
DTU Office for Research, Advice and Innovation

Science Writer Morten Andersen
manjourn.dk

Special Advisor Leon Aahave Uhd
DTU Office for Research, Advice and Innovation (Coordinator)

List of interviewees

DI Energi
GREEN POWER DENMARK
CIP Copenhagen Infrastructure Partners
Danish Energy Agency
Danish Ministry of Climate, Energy and Utilities
European Commission Directorate-General for Energy
DI Byggeri
ENERGINET
elia group
entsoe
HALDOR TOPSØE
MAERSK SUPPLY SERVICE
RAMBØLL
SIEMENS Gamesa RENEWABLE ENERGY
SWECO
Vestas
TotalEnergies
Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping

Denmark as the energy island pioneer

The largest infrastructure project in Danish history has been decided by the Parliament. In combination with an initiative which will turn Bornholm into the first energy island, the upcoming artificial island in the North Sea will mark the realization of a dream. Namely to base Danish power production entirely on renewable energy. This will be a key element in putting an end to fossil fuel imports. The energy islands will impact our society in numerous ways, both economically, socially, and environmentally. Thus, it is important to establish a solid knowledge base and thereby ensure that the project takes the optimal direction from day one.

Firstly, the energy islands will need to fit the overall energy system. Seamless integration is not only necessary at the respective dates of inauguration in 2030 (Bornholm) and 2033 (the North Sea island). The energy system is bound to see many changes happen during their operational lifetime, including the establishment of more energy islands.

Secondly, the energy islands need to be safe. This does not only relate to the working conditions of personnel engaged in constructing and operating the islands. The sabotage against the Nord Stream 2 gas pipe is a reminder that energy infrastructure is a potential target. The energy islands must be designed to withstand both cyber and physical attacks. Still, it would be naïve to assume that absolute security is possible. The system needs to be designed to be resilient. Failure in any given sub-system must be contained so fatal consequences for major parts of the European energy system will be prevented.

Thirdly, harmful consequences to the marine environment and biodiversity must be minimized. Furthermore, sustainability needs to be guaranteed; carbon emissions and resource consumption during both construction and operation must be kept as low as possible. Notably, environmental and sustainability implications are known to be key to public acceptance of infrastructure projects.

Why are energy islands necessary?

In collaboration with a range of other nations, Denmark has committed to a massive increase in renewable energy production. For the North Seas alone, a 300 GW (Giga Watt) wind power capacity has been agreed for 2050. In comparison, the total Danish offshore wind power capacity today is 2.3 GW. Meeting these commitments through near-shore wind power parks alone will just not be possible. Even if existing local planning and protests from citizens were disregarded, the available space would fall short by a large margin. Thus, the build-out needs to be based on the use of the open sea wind resource.

Fortunately, the potential for open sea wind power production is huge. However, the technical setup around near-shore wind power parks cannot be transferred to the open sea. At today's near-shore parks, power is produced as an alternating current (AC) and transmitted directly to shore. This would not work for an open sea park. Due to the longer distance, the power must be converted into a direct current (DC). The space requirements for the converters and related equipment demand housing at a physical structure close to the production site. In other words, a build-out of the scale in question would be impossible without energy islands.

A dream is coming closer to realization. Namely to base Danish power production entirely on renewable energy. *Photo credit: Shutterstock.*

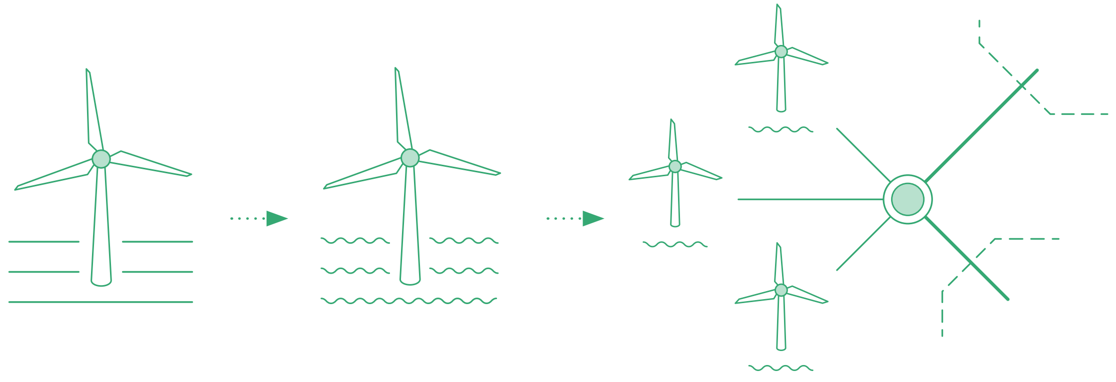
A further advantage of energy islands is the possibility of installing technologies such as a production of hydrogen, renewable fuels, or chemicals (power-to-X). Production of green fuels is imperative for meeting the Paris Agreement goal which is to keep the increase in global mean temperature at or below 2.0 degrees C, and preferably at 1.5 degrees C.

The largest renewable energy project in the world

The scale of the challenge at hand is illustrated by the budget for the new island in the North Sea. Construction of the artificial island and the surrounding new wind power farms is estimated at 210 billion DKK. This is the equivalent of five Great Belt connections.

To date, no other renewable energy project in the world has been built at a similar physical and economic scale. An energy island is not an off-the-shelf product. Several of the involved solutions are not yet ready. For instance, conventional power plants have large synchronizing generators which add inertia to the power system. These generators safeguard the system from collapsing in situations where the supply/demand balance is disturbed. At an energy island, the power grid will consist solely of converter-based units without inertia and other power plant functionalities which are key to system stability. Thus, it is necessary to develop radically new concepts for power system control at energy islands.

The evolution of wind energy



Even for well-known elements such as the offshore wind turbines, it is highly likely that significant improvements can be found through optimization for energy island application. Furthermore, integration of energy islands into the overall society holds a large potential. To the best of our knowledge, no macroeconomic estimates on the societal impacts of energy islands have been produced. Neither macroeconomic cost and gains, the potential for local development and job creation, or targets for nature preservation and biodiversity seem to have been assessed.

In the present sector development project, DTU has partnered with key companies and trade associations to map challenges related to energy islands. The main aim has been to identify research initiatives which may enable high-quality and cost-effective solutions.

Suggestions for immediate joint initiatives

We have identified six joint industry/research initiatives as critical for a successful energy island implementation. Furthermore, solutions in these areas will strengthen the export potential of Danish industry.

- Optimal decision-making regarding design and operation of GW wind / P2X systems for energy islands addressing questions such as electrolyze technology, over-planting, grid-connection, and market integration.
- Resilient design of energy islands in terms of cyber-physical environment, fault management, power system stability and security, and converter interactions.
- Baseline study of wind resources and metrological-ocean conditions for design and environmental impact. Scientific perspectives, actual procedures, and guidelines all need to be addressed.
- Use of modular approach in design. For instance, picturing a modular development of an energy island from power to P2X.
- Assessment of demand for electricity and P2X fuels for the next two decades in a European and international context, given temperature increase stabilization at 1.5 and 2.0 degrees respectively. The scenarios should reflect national targets, EU policies, time profile of reductions, sectors, and related carbon prices.
- The EU Emission Trading System (ETS), carbon taxes, and subsidies and technology-oriented standards are assessed and compared as instruments to meet EU plans and national Danish policy targets for the green transition and the energy islands with P2X. International trade issues and protective measures are reviewed.

Saving opportunities worth billions of DKK

On top of the six suggestions for immediate joint activities, the present sector development project recommends a range of research projects to be initiated as soon as possible. These projects will be critical for a successful implementation and/or allow significant savings in the costs of energy islands.

All wind turbines connecting to today's power grid must comply to a set of technical specifications. This is necessary to guarantee overall grid power quality but does impose additional costs on wind turbines. Since the power grid at an energy island will be an alternating current (AC) system operating in isolation without direct consumers, the wind turbines will not need to comply with the same strict specifications. Compliance of the converters at the large direct current (DC) connections which transport the power to shore will suffice. Thereby, the costs of the wind turbines can be reduced significantly. Similar optimizations are possible for transformer stations. Also, savings can be achieved through better integration of power/hydrogen solutions. We estimate the joint cost savings enabled by these innovations at 20 billion DKK at the scale planned for the new island in the North Sea.

Further potential cost reductions relate to the physical construction of the island. The design of offshore structures is based on the loads imposed by wind, waves, and currents. For a large part, guidelines are based on methodologies which were developed 40-50 years ago. Moreover, industry rely, to a large extend, on experience in design procedures rather than evidence-based methods. This can lead to overly conservative choices, resulting in more expensive and less sustainable solutions. Through modern, evidence-based methodology it will be possible to achieve large savings without compromising safety.

