MAKING ENERGY ISLANDS A SUCCESS

ENERGY ISLAND FORUM

Front page picture, Siemens Gamesa Renewable Energy

Graphic design, Isabella Marckmann Hansen

An executive summary

Introduction

This roadmap outlines what needs to be in place to realise the ambitious projects of building offshore energy hubs (OEHs), that, while feasible, are often likened to a ”Mars mission for the energy system” due to their scale and complexity. These hubs are crucial for integrating large amounts of offshore wind energy into the power grid, supporting climate goals, and enhancing energy stability and security.

A potential European stronghold

European nations are uniquely positioned to benefit from offshore energy hubs due to their vast maritime space, advantageous wind resources and ambitious climate goals. Offshore energy hubs can significantly contribute to the European Union’s (EU’s) 2030 and 2050 greenhouse gas reduction targets by providing a robust infrastructure for renewable energy integration. They also offer economic benefits through job creation, technological advancements, and enhanced energy security by reducing reliance on imported fossil fuels. This makes offshore energy hubs a highly attractive option for achieving the EU’s climate goals while minimising expenses.

Two horizons for actions – 2030 and 2050

The roadmap focuses on two key horizons: 2030 and 2050.

- **2030 Horizon:** The goal for 2030 is to identify actions that will ensure the realisation of the first offshore energy hubs before or shortly after 2030. Efforts leading up to this horizon will prioritise the demonstration and implementation of initial projects, which are crucial for generating insights to guide subsequent offshore energy hubs. Several projects are currently underway. For example, Belgium is constructing the Princess Elisabeth Island, an artificial island expected to be operational by the late 2020s. Meanwhile, Denmark is advancing plans for Energy Island Bornholm, which will repurpose an existing island into an offshore energy hub (OEH).
- **2050 Horizon:** The focus for 2050 is to outline pathways for research, innovation, and demonstration that will enable offshore energy hubs to be fully aligned with the future energy strategy of the EU and hence integrated into energy grids. By 2050, offshore energy hubs should be cost-effective, reliable, and safer, serving as the backbone of future European energy systems and laying a pivotal role in the global green transition.

Key actions for politicians, universities, and industry

For both the 2030 and 2050 horizons, key actions must be initiated today. The 2030 Horizon focuses on delivering the first offshore energy hubs, while the 2050 Horizon emphasises fostering innovation to make offshore energy hubs increasingly cost-effective and impactful by mid-century, developing offshore energy hubs as a stronghold for Europe.

2030 Horizon

1. **Develop and Implement Regulatory Risk Management Measures:** Establish regulatory frameworks to manage risks associated with OEH projects, enabling and encouraging investments in offshore wind within OEHs.

2. **Create a Comprehensive EU Financing Mechanism:** Design and implement a robust EU-wide framework to facilitate and streamline funding, and/or a financial risk sharing mechanism for OEH infrastructure, ensuring alignment with broader energy goals.

3. **Foster industry collaboration:** Encourage partnerships between industry stakeholders to share knowledge, resources, and best practices, accelerating the deployment of OEHs.

4. **Establish a Shared Framework for Innovation and Research:** Leverage the first OEHs to generate essential knowledge on OEH technology and regulation. Develop a common framework to utilise these projects as a foundation for further innovation and research.

5. **Engage Local Communities:** Foster societal acceptability and support by involving local communities in the planning process and effectively communicating the tangible benefits of OEHs.

2050 Horizon

1. **Promote regional planning:** Encourage coordinated regional planning to optimise seabed usage and ensure the successful realisation of OEH projects.

2. **Support long-term innovation and research:** Invest in research and development to address emerging technical challenges, improve efficiency, and foster innovation in offshore hubs and renewable energy technologies. Universities and industry should collaborate on cutting-edge research and pilot projects.

3. **Develop educational initiatives:** Universities should develop specialised programs and courses to train the next generation of engineers and scientists in renewable energy technologies and OEH development.

4. **Create European excellence:** Foster an ecosystem enabling excellence and innovation in the multidisciplinary topic of OEHs.

5. **Align sustainable development goals:** Align OEH projects with broader sustainable development goals, ensuring they contribute to environmental, social, and economic sustainability.

Five innovation fields

The roadmap is organised into five key fields of innovation, each addressing critical aspects of offshore energy hub development and giving more specific actions:

1. **Power & Energy Systems:** Focuses on developing electrically islanded AC (Alternating Current) systems connected to multiple onshore substations via DC (Direct Current) transmission systems. It emphasises the need for standardised grid codes and simulation tools for reliable and scalable operations.