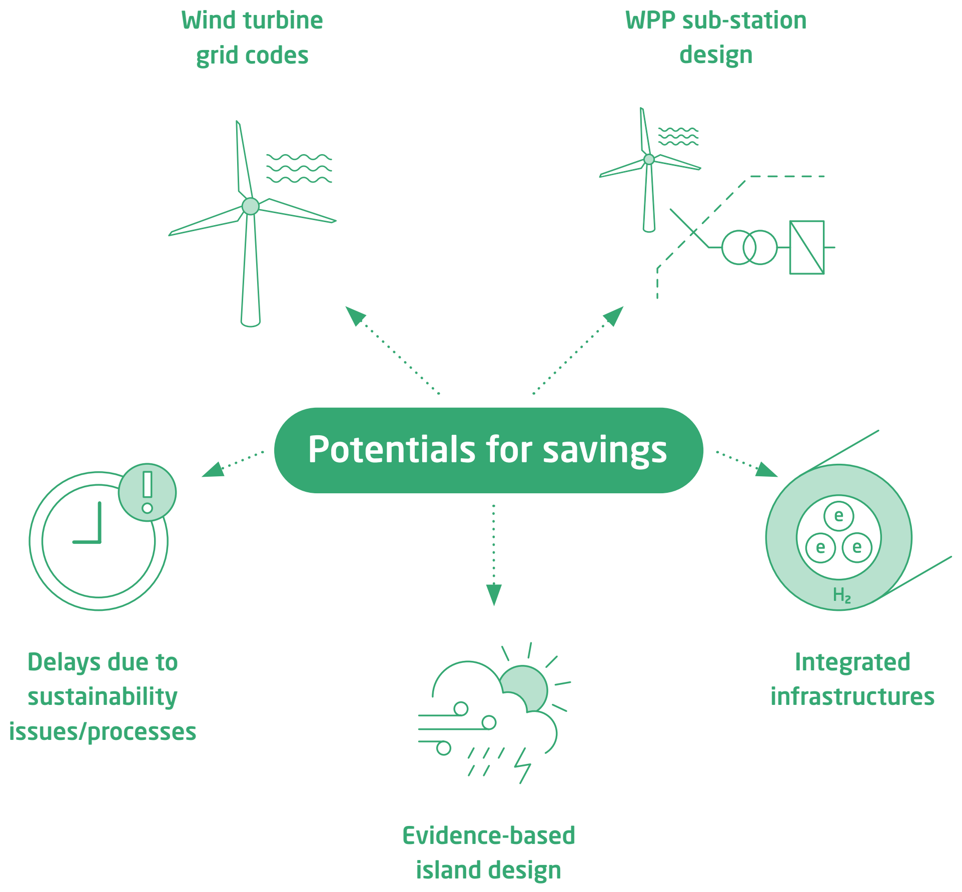
Finally, timely considerations of sustainability, biodiversity, and environmental impact may have significant positive effects on the economic feasibility. Experience from other large infrastructure projects such as the Fehmarn Belt and Lynetteholm shows how uncertainty around these issues may lead to considerable delays. At the scale of an energy island, delays will quickly amount to several billion DKK.

Cost efficiency will help save the planet

In total, we estimate savings resulting from the recommended research effort in the range of 20-30 billion DKK for a 10 GW energy island, equivalent of the North Sea Energy Island.

Notably, savings in this order will not only ease the burden on the budgets of the Danish state and energy consumers. Since the Danish energy islands will be among the first of their kind globally, they are bound to become showcases. The economic performance in particular will influence the willingness of other countries to follow suit. This will in turn decide whether the Danish energy sector will be able to sustain its current leading role and create a new business adventure around energy islands.

Denmark is a small country, but if we can inspire others, the implications can become of a global nature. In this way, the Danish energy islands can contribute to the green transition and ultimately to slow down the rise in global temperature.



Offshore wind is a key element in putting an end to fossil fuel imports
Photo credit: Shutterstock.

Sector development at DTU

DTU regularly initiates sector development projects aiming to improve the competitiveness of technology-intensive sectors.

Each project is created in a forum comprising representatives of companies, public authorities, and trade associations, in Denmark and abroad, and researchers from DTU.

In the initial phase, the given sector is mapped through workshops and interviews with key stakeholders. Hereafter, bottlenecks and development needs of companies, public authorities, and DTU (universities) are identified. On basis of the results, recommendations for research, education, and framework conditions are produced.

Our approach

In collaboration with leading companies, public institutions and authorities, and trade associations within the energy island sphere, we have identified:

- Six joint industry-research initiatives which must be initiated as soon as possible. The solutions to the issues mentioned under the six initiatives are critical for a successful establishment of energy islands.
- A range of research, education, research infrastructure, and system research funding needs. Meeting these needs will be critical and/or will enable significant economic saving opportunities.

Both the six suggestions for immediate initiatives and the recommendations for research, education, research infrastructure, and system research funding have been reviewed and accepted at a workshop attended by interviewees and at steering committee meetings attended by industry, trade organization representatives, and DTU department heads. Furthermore, the insights obtained during the project have been discussed by DTU researchers at monthly working group meetings. Researchers at DTU Aqua, DTU Chemistry, DTU Chemical Engineering, DTU Compute, DTU Construct, DTU Engineering Technology, DTU Electro, DTU Management, DTU Physics, and DTU Wind and Energy Systems have contributed to the project. The Office for Research, Advice, and Innovation at DTU has coordinated the project.

HVDC (High-voltage direct current) transformers for longrange power transmission. *Photo credit: Hitachi Energy*

Introducing: the world's largest renewable energy project

Based on the present sector development project, we estimate that a dedicated, timely research effort may reduce the cost of a 10 GW energy island in the order of 20-30 billion DKK.

On top of ambitious national policies, Denmark has committed internationally to massive increases in renewable energy production, primarily wind energy. Most recently, the participating countries at the 2023 North Sea summit in Ostend, Belgium, have agreed to establish 300 GW of offshore wind power by 2050. In comparison, the current total offshore wind capacity in Danish waters is 2.3 GW.

The available land-based and near-shore offshore locations for wind power are far from sufficient for power generation of the magnitude in demand. It is thus imperative to harvest the wind power resources of the open seas. Both the North Sea and the Baltic Sea offer vast amounts of unexploited open sea wind power resources (180 GW and 93 GW, respectively).

However, it is not technically feasible to use the same design for an open sea park as for a near-shore park. While for the near-shore parks of today, power is transported as an alternating current (AC) to shore, this would not work for an open sea park since the charging current of the cable would exceed the nominal current. Instead, power must be converted offshore into a direct current (DC). The large-scale equipment for this conversion and the related functions need to be housed at a physical structure close to the production site. In other words, without energy islands, which will be a Mars-mission for the energy system, the planned build-out cannot happen.

To justify the construction costs, an energy island needs to receive power from a very large number of wind turbines equivalent to several of the largest current offshore wind parks. However, this is not really a downside, as the purpose is already to establish a renewable energy production of a much larger scale than today.

A further advantage of energy islands is the possibility of installing technologies such as a production of hydrogen, renewable fuels, or chemicals (power-to-X). Production of green fuels is imperative for meeting the Paris Agreement goal which is to keep the increase in global mean temperature at or below 2.0 degrees C, and preferably at 1.5 degrees C.

Savings of 20-30 billion DKK are achievable

The cost of constructing the new North Sea energy island off the coast of Jutland and the related new wind power plants is estimated at 210 billion DKK (Energistyrelsen). When costs associated with operation and maintenance over the entire life cycle of the island are included, the expected lifetime cost will be 280 billion DKK.

In the present sector project, we have identified a range of urgent issues that need to be resolved to ensure that energy islands can be built safely, economically, and sustainably. As a bonus, the necessary research will not only improve the security of the energy supply but may also spur innovations which will allow a significant reduction in construction and operational cost.

Large potential cost savings relate to the equipment and management of the island's electrical system. At the near-shore offshore parks of today, power is converted into a 50 Hz alternating current (AC) and transported onshore through AC cables. Due to the longer distance, power produced at an open sea park must be converted offshore into a direct current (DC) before transmission to land. This is known as a high-voltage direct current (HVDC). To date, all wind turbines have had to comply with a set of technical specifications that guarantee the overall grid power quality. However, since the electrical system of an energy island will be an AC system operating in isolation without direct consumers, the wind turbines will not need to comply with the same strict specifications. The compliance of the HVDC converters will suffice. Consequently, the cost of the wind turbines can be reduced significantly. Similar optimizations are possible for transformer stations, as are savings through an improved integration of power/hydrogen solutions. We estimate the joint cost savings enabled by these innovations to be 20 billion DKK at the scale planned for the new island in the North Sea.

Further potential cost reductions relate to the physical construction of the island. The design of offshore structures is based on the loads imposed by wind, waves, and currents. For a large part, guidelines are based on methodologies which were developed 40-50 years ago. Moreover, industry rely to a large extend on experience in design procedures rather than evidence-based methods. This can lead to overly conservative choices, resulting in more expensive and less sustainable solutions. Through modern, evidence-based methodology it will be possible to achieve large savings without compromising safety.

A third area of the potential savings relates to the sustainability and environmental impact of energy islands. It is worth remembering that negative environmental consequences may influence public acceptance. For instance, both the Fehmarn Belt and the Lynetteholm projects have been delayed. At the scale of an energy island, delays will quickly amount to several billion DKK.

Some of the potential savings are difficult to quantify. An example is the value of avoiding a loss of biodiversity. Still, it is safe to say that the potential savings go beyond the 20 billion DKK on equipment and control systems for the electric offshore system. A conservative estimate would be that it is possible to achieve total savings in the range of 20-30 billion DKK through a timely research effort dedicated to energy islands.

Hurrying, but wisely

Understandably, some may fear that research would delay the project. The proposed research

300 GW wind power capacity in the North Seas

With the dual purpose of mitigating climate change and securing energy independence, the EU is gearing up for a massive increase in renewable energy production. The new geopolitical reality following the Russian invasion of Ukraine in particular highlighted the need for a security of supply in the energy sector. Vast amounts of fossil fuels need to be replaced with alternative energy sources that are sustainable both in relation to the climate and politically.

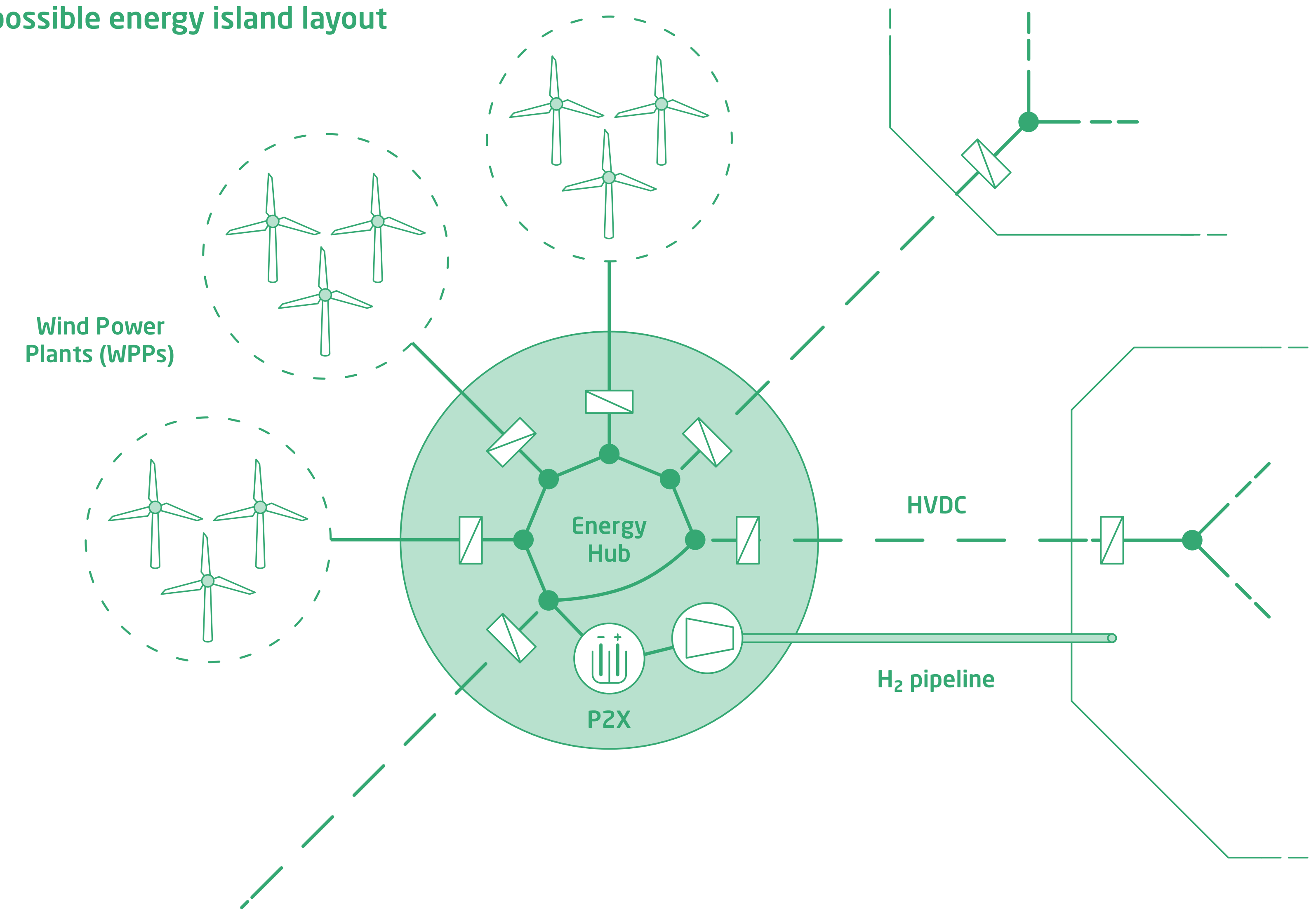
On top of its already ambitious domestic planning, Denmark has committed internationally in two respects. Joining forces with Belgium, Germany, and the Netherlands in the Esbjerg Declaration, Denmark is to develop an offshore renewable energy system connecting all four countries in the North Sea. And the Marienborg Declaration commits the Baltic states, Poland, Sweden, Finland, and Denmark to accelerate the establishment of wind power in the Baltic Sea basin.

The Esbjerg Declaration commitments have recently been expanded at the 2023 North Sea summit in Ostend, Belgium. By 2050, the participating nations have agreed to have 300 GW offshore wind power capacity in the North Seas (meaning the North Sea plus neighboring waters around the UK, parts of the Norwegian Sea etc.). In comparison, the total EU wind power capacity today is 12 GW. A wind power capacity of the planned scale can only be realized through the establishment of several energy islands in the North Sea.

For the Baltic Sea, the Marienborg Declaration has set an ambitious goal of at least 19.6 GW by 2030 – seven times the current capacity.

Marienborg Declaration. EU Commission President Ursula von der Leyen and heads of state from the Baltic states, Poland, Sweden, Finland, and Denmark agreed to accelerate wind power in the Baltic Sea basin.
Photo credit: Mads Claus Rasmussen/Ritzau Scanpix

A possible energy island layout



Two Danish energy islands

The Danish parliament has mandated two energy islands. Bornholm will be the first Danish energy island in 2030 with a 3.2-3.8 GW wind energy capacity. An energy island in the North Sea some 80 km off the coast of Jutland is planned for inauguration in 2033 with an initial capacity of 3 GW, to be expanded to 10 GW towards 2040.

effort should not be seen as an inserted step to be completed before the first construction works are initiated. Rather, the research must be carried out as a parallel activity interacting with the core construction processes.

Admittedly, this is easier said than done. A setup with research feeding new insight into the construction process while the builders and the future operators keep challenging researchers with upcoming problems is far from standard. Still, the potential benefits will be huge. Furthermore, we can point to an excellent track record from previous projects on integration of wind power into the Danish energy system. Without such efforts, renewable energy could not have covered a substantial part of our energy supply as is the case today.

In this regard, it is worth noting the synergy between Bornholm as the Baltic Sea energy island and the new artificial island in the North Sea. Several activities for the Bornholm project are already initiated or will begin very soon. The results can thus be put directly into use in the design of future energy islands.

The present sector development project offers two sets of recommendations. Firstly, we recommend six initiatives which should be introduced immediately and carried out jointly by industry and researchers. Secondly, we suggest a range of research efforts.

The 'Mars Mission' of green transition

While many of the technologies needed for building energy islands are ready, nobody has undertaken anything remotely similar in terms of scale and level of ambition. So, the energy island constitutes a "Mars Mission" for the green transition. Several questions need to be answered.

Firstly, an energy island will need to be integrated into the network of other future islands. How should this system be designed to achieve optimal cost efficiency? And how should this system be designed to best achieve resilience to breakdowns caused by lack of inertia, extreme weather events, physical sabotage, cyberattacks, etc.?

Secondly, green power is not the only type of renewable energy in high demand. Both hydrogen and various types of green fuels are projected to conquer increasing market shares. Ideally, the energy islands should be designed as flexible production facilities.

Thirdly, it remains to be seen which business case will be better for Denmark. Should surplus power and hydrogen be exported directly to other nations or rather be utilized for the production of green fuels (for instance for aviation and shipping), also known as Power-to-X (P2X). And should production facilities be placed offshore or onshore?

Importantly, the solutions should be picked not only to meet the needs of the Danish energy system and the Danish carbon emission reduction targets. Other nations have similar challenges—and often on a much larger scale. Therefore, designing a system which can promote the international, or even global, green transition can both contribute significantly to mitigating climate change and providing extensive business opportunities for the Danish energy sector.

Focus on extreme weather events and sustainability dimensions

Both through the existing offshore wind farms and decades of oil and gas activities, Danish contractors and operators have extensive experience with offshore construction works. This could lead some to think that building an artificial island will be relatively straightforward. However, the increased depth and the harsher environment in terms of winds and waves implies challenges of a new type.

In the wind power industry, fatigue caused by the steady vibrations during years of wind turbine operation is traditionally seen as the number one problem. In other words, if the design can tackle fatigue, the wind turbine will also be able to tolerate extreme winds. Moving to harsher conditions, this paradigm may well have to be revised with extreme winds becoming the defining design parameter. The same may apply to the effect of extreme waves impacting the construction.

Another issue is how an artificial island will impact its environment. The island and the many wind turbines will surely change both wind and wave patterns. This is not necessarily a bad thing. For instance, the island and other constructions are hard surfaces which may provide new habitats for mussels and other forms of marine life. Similarly, the changes in wave patterns could have positive effects by shielding the Jutland coastline against erosion. However, the effects might also be negative. This calls for a comprehensive sustainability assessment, including economic, social, and environmental impacts carried out as part of planning the energy islands. The point is: we will not know before we investigate these issues. And once the island has been built, it is too late to suggest modifications.

Managing a new extreme type of power system

A key research effort would relate to power conversion and balancing of the power grid. Unlike a conventional power grid, the offshore grid will have very little inertia and short circuit power. Management of a power system of this type is unknown today. Entirely new concepts must be developed, for instance to ensure the interoperability of the HVDC converters and allowing these converters to generate the AC voltage level offered by today's major power plants. This is known as grid-forming converters. Due to the extreme features of the power system of an energy island, a wide range of aspects must be reconsidered. Not least protection when short circuits cannot be detected as usual due to the low short-circuit power and cyberattacks and disturbances, stability, and security of supply.

Should, for instance, production from a 10 GW energy island suddenly lack in the system, it could potentially cause the entire Northern European power system to fail, leading to nothing less than a disaster. It is therefore imperative that solutions are developed for resilience, meaning the ability of the system to contain a given failure to the smallest possible sub-part. Furthermore, these solutions should be tested thoroughly by large-scale simulations and verified under realistic conditions.