2. **Offshore Wind:** Highlights the importance of tailoring wind turbines to the unique requirements of OEHs, optimising hardware and software for island-mode operation, and addressing cyber-security concerns.

3. **Power-to-X & Green Fuels:** Discusses the integration of Power-to-X facilities for green hydrogen production, the challenges of fluctuating wind energy, and the need for coordinated infrastructure development.

4. **Society & Environment:** Examines the socio-economic and environmental impacts of OEHs, emphasising early community engagement, bio-diversity standards, and comprehensive life cycle assessments.

5. **Regulation:** Addresses the regulatory challenges and risks associated with OEHs, proposing new risk management measures, new financing mechanisms and regional planning approaches to support investment, including from private investors, and development.

Key Concepts

Offshore Energy Hubs: Central points where energy from offshore wind farms is collected, potentially utilised for offshore hydrogen production, and transmitted to onshore grids via optimised grid connections.

Different kind of islands: Offshore energy hubs can be built on either platforms, artificial islands, or consisting physical islands.

Different kind of configuration: An offshore energy hub can be configured as a hybrid interconnector with limited demand at the hub. An offshore energy hub can also be configured with Power-to-X production at the hub to take advantage of excess wind and balance the grid.

Benefits: Offshore energy hubs reduce infrastructure needs, enhance operational stability, improve cost-efficiency, give access to more wind resources to be harvested, and support large-scale renewable energy production and storage.

This summary highlights the strategic vision and detailed planning needed to make energy islands a success. If you have any questions or need more specific details on any section, please don't hesitate to reach out.

Enjoy the read!

Foreword

Building offshore energy hubs is a "Mars mission".

Building offshore energy hubs has been described as a "Mars mission." While this analogy may seem daunting, it speaks to the scale of ambition required to tackle the next frontier in international offshore development and not their feasibility. Offshore energy hubs are feasible. When designed, constructed, and operated effectively, these hubs can deliver significant economic, social, and environmental benefits. However, without proper planning and execution, they also carry the potential for negative impacts, underscoring the importance of meticulous attention to detail throughout the process.

To mitigate potential negative impacts and pave the way for future projects, it is essential to consolidate experience and insights from across the industry, developers, academia, and investors on a global scale. Preparing for the next wave of projects requires identifying knowledge gaps, determining where new research is needed, and recognising where existing knowledge can be adapted or integrated in innovative ways.

This is where the Energy Island Forum (EIF) plays a pivotal role. The Forum unites key international stakeholders essential for advancing third-generation wind energy and fostering the collaborative innovation required for success. It also provides a platform to develop concrete actions that address challenges and ensure energy islands succeed within an international framework.

The challenges we face in developing offshore energy hubs extend beyond technology. They are systemic issues that span technology, regulation, and society, all requiring collective solutions. To tackle these complexities, the current roadmap is organised into five key workstreams, each focusing on critical aspects of offshore energy hub development: generation and conversion technology (offshore wind and Power-to-X), system integration, regulation, and society & environment. While these workstreams are addressed individually, we recognise that they are deeply interconnected, with each influencing and being influenced by the decisions made in others.

This is just the beginning. A roadmap is not the final goal but a tool to guide us toward our objectives. Our roadmap will be a living document, continuously updated and refined as new knowledge is shared, and as insights are gained from the first projects. As this process unfolds, we will deepen our understanding of both the potential and the challenges associated with offshore energy hubs. With this in mind, we encourage readers to approach the first version of this roadmap with an open mind. If it prompts thoughts about what should be revised or what is missing, we invite you to join us on this journey. Your participation is welcome, and together, we can shape the future of offshore energy hubs.

Nicolaos Cutululis
chair EIF

Anders Vedel
vicechair EIF

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The concept of Offshore Energy Hubs

World's largest renewable energy project

What are Offshore Energy Hubs?

Over the past few decades, renewable energy sources and technologies have become household names. The ways in which we harness and commercialise these resources have advanced significantly, making them more accessible and marketable. In the 1980s, the first generation of wind turbines was installed on land. About 20 years later, the second generation of turbines was deployed at sea. Now, the industry is focusing on a new evolution.

Offshore Energy Hubs

Offshore energy hubs are crucial for achieving national and EU greenhouse gas reduction goals, providing a pathway to a sustainable future. Offshore energy hubs are innovative infrastructures designed to integrate large amounts of offshore wind energy into the energy grid, enhancing operational stability, improving cost-efficiency, and supporting ambitious climate goals. Offshore energy hubs serve as central points where energy generated from offshore wind farms is collected and then transmitted to onshore grids.