The protection of transmission lines and pipes as well as the stability and safety of the challenging energy system of an energy island is especially important. A range of challenging issues needs to be addressed both from a defense perspective and in relation to ensuring resilient construction of the energy system of the energy island.

Notably, special emphasis should be given to cybersecurity. Regrettably, an offshore energy system will be seen as a target for hackers including cybercriminals, politically motivated groups, and entities operated by hostile governments.

Potential savings in modularization and preventive maintenance

A physical energy island will mainly be built of sand and concrete. While sand and concrete are well-known materials, construction of concrete energy islands in a harsh open sea environment—above and below the water surface and at sea bottom—is a huge endeavor likely to involve many yet unknown challenges. Research in the production of building materials, the building process, and the organization hereof—e.g., modularization—must be undertaken as soon as possible.

Similarly, Life-Cycle Assessment modelling of the building materials and processes needs to be carried out. An important element will be assessing if the energy island is sustainable when measured on CO2 emissions and use of resources.

For a 10 GW artificial island, like the Danish energy island in the North Sea, the costs for operation and maintenance would amount to about 70 billion DKK—even without costs relating to resource provision, dismantling, and end-of-life management. Research into automation of both technical and manual work processes and into preventive maintenance (Industry 4.0) could help reduce such costs.

The construction of the energy island includes several new advancements, such as very large concrete structures, huge challenges with cable logistics to and from the island in a harsh sea, and new operations methodologies. Cables are often treated as an afterthought in offshore wind farm development, even though cable damage accounts for as much as 80 % of insurance pay-outs on these projects.

Pioneering through cost efficiency

Notably, savings in the 20-30 billion DKK order mentioned above would not only be highly popular with the many other sectors needing funding in the Danish society. By significantly reducing the cost of establishing the world's largest renewable energy infrastructure, the chance of having the new island serve as a shining example for the rest of the world is greatly elevated. Thereby, the project may motivate a green transition firstly in Northern Europe, and consequently in the entire EU, and in the world.

In this way, the energy islands will not only be imperative for Denmark to reach its ambitious target for the reduction of carbon emissions, but also contribute to the end goal of limiting the increase in global temperature change and reduce the risks of climate change.

On top of the huge societal benefit comes the export potential for Danish industry. Denmark was the pioneer in land-based wind turbines and later became the pioneer in offshore wind. Through the two Danish energy islands Denmark could, and should, become the pioneer in energy islands.

An added benefit of energy islands is the possibility of installing technologies such as production of hydrogen, renewable fuels, or chemicals (power-to-X).
Photo credit: Shutterstock

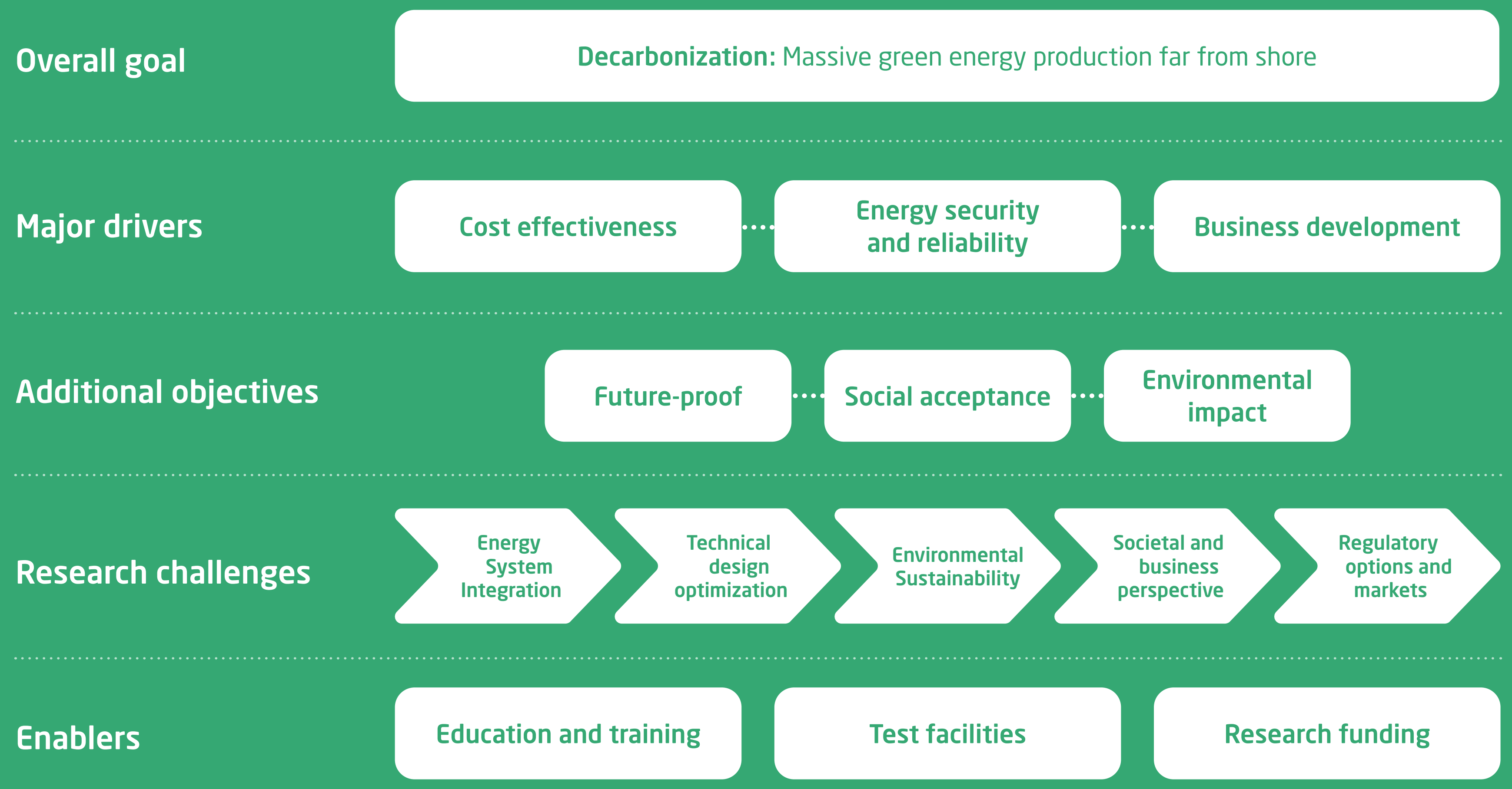
Definition of an energy island

Energy islands are hubs at sea that enable efficient harvesting of wind energy far offshore. Energy islands are islands/hubs with surrounding wind farms connected to the hub and transmission infrastructures between the hub and the neighboring energy systems. The connections to land will also be used for an exchange of energy between the connected energy systems/countries when not utilized for bringing the wind energy to land. The energy islands can involve electricity (AC/DC) as well as hydrogen (electrolysis at-turbine or electrolysis at-island) and be the first step towards a complete offshore energy grid with multiple interconnected islands/hub.

Scope of the project

The scope of the sector development project is restricted to research needs that are specific to energy islands. Research needs that are generic of kind are only covered to the extent it is critical for the energy island application.

Basic Model for the Energy Island Sector Development Project



Suggestions for immediate joint industry/research initiatives

Due to the urgency associated with the establishment of energy islands, the sector development project has selected six initiatives which should be initiated as soon as possible with participation from both industry and academia.

Energy system integration

- Optimal decision-making regarding design and operation of GW wind / P2X systems for energy islands addressing questions such as electrolyze technology, over-planting, grid-connection, and market integration.
- Resilient design of energy islands in terms of cyber-physical environment, fault management, power system stability and security, and converter interactions.

Technical design

- Baseline study of wind resources and metrological-ocean conditions for design and environmental impact. Scientific perspectives, actual procedures, and guidelines all need to be addressed.
- Use of modular approach in design. For instance, picturing a modular development of an energy island from power to P2X.

Environmental, societal, and regulatory perspectives

- Assessment of demand for electricity and P2X fuels for the next two decades in a European and international context, given temperature increase stabilization at 1.5 and 2.0 degrees respectively. The scenarios should reflect national targets, EU policies, time profile of reductions, sectors, and related carbon prices.
- The EU Emission Trading System (ETS), carbon taxes, and subsidies and technology-oriented standards are assessed and compared as instruments to meet EU plans and national Danish policy targets for the green transition and the energy islands with P2X. International trade issues and protective measures are reviewed.

Recommendations

Research recommendations*

Energy System Integration

Integration into the future energy system
The energy islands will be part of a market-based, integrated, and complex energy system. The electrical and market-interface designs of the energy islands need to set the right course for the future offshore wind power development and offshore P2X / electric grid infrastructure.

Energy island design optimization
Analytical tools must be developed in support of investment decisions regarding sizing, over-planting, electricity/hydrogen ratio, and other key questions for energy islands. The research must be dynamic, adjusting to developments in the larger energy system as well as in sustainability and life cycle analysis tools. Also, the bunkering of green fuels needs to be addressed.

Converter-based power systems
Operating an electrical system almost without inertia, as will be the case for energy islands, is unknown today. There is a need to develop AC/DC topologies, protection concepts, and control methods which can ensure safe operation and security of supply. Furthermore, innovations in components can limit the need for hardware and thus significantly reduce costs.

Optimizing wind turbines and HVDC converters
Large gains can be achieved by optimizing today's wind turbines, HVDC (high-voltage direct current) converters, and other electrical system components for a hub-based system such as an energy island. These optimizations will simultaneously make the energy system cheaper and provide business opportunities for Danish industry.

Digital analysis of security of supply and cybersecurity
The energy island power system will by far exceed known systems in complexity. Therefore, new tools must be developed based on e.g., digital twins, trustworthy artificial intelligence, quantum technology, and electromagnetic transient calculations, to continuously ensure security of supply and defend against cybersecurity threats.

* More detailed research recommendations can be found in the appendices.

Technical Design

Evidence-based design methodologies

The design of offshore structures is based on the loads imposed by wind, waves, and currents. For a large part, guidelines are based on methodologies which were developed 40-50 years ago. Furthermore, industry rely to a large extend on experience in design procedures rather than evidence-based methods. This can lead to overly conservative choices, resulting in more expensive and less sustainable solutions. At times, experience-based procedures even lead to conservative and unsafe methodologies. Through modern, evidence-based methodology it will be possible to achieve large savings without compromising safety.

Improved cable installations and bottom protection

Extreme loading conditions and performance requirements over the operational lifetime of an energy island challenges the prediction of geotechnical changes, i.e., ground deformations. The potential for reducing the costs and risk of failure for cable systems in particular is immense, as approximately 10 % of the costs related to an offshore wind farm involve cables. Development of evidence-based methods that cover the hydraulic and geotechnical conditions relevant to energy islands is needed.

Automation and preventive maintenance

Through more stable operation and reduction of man-hours, automation and use of preventive maintenance has been shown to enhance the operational time of large assets significantly. In relevant fields such as offshore oil and gas, power plants, and wind farms the availability has been increased by approximately 4 %. To achieve similar results for an energy island- corresponding to billions of DKK saved—digital models for the purpose must be developed. Also, modularized design should be addressed.

Placement and design of P2X facilities

P2X facilities require power, hydrogen, and CO_2 as well as the possibility of supplying consumers with by-products such as oxygen and heat. Identifying optimal locations requires modeling and analyses. Furthermore, research must establish the pros and cons of offshore compared to onshore production of P2X molecules.

Management of water for hydrogen production

For every GW power for hydrogen production, ~1.8 million m^3 of water is needed annually. Notably, this water must be ultrapure, meaning that comprehensive processing is needed before sea water can be utilized for the purpose. Research is needed to design a desalination system and develop pipes which are both corrosion resistant and able to tolerate high hydrogen pressures.

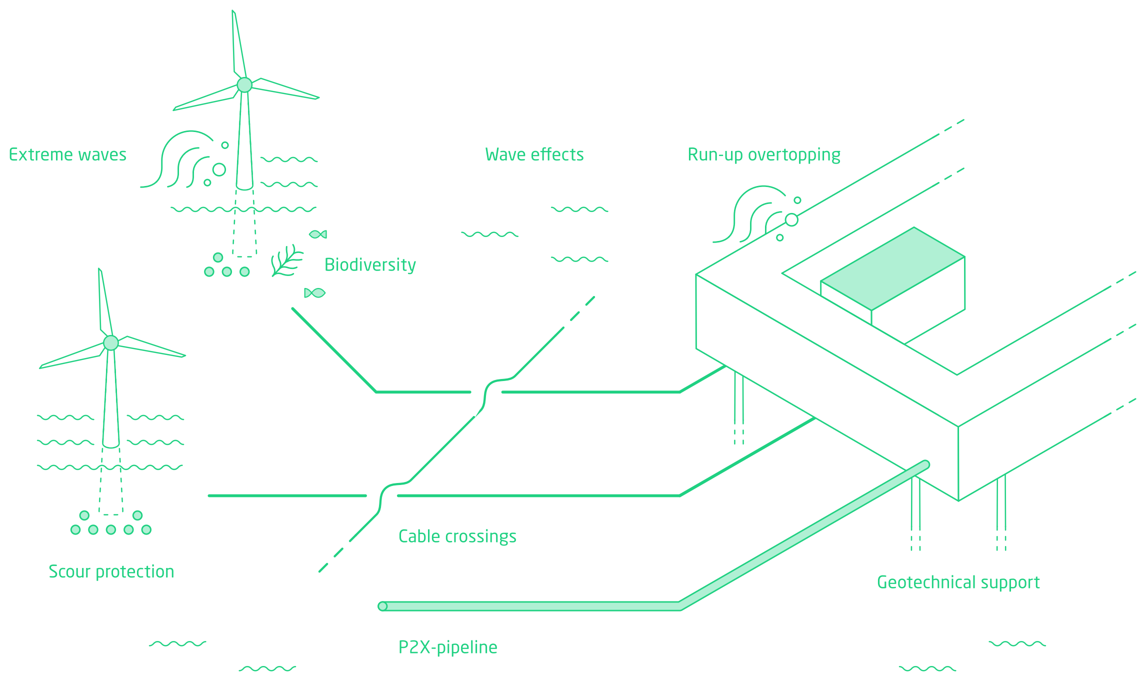
Environmental Sustainability

Life cycle assessment (LCA) of infrastructure

Infrastructure, construction, and facility operation of energy islands are at a scale which exceeds most other installations in society. Thus, the associated environmental impacts are currently unknown. While life cycle assessment (LCA) is a well-established methodology, data for infrastructure, technologies, and surrounding systems need to be acquired and later evaluated throughout construction, operation, and end-of-life phases.

LCA of P2X and system integration

Energy islands may have profound effects on other sectors, for example through associated P2X technologies, fuels, etc. Thus, assessment should involve relevant technology development pathways, potential technology alternatives, and options for system integration.



Consequences for biodiversity and ecosystem service provisioning to society

Based on the projected scale, the energy islands and associated wind farms are likely to impact marine ecosystems and biodiversity more than anything previously seen in Danish waters. Studies are needed to account for the impacts on currents, artificial light regimes, noise levels, wake and wind effects, sedimentation rates, and habitat structure, abundance, distribution, and diversity of marine life at local and sea basin scale. Changes in biodiversity and ecosystem services need to be addressed to manage trade-offs among maritime stakeholders and to optimize options for mitigating negative or enhancing positive impacts related to restoration of lost biodiversity.

PowerLab.dk at DTU has made a visual representation of the energy system of Bornholm. *Photo credit: DTU*

Societal and Business Perspectives

Macroeconomic perspectives, cost-benefit, and sustainable development

Energy islands imply very large investments and consequently large impacts on societies' welfare in terms of income generation, greenhouse gas (GHG) emissions, ecosystems, and social factors including employment and local participation in addition to business opportunities and exports. Research is needed into the economic, technical, legal, environmental, and safety risks, costs, benefits, and business opportunities with a focus on addressing how sustainable development can be supported by the energy island projects.

Finance opportunities and partnerships

The energy island construction and operation value chains involve multiple elements such as investment and finance opportunities, risks, models, and public-private and public partnerships. Research is needed as a basis for designing risk and coping strategies. A key element will be the opportunity costs related to developments in European and national energy markets and GHG emission reduction prices.

Local acceptance and use of ocean space

Energy islands and P2X systems will have major impacts on the economic, social, and environmental dimensions of sustainable development. Notably, the research should involve multi-purpose use of ocean space and resources, for example aquaculture, fisheries, container transport, tourism, science, etc. Moreover, social participation in decision-making should be addressed as part of processes which could support local acceptance.

Regulatory Options and Markets

Alignment of EU and national regulation

Energy islands will challenge the current EU mandate regarding cross-border activities. Furthermore, existing national regulatory policies and incentive schemes will need alignment as a basis for effective policy instruments. Studies need to involve fiscal interests, environmental laws, bidding systems. Effects of the EU Emission Trading System (ETS) should have special emphasis.

Integration with neighboring markets

Since the energy islands and P2X will be integrated into the European energy markets, research is needed into optimal system operation and integration with neighboring markets and price zones. This should include optimization of re-dispatch costs and welfare losses.

Recommendations for Education

The green transition is expected to create about 290,000 new jobs over the course of the next decade (Dansk Energi). To meet this demand for labour many employees in non-energy sectors must acquire new skills relevant for the green transition. The present sector development project shows that the planning, development, construction, operation, maintenance, dismantling, and end-of-life management of energy islands require many new technologies and new combinations hereof. Thus, an upgrade of the competencies of the existing workforce is essential. Consequently, continued education is needed. The solution would be courses targeting the different organizational levels of private companies and public institutions.

Special emphasis is recommended for the first Danish energy island, Bornholm. Establishing a DTU residential college at Bornholm in support of educational activities around power control systems and sustainable energy should be considered. Notably, this would be a natural fit for the DTU strategy of enhancing the engineering educational efforts of the university across Denmark ("Ingeniører til hele Danmark"). Furthermore, establishment of facilities for introducing primary school students to the Baltic Energy Island efforts should be considered.

Recommendations for Research Infrastructure

Several existing DTU research facilities have direct relevance to energy islands. Examples are PowerLab, the wind tunnel at DTU Risø, and test centre Østerlid. Still, new types of infrastructure will be needed to fulfill the research recommendations outlined above.

First and foremost, experimental facilities will be essential in supporting research and training activities and thereby increase the speed from idea to proof-of-concept and demonstration in a realistic operating environment:

- A test centre for energy island technology and the interaction between the technologies, including e.g., multi-terminal HVDC, storage and electrolysis including composite testing HVDC/wind power, and electrolysis control.
- A test facility for hardware and control-in-the-loop of HVDC converters and new control concepts.
- A digital twin with a real-time simulator integrated with Energiø Bornholm, which enables optimization of subsequent energy islands.

Near Shore Test Centre (NSTC) for detailed field measurements. The aim is to save resources by building as robustly as needed. The location must represent typical North Sea conditions in a scaled environment. This will enable simulation of 100 and 1,000 years of events of waves, forces, dynamics, etc. in an open sea environment from scaled field measurements. Thereby, the scale effects in laboratory flumes will be minimized. A location at Anholt has been identified as suitable for the test centre.