How do Offshore Energy Hubs work?

The advantages of offshore energy hubs are vast and broad and their main operating mechanism is quite simple. The offshore energy hubs themselves don't generate power but gather the energy from nearby offshore wind farms instead. The energy is then transported through its infrastructure as either electricity, hydrogen or other Power-to-X fuels to multiple markets, thereby creating a dual purpose for their infrastructures. Through this method and infrastructure, they can support the connecting markets and utilise connection capacities much more efficiently than has been done until now. This approach supports the infrastructure needed for widespread adoption of clean energy, making the green transition more efficient and scalable and will provide access to many more potential wind resources than lots of radial parks.

Benefits of Offshore Energy Hubs

Cost Efficiency: Offshore energy hubs reduce the need for extensive transmission lines and lower operation and

Anholt offshore wind farm, Ørsted

maintenance costs by serving as centralised distribution points for energy generated by various offshore renewable sources.

Scalability: Designed to meet growing global energy demand, offshore energy hubs provide a foundation for future renewable energy sources.

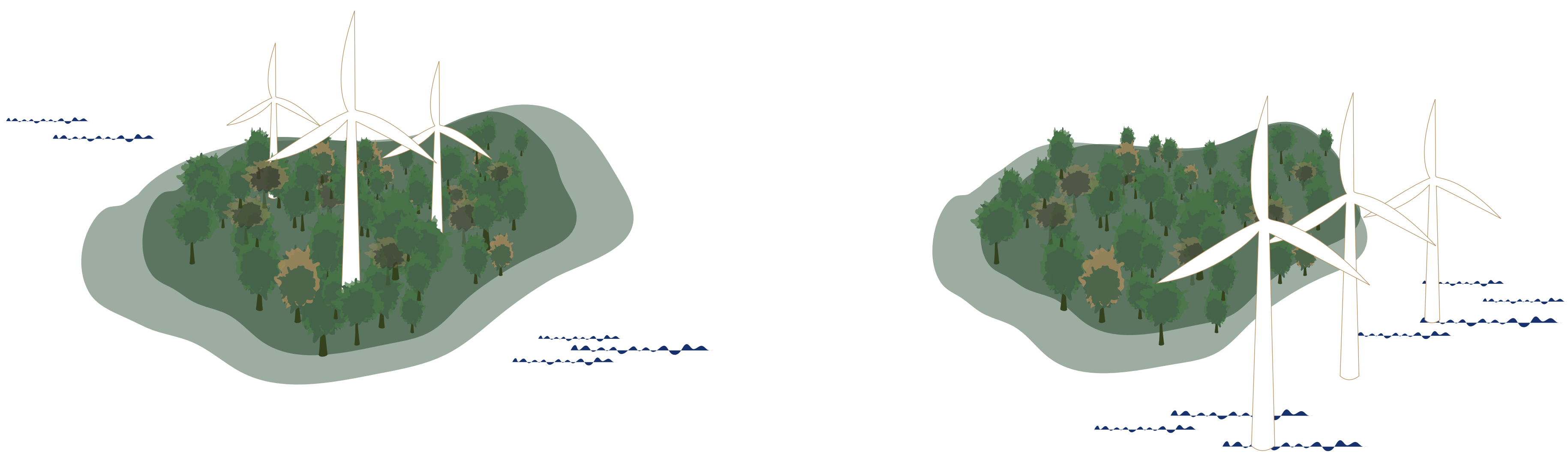
Land Conservation: By moving energy production offshore, countries can free up land space and reduce reliance on fossil fuels, aiding in climate goal achievement.

Power-to-X Integration: Offshore energy hubs can support technologies like Power-to-X, which converts electricity into other energy carriers like green hydrogen, providing large-scale energy storage and green fuel production.

Relevance for Europe

European Energy Market: European nations need to collaborate to reduce their collective greenhouse gas emissions. The EU has set ambitious goals for 2030 and 2050, requiring robust infrastructure to support current efforts and future innovations. With access to vast maritime space, Europe is well-positioned to benefit from offshore energy hubs, which can simplify the integration of new technologies and ensure the energy sector remains resilient and upgradeable long after 2050.