Real Life Experimental Research Centre for Testing Economic and Social Responses to Energy Islands and PtX. Experiments will be conducted to assess the responses of local stakeholders and communities to alternative designs and the location of energy islands and PtX projects in relation to social and economic costs and benefits, biodiversity, and local participation and benefit sharing. This will create knowledge about how projects can attract both political support and acceptance in the society at large, and thereby support a fast and cost-effective implementation, where both climate policy goals and sustainable development objectives are met simultaneously.

Recommendations for System Research Funding

Public research funding is generally characterized by a) short-term monetization, b) priority to short-term product innovation over pre-competitive technologies, c) priority to business opportunities of private companies over solutions to societal challenges.

Consequently, the current funding system does not encourage research and innovation in system aspects. This is problematic, not least in relation to energy islands since—as demonstrated in the present sector development project—solutions to the involved system integration challenges will be key successful establishment of energy islands and the related technical and economic systems.

Furthermore, the current limitations serve as an impediment to the fulfillment of the 2030 emission reduction target for CO_2. The funding system should therefore embrace research into system aspects and enablers of energy islands.

Credit: Energinet

Cases

The Baltic Energy Island

Bornholm has long been a leader in offshore wind. Moreover, the island has played host to extensive research and development activities led by Energinet.dk and DTU demonstrating the potential for integrating large amounts of renewable energy, mainly wind power, into the Danish energy system.

By late 2022, industry and academic partners joined forces with local authority Bornholms Regionskommune to establish The Baltic Energy Island at Bornholm foundation. The partnership aims to establish Bornholm as a hub for green energy innovation.

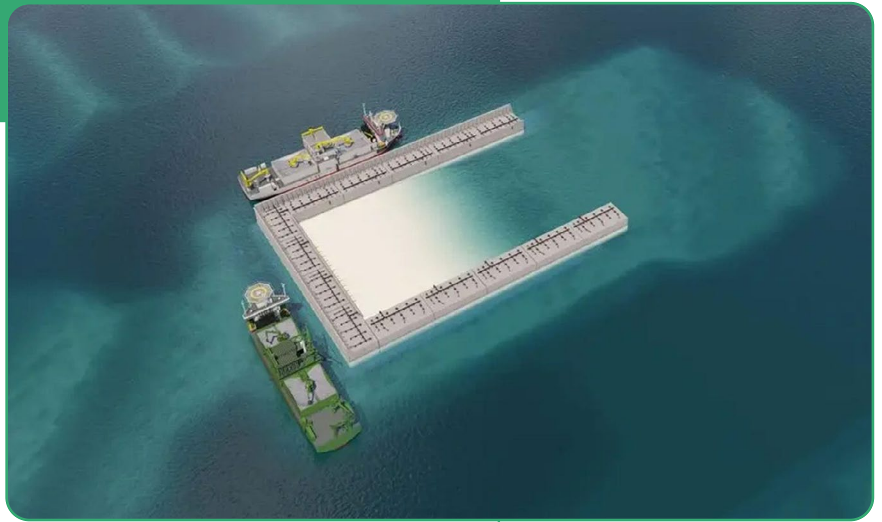
Current plans for offshore wind around Bornholm total 6.9 GW. This is equivalent to all wind power in Denmark today. Together, the projects represent investments of more than 125 billion DKK.

Bornholm's location is well-suited in relation to the green transition. Besides the ample wind resources, the island is close to Germany which is a large market for future production of green hydrogen and/or green wind power. Bornholm is also recognized internationally for its track record in developing, testing, and demonstrating energy technology solutions.

The Baltic Energy Island at Bornholm partners are Bornholms Energi & Forsyning, Bornholms Regionskommune, Rønne Harbor, Siemens-Gamesa, Ørsted, DTU, and Energinet.

Bornholm will become the first Danish energy island. Image : The Sanctuary Rocks (Helligdomsklipperne) near Gudhjem.
Photo credit: Shutterstock

Belgium builds one of the world's first energy islands



Construction of the Belgian energy island is to commence in early 2024. *Photo credit: Elia BE*

Construction of one of the world's first energy islands—meaning an artificial island built exclusively for green energy production—is under preparation 45 km off the coast of Belgium. The name will be Princess Elisabeth Island, and the project will occupy approximately 5 hectares above the waterline. The surrounding offshore wind farms are projected to generate 3.5 GW. Furthermore, Princess Elisabeth Island will serve as a link between the wind farms and the Belgian onshore high-voltage grid.

The energy island will be built with concrete caissons filled with sand and will feature a small harbor and a helicopter platform. Once completed, the island will be operated by TSO's Elia Group (Belgium) and 50 Hz (Germany). The tender for construction has been won by a consortium led by DEME and Jan De Nul. Construction is to commence in early 2024 and the artificial island is scheduled to be ready by August 2026. Hereafter, work on installing the high-voltage infrastructure will begin.

"The energy island will provide access to new wind farms from the Belgian North Sea and wind energy from Denmark and the United Kingdom. Thanks to the energy island, we will strengthen our energy independence, lower our bills, and reduce CO2 emissions," said Tinne Van der Straeten, Belgian Federal Minister of Energy, when announcing the result of the tender for construction of Princess Elisabeth Island by March 2023.

Next frontier: the US East Coast

Following some years of hesitation, the federal administration and state authorities in the US have opened opportunities for offshore wind power. Together, New York, New Jersey, Virginia, Massachusetts, Connecticut, Rhode Island, and Maryland have committed to buying 30 GW of offshore power by 2035. So far, projects totaling 11 GW have been awarded.

Two Danish companies, Copenhagen Infrastructure Partners (CIP) and Ørsted, are involved. CIP is developing, jointly with Avangrid Renewables, the Vineyard Wind Park, 15 miles off Martha's Vineyard, Massachusetts. The park will generate 0.8 GW, the equivalent of supplying about 400,000 American homes. Scheduled for inauguration in 2023, the park will become the first large-scale US offshore wind farm.

Investments by companies like Ørsted are expected to create about 38,000 direct and indirect jobs in development and construction in the New York / New Jersey area until 2030, according to a 2020 study by consultants Wood Mackenzie. Notably, many of the upcoming wind farms will be built quite far from the coast to limit the number of objections from coastal residents that would complain about having their ocean view spoiled. Building further from the coast will usually mean building at greater depths which in turn makes the establishment of energy islands additionally attractive. Therefore, many believe that the US East Coast may well become the new frontier for energy island development.

Offshore wind turbines near the US state of Rhode Island. *Photo credit: Shutterstock*

A locally anchored sustainable energy system

GreenLab in Skive is a green and circular industrial park dedicated to green transition. Here, various types of sustainable energy are generated and transformed into heat, green power, electro-fuels, and other green products depending on the specific needs of the industry residents.

A trademark of Greenlab is local community involvement. While GreenLab became a reality in 2019, Skive Municipality began preparations already in 2008. From early on, a key focus was strengthening local roots by demonstrating growth, creating new jobs and increasing employment.

These efforts were instrumental in recruiting a group of companies that all wanted to establish an energy symbiosis. Vestjyllands Andel produces protein-rich animal feed from starfish and thus offers a sustainable alternative to imported soy protein. Skive Biogas produces biogas of manure and waste. Stiesdal's SkyClean plant utilizes straw and other agricultural residues to make biochar to capture and store CO2. Eurowind Energy owns GreenLab Skive Vind which generates green electricity—wind and solar power - for the entire industrial park. NOMI4S handles waste—or rather: resources—for GreenLab and four municipalities. Quantafuel turns plastics that cannot be recycled in other ways into chemical oil.

All companies and energy streams are to be physically and digitally connected by GreenLab's unique SymbiosisNet. It will enable an exchange of surplus energy and resources between the various industries in the park. GreenLab also expects to launch 100 MW and 12 MW Power-to-X facilities. In other words, GreenLab is a living lab for the flexible, sustainable energy system of the future.

Neighbours are shown around GreenLab by the COO, Thomas Hagelund Helsgaun. Community involvement is key for GreenLab's success.
Photo credit: GreenLab

International initiative on energy islands

Headquartered in Paris, the (IEA) is broadly involved in energy solutions globally. One instrument is setting up task forces for specific technology development fields. A new initiative is a potential task force for energy islands under the IEA Technology Collaboration Program (TCP) on wind energy.

"Besides Denmark, interest in joining the task force has been expressed from other countries which are planning or considering energy islands in the North Sea, namely Belgium, Holland, Germany, and Norway. Also, USA seems keen to join the task, experiencing growing offshore wind activity especially off the US East Coast and more countries are expected to join along the way," says Birte Holst Jørgensen, Senior Scientist at DTU Wind and Energy Systems, coordinating the Danish participation in close cooperation with Nicolaos Cutululis, Professor, also at DTU Wind and Energy Systems.

"Leading academic groups from all countries with energy island activities have expressed their interest. The next step will be for government representatives from these countries to commit to financing the task," comments Birte Holst Jørgensen, noting that a decision by the Executive Committee of IEA Wind TCP can be expected by October 2023.

Provided a positive outcome, the IEA task on offshore energy hubs can commence its work by January 2024. IEA tasks will generally function for 3-4 years, delivering increased momentum for the technology or field in question during this period.

The International Energy Agency (IEA) is looking to set up a task force on energy islands.
Photo credit: Schneider/Shutterstuck

Appendix A

Detailed recommendations for research

Energy system integration

Integration into the future energy system

The energy islands will be part of a market-based, integrated, and complex energy system. Major gains are achievable from ensuring that the electrical and market designs for the first islands set the right course for future offshore wind power development and offshore P2X/electric grid infrastructure. As part of this, a better understanding of the wind resources in clusters of wind farms around the energy islands must be ensured. This includes knowledge of the spatial and temporal variability of production and our ability to predict lead times appropriate to facilitate system integration and inform energy markets.