Economic and Environmental Impact: Offshore energy hubs can generate significant job opportunities and boost maritime industries like shipping, which are culturally and economically important in Europe. They would also optimise the European electrical grid, providing a more efficient, cost-effective way to meet the



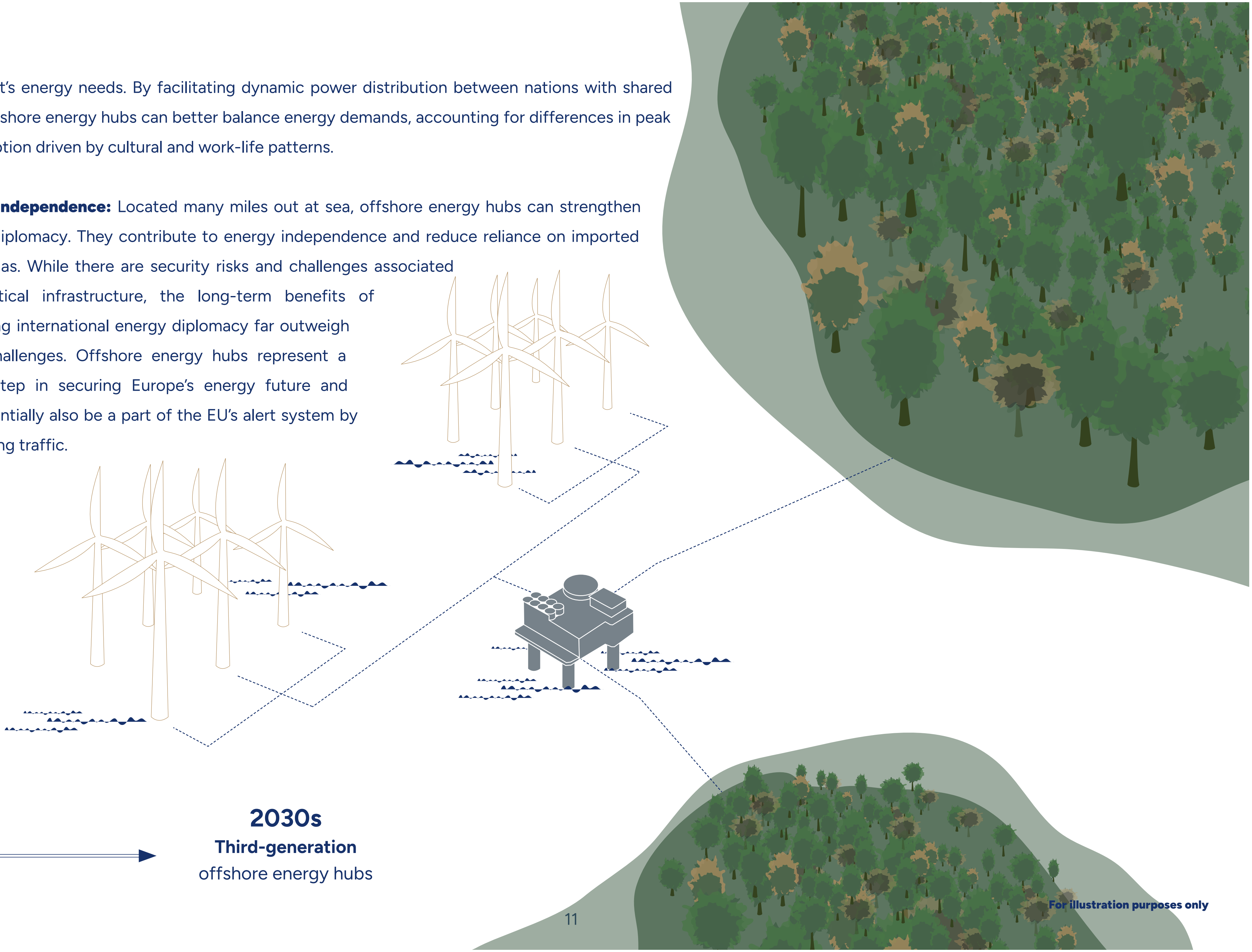
1980s
First-generation
onshore wind energy

2000s
Second-generation
offshore wind energy

For illustration purposes only

continent's energy needs. By facilitating dynamic power distribution between nations with shared hubs, offshore energy hubs can better balance energy demands, accounting for differences in peak consumption driven by cultural and work-life patterns.

Energy Independence: Located many miles out at sea, offshore energy hubs can strengthen energy diplomacy. They contribute to energy independence and reduce reliance on imported natural gas. While there are security risks and challenges associated with critical infrastructure, the long-term benefits of enhancing international energy diplomacy far outweigh these challenges. Offshore energy hubs represent a crucial step in securing Europe's energy future and can potentially also be a part of the EU's alert system by monitoring traffic.