There is a need for research in marked design for energy islands, including offshore bidding zones, transmission access guarantee designs, and management of congestion revenues. To keep costs down, it is key to make robust investments in infrastructure for electricity and hydrogen. Therefore, there is a need for research that gives a better understanding of the potential synergies of sector coupling, benefits of access to seasonal storage such as salt caverns, as well as the competition in a European perspective. These problems imply a need for further development of large-scale models for power system modeling, power market modeling and integrated energy system modeling.

Energy island design optimization

Analytical tools must be developed in support of investment decisions regarding sizing, over-planting, electricity/hydrogen ratio and other key questions for energy islands. There is an unmet need for well-founded technical-economic analysis tools that can contribute to the de-risking of investment decisions in the energy islands, for example questions about sizing, over-planting, electricity/hydrogen ratio, etc.

Design optimization requires models for e.g., wind resources, electricity markets, wind farms, and electrolysis plants. More knowledge is needed regarding electrolysis plant design options (various technologies, modularization, infrastructure layout, plant control, etc.) and proper representation of the various plant components in such models.

Furthermore, dynamics must be considered to allow for proper optimization. This research needs to be kept informed about developments in the research topic of the larger energy system integration as well as sustainability and life cycle analysis, which may guide matters relating to spatial and operational constraints of wind farms around energy islands. Also, optimal solutions for integration with bunkering of green fuels should be investigated.

Converter-based power systems

Operating an electrical system almost without inertia, as will be the case for energy islands, is unknown today. A system of this kind must be based on HVDC (high-voltage direct current) and electronic power converters.

There is a need to develop AC/DC topologies, protection concepts, control methods, and other devices and systems that can reduce the need for hardware and thus significantly reduce costs. These solutions must guarantee the robustness of the energy island's power system, thereby ensuring the integrity and safety of the overall energy system.

Energy islands offer an important opportunity for new design, operation, and maintenance models due to the potential location of high value/availability subsystems such as the substation of the wind farm onshore. Integrated models can be developed that can investigate different strategies (system wide) towards optimization and reduction of OPEX costs.

Optimizing wind turbines and HVDC converters

Large gains can be achieved by optimizing today's wind turbines, HVDC (high-voltage direct current) converters, and other electrical system components for a hub-based system such as an energy island. Also, effective design of the energy islands requires innovative solutions within electrolysis, storage, etc. For example, development of multi-terminal DC networks, multi-vendor HVDC, DC wind turbines and offshore electrolysis, which do not yet exist today. The technologies hold significant business opportunities that can simultaneously make the energy islands and the overall energy system cheaper.

Digital analysis of security of supply and cybersecurity

The energy island power system will by far exceed known systems in complexity. In terms of control, the energy islands are an unprecedented form of complex power system.

Optimum coordination of just a few HVDC converters requires complex analysis that lies beyond conventional calculation methods. Thus, new tools must be developed based on e.g., digital twins, trustworthy artificial intelligence (AI), quantum technology, and hybrid RMS/EMT (Root Mean Square/Electromagnetic Transient) calculations. For example, quantum computers can provide critical stability and grid optimization calculations, and quantum-safe cryptography is necessary for future-proof cybersecurity.

'Local' digital twins can be integrated through appropriate interfaces to simulate the performance of sub-systems or the whole system, setting a very interesting research challenge that can contribute to the development of complex digital architectures.

Technical design

Evidence-based design methodologies

The design of offshore structures is based on the loads imposed by wind, waves, and currents. Methodologies described in guidelines were largely developed 40-50 years ago. There is room for using modern methodologies.

First and foremost, the industry must go from experience-based to evidence-based solutions. Using experience and not evidence can lead to overly conservative results, which makes the solutions more expensive one way or the other. Through modern, evidence-based methodology it will be possible to achieve large savings without compromising safety.

An internal industrial understanding emerges, which might not be based on scientific evidence and in worst cases non-conservative. Often simplified versions of for instance wave dynamics are used to translate the environmental conditions into loading.

Research is needed to provide evidence-based methods for environmental interaction with offshore structures in full scale under natural conditions over a long time span. This shall be based on enhanced research infrastructure and associated research, for example of meteorological and oceanographic conditions.

Improved cable installations and bottom protection

Extreme loading conditions and performance requirements over the operational lifetime of an energy island challenges the prediction of geotechnical changes, i.e., ground deformations. One of the challenges is the uncertainty related to soil characterization, where currently conservative methods or 'experience-based solutions' are used.

Extreme loading conditions and performance requirements over the operational lifetime of the project pose another challenge for the prediction of the deformations (settlements) in the ground. Furthermore, the industry faces challenges with cable protection systems from the wind turbine to the seabed, interaction with the seabed itself, and cable crossings. There is an immense potential for reducing costs on cable systems and risk of failure, as approximately 10 % of the LCOE for an offshore wind farm is spent on cables and cable installations.

Many of the installations for the energy island concept are facilities on the seabed, e.g., transition from caisson to seabed. The whole array of cables and the risk of failure due to hydraulic or human impacts pose a major risk to the functionality of transport systems to and from the energy island. The geotechnical site characterization in offshore conditions is instrumental in the assessment of the performance of foundations, and it is crucial for the resilience and durability of the island. Fundamental evidence-based methods for protection systems are lacking or at least scarce.

Research is needed for the development of evidence methods that cover a larger area of conditions including full-scale measurements and analyses. The research should lead to optimization of the employed methods and for development of innovative solutions that contribute to minimization of the environmental impact.

Automation and preventive maintenance

Through more stable operation and reduction of man-hours, automation and use of preventive maintenance has been shown to enhance the operational time of large assets significantly.

There are significant cost-saving opportunities in aligning the life cycle systems in an effective delivery chain all the way from component manufacturing to complete installation. One area of particular interest is the maintenance of large assets. Experience shows that use of automation of technologies and manual work processes for stable technical operation and saving of man-hours and by use of preventive maintenance can enhance the availability by approximately 4 % if carried out in a more systematic way.

Experience from large scale installations such as oil and gas, power plants, wind farms etc. show that design of the so-called life cycle systems, i.e., manufacturing, installation, operation, maintenance, and decommission plays a major role in the total investment and operational efficiency. Traditionally all these systems are designed uniquely with relatively little coordination in relation to the asset design. Modularization is a new paradigm that comes from mass manufacturing, but it has not systematically been applied in low volume or one-of-a-kind asset design, manufacturing, operation, and maintenance.

There is a need for research in support of the development of electronic definition models for both assets and life cycle systems that enable different alternative comparisons concerning asset and life cycle design. For instance, this includes the balance between manufacturing onshore versus installation offshore and the balance between preventive and corrective maintenance.

Placement and design of P2X facilities

P2X facilities require power, hydrogen, and CO2 as well as the possibility of supplying consumers with by-products such as oxygen and heat. Identifying optimal locations requires modeling and analyses. Furthermore, research must establish the pros and cons of offshore relative to onshore production of P2X molecules.

There is an opportunity in finding an optimum location of industrial facilities for hydrogen and derivatives such as ammonia. Furthermore, there are substantial challenges to achieve cost reduction in the Haber-Bosch process, a process that fixes nitrogen with hydrogen to produce ammonia. These challenges include for instance cost-competitive decentralization with smaller-scale ammonia production, process intensification and integration (e.g., hydrogen from electrolysis of water and an air separation unit integrated).

The cost of installation and operation of a pipe for hydrogen transport is expected to be significantly lower than transporting electricity over large distances. On the other hand, offshore facilities are known to be more expensive in installation and operation. As the electrolyzer field is advancing, flexibility is necessary, which calls for a modular design approach. The development of 'plug and play' integration is essential as this will allow easy replacement of parts, and a more competitive market for electrolyzers. Analysis and protocols could greatly reduce costs and mitigate risks.

Research is needed on the benefits of cheaper transport with P2X molecules versus challenges in operation and maintenance offshore, compared to onshore production but with higher transportation costs for power.

Management of water for hydrogen production

For every GW power for hydrogen production, ~1.8 million m3 of water is needed annually. Notably, this water must be ultrapure, meaning that comprehensive processing is needed before sea water can be utilized for the purpose.

In addition, high-quality cooling water is needed due to the waste heat generation. A challenge is to make pipes that are both compatible for hydrogen and viable for corrosive seawater.

State-of-the-art seawater desalination technologies such as reverse osmosis are characterized by high maintenance, complex systems and large energy consumptions. Thermal integration of electrolyzers and seawater desalination processes could offer a highly dynamic and efficient system to meet transient water demand for future offshore H2 production. An alternative to water purification is developing salt/sea-water tolerant electrolysis. Hydrogen intercalates into many metals, expanding their lattice, and negatively affecting the metal's mechanical properties.

There is a need for research for the design of a reliable, efficient, and compact seawater desalination system, and research is needed for creating and analyzing new materials that are both corrosion resistant, and do not lose their material properties under high H2 pressures.

A legacy of technical design challenges

Numerous projects relevant to construction of energy islands have experienced challenges regarding cable system installation and other technical design issues.

At the Horns Rev offshore wind power farm, platforms proved unable to tolerate even moderate storms. Notably, the guidelines at the time of construction had been followed.

Also at Horns Rev, the erosion protection sunk by 1.5 m partly due to overly cautious use of protective stones.

At the Robin Rigg Wind farm, Scotland, geotechnical and hydraulic challenges caused problems for the foundation. It was later demonstrated that the technical standard contained a calculation error. The project was delayed by a full year.

At the Great Belt project, geotechnical issues caused several years of delay.

Environmental sustainability

Life cycle assessment (LCA) of infrastructure

Infrastructure, construction, and facility operation of energy islands are at a scale which exceeds most other installations in society. Thus, the associated environmental impacts are currently unknown. Environmental sustainability involves a wide range of environmental impacts, including climate, resources, toxicity, and biodiversity.

Life cycle assessment (LCA) is a well-established methodology for quantification of environmental impacts; however, good assessments require good data describing infrastructure, technologies, and surrounding systems throughout construction, operation, and end-of-life phases.

Research is needed to provide the data required to describe the full life cycle of energy islands and associated installations. Consistent LCA models and methodologies need to be established to make holistic quantification of environmental impacts, not only for climate but also other impact types. Energy island infrastructure, design, and construction should be based on LCA modelling to identify environmentally optimal installations. The environmental impacts should be evaluated in relation to relevant biophysical boundaries that can be allocated to energy islands.

LCA of P2X and system integration

Energy islands may have profound effects on other sectors, for example through associated P2X technologies, fuels, etc., depending on the technologies included in the energy island installations.

Assessments should involve relevant technology development pathways, potential technology alternatives, and options for system integration. Potential implementation scenarios should address routes for implementing the technologies into full systems, the importance of sector-coupling, infrastructure lifetimes, and end-of-life options.

Consequences for biodiversity and ecosystem service provisioning to society

Based on the projected scale, the energy islands and associated wind farms are likely to impact marine ecosystems and biodiversity more than anything previously seen in Danish waters. Impacts will include changes in currents, artificial light regimes, noise levels, wake and wind effects, sedimentation rates, habitat structure, distribution, and diversity of marine life. This raises questions about how to plan and operate renewable offshore energy without adding further to the ongoing biodiversity crisis.

To understand the complexity of these consequences, including how to avoid or mitigate them, research is needed into modelling of both short and long-term ecosystem impacts caused by the infrastructure's direct and indirect alteration of ecosystem states and processes. This includes studies on present and future impacts on the abundance, distribution, and behaviour of marine life throughout their lifecycles, at local and sea basin scales.

All these topics are increasingly feasible to study through a new wave of ocean observation systems ranging from automated sampling of environmental DNA to monitor species presence, to large scale scanning of water columns and 3D bottom mapping using sensors combined with automated object identification and tracking (e.g., fish species, vegetation, other marine life).

Societal and business perspectives

Macroeconomic perspectives, cost-benefit, and sustainable development

Energy islands imply very large investments and consequently large impacts on societies' welfare in terms of income generation, greenhouse gas (GHG) emissions, ecosystems, and social factors including employment and local participation in addition to business opportunities and exports.

The large construction activities could furthermore include both large export and business opportunities and bottlenecks from a Danish and European perspective, which need to be addressed to ensure cost-effective project development and implementation.

Research is needed into quantitative studies of the economic, technical, legal, environmental, and safety risks, costs and benefits, and business opportunities of energy island projects including impacts on power production, system flexibility, and fuels for off-take sectors or higher value products. Project level, sectoral, and macroeconomic studies are needed.

Finance opportunities and partnerships

The energy island construction and operation value chains involve multiple elements such as investment and finance opportunities, risks, models, and public-private and public partnerships.

The risks associated with energy islands and P2X projects are related to the respective value chains of the construction and maintenance of the projects including both aspects of technologies, costs, markets, and future climate and energy security policies influencing demand for the outputs.

Research is needed into the systematic mapping studies of risks and coping strategies as a basis for risk proofing of projects as a basis for finance and public-private partnerships. A key component will here be to assess the opportunity costs of the technologies in the context of energy system costs, European energy markets, and GHG emission reduction prices and climate policy commitments nationally and in the EU context.

Local acceptance and use of ocean space

Energy islands and P2X systems will have major impacts on the economic, social, and environmental dimensions of sustainable development. The impacts can be both positive and negative. Addressing these impacts is important in project and policy design due to the large scale of the projects and because meeting sustainable development goals are very high priorities among European decision makers, civil society, and companies.

Research is needed into the sustainable development impacts of energy islands and P2X including economic impacts (macroeconomic, sectoral, and project related), social impacts (employment, participation, local benefits, and costs) and environmental impacts (climate and other environmental impacts).

Detailed LCS analysis should address specific technologies and constructions, and economic and social impact studies based on modelling and stakeholders can address the larger-scale impacts of energy islands and P2X. Multi-purpose use of ocean space and resources (aquaculture, fisheries, container port, tourism, research etc.) would be important to address in this context. Social participation in decision-making and in the design, and implementation of energy islands should also be studied as part of processes that can support local acceptance.

Regulatory options and markets

Alignment of EU and national regulation

Energy islands will challenge the current EU mandate regarding cross-border activities. The implementation of energy islands and P2X will need support of regulatory options and markets going beyond the current limited EU mandate within cross-national borders. Existing national regulatory policies will also need alignment, and integrated modelling of demand and supply for electricity and P2X in different European and international regions will be needed as a basis for designing effective policy instruments.

Research is needed into the assessment of how regulatory options including economic instruments, innovation policies, and public-private partnerships can support uptake of solutions among energy island developers. Given the regulatory options, the perspectives of decision makers, including fiscal interests and environment laws and bidding systems, should also be studied. Adjustments and development opportunities for aligning the EU Emission Trading System (ETS) with CO2 taxes and broader tax systems should be addressed. Research should also address how local societies can obtain a share of benefits created by the projects to compensate for any possible downsides of having the projects in the area.

Integration with neighboring markets

Since the energy islands and P2X facilities will be integrated into the European energy markets, research is needed into optimal system operation and integration with neighboring markets and price zones. Price structures and trading possibilities will be critical to the cost effectiveness of projects.

Research must include adequate market configuration (optimal price zones) for energy islands to optimize redispatch costs and welfare losses to reach the lowest system cost. The economics of the projects in terms of optimal coupling of electricity and X markets offshore and onshore including price and market structures are also a key research topic.

Credit: Energinet

Appendix B

Members of the steering committee and interviewees

Members of the project steering committee

Department Director Morten Willaing Jeppesen,
DTU Wind and Energy Systems

Department Director Jane Hvolbæk Nielsen,
DTU Physics

Department Director Friedrich Wilhelm Köster,
DTU Aqua

Department Director Kim Dam-Johansen,
DTU Chemical Engineering

Department Director Claus Hélix-Nielsen,
DTU Sustain

Department Director Jan Madsen,
DTU Compute

Department Director Søren Linderoth,
DTU Energy

Department Director Hans Nørgaard Hansen,
DTU Construct

Department Director Malene Kirstine Holst,
DTU Engineering Technology

Department Director Mette Wier,
DTU Management

Department Director Erling Halfdan Stenby,
DTU Chemistry

Senior Vice President Klaus Winther Ringgaard,
COWI

Climate and Environmental Manager
Camilla Rosenhagen,
Danish Harbours

Chief Technical Officer Jørgen S. Christensen,
GreenPowerDenmark

Chief Executive Officer Anders Stouge,
The Danish Construction Federation (DI Byggeri)

Senior Vice President Marianne Thellersen,
DTU (Chair)

List of interviewees

Chief Innovation and Product Officer
Per Hessellund Lauritsen,
Siemens Gamesa

Innovation Manager (PtX) Finn Daugaard Madsen,
Siemens Gamesa

Managing Partner Charlotte B. Jepsen,
CIP Foundation

Senior Project Manager Gorm Boe Petersen,
CIP Foundation

Chief Technical Officer Frederik Smidth,
Maersk Supply Services

Commercial Manager Torben Nørgaard,
Maersk Zero Carbon Center

Liaison Officer, Research & Innovation
Henrik Tirsgaard,
TotalEnergies

Chief Executive Officer Anders Stouge,
The Danish Construction Federation (DI Byggeri)

Senior Executive Officer Søren Mensal Kristensen,
The Danish Energy Industries Federation (DI Energi)

Module Design Owner Torsten Lund,
Vestas

Chief Consultant Morten Stryg,
Green Power Denmark

Principal Adviser Hans Van Steen,
European Commission, Directorate General for Energy

Senior Engineer Fitim Kryezi,
Energinet

CTO Power-to-X Poul Georg Moses,
Haldor Topsøe

Chair of System Development Committee
Gerald Kaendler,
ENTSO-E

Senior Specialist Léa Dehaudt,
ENTSO-E

Head of Grid Development Kristof Sleurs,
Elia Transmission Belgium

Consultant Torben Glar,
CIP Projects

Head of Division Carl-Christian Munk-Nielsen,
Danish Energy Agency

Head of Section Rasmus Tind Kristensen,
Danish Ministry of Climate, Energy and Utilities

Business Unit Manager Tore Lucht,
Sweco

June 2023
Cover: The Danish Energy Islands,
credit: Energistyrelsen / Danish Energy Agency

PUBLISHER
Technical University of Denmark
Anker Engelunds Vej 101
2800 Kongens Lyngby

CONTACT
Professor Jacob Østergaard,
jaos@dtu.dk, DTU Wind and Energy Systems

Professor Erik Damgaard Christensen,
edch@dtu.dk, DTU Construct

Professor Kirsten Halsnæs,
khal@dtu.dk, DTU Management

Project Manager Leon Aahave Uhd,
laauh@dtu.dk, DTU Partnerships

Technical University of Denmark

Anker Engelunds Vej 1
2800 Kgs. Lyngby
Denmark

www.dtu.dk