2030s
Third-generation
offshore energy hubs

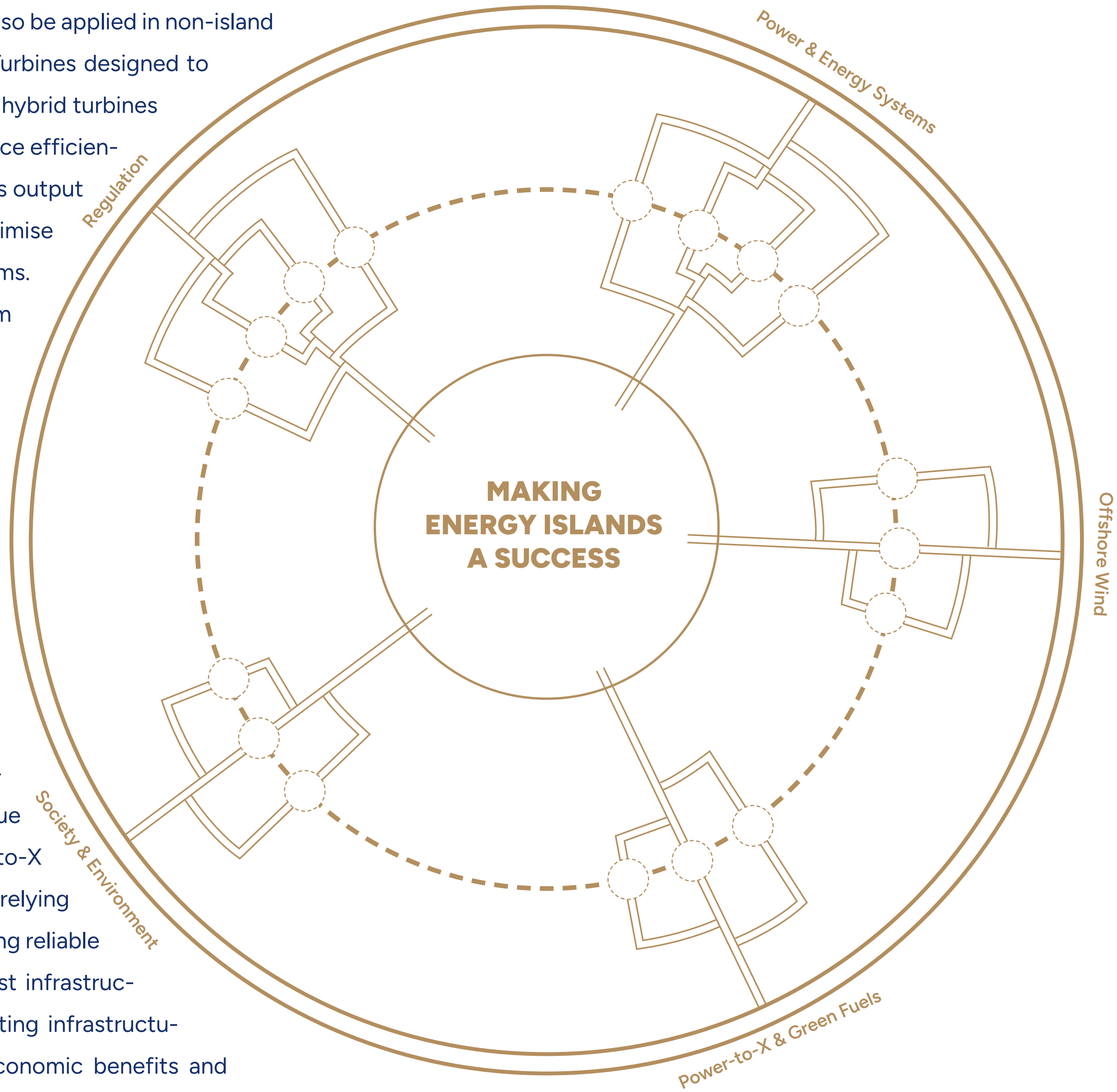
The Five Innovation Fields

Through the work of the Energy Island Forum, the members contribute broad and extensive knowledge regarding all aspects of Offshore Energy Hubs. To best utilise and activate this knowledge bank, EIF works with five different workstreams where its members can contribute to the topics, they find important. These workstreams are Power & Energy Systems, Offshore Wind, Power-to-X & Green Fuels, Society & Environment, and Regulation. The topics themselves cover broad areas, and many partners contribute to multiple workstreams. An appetizer on the content of each workstream is given below.

Power & Energy Systems: Creating electrically islanded AC systems linked to multiple onshore substations via DC transmission, including multi-terminal configurations, demands a clear and practical framework. These systems must enable efficient power generation, integrate supporting technologies like battery storage, and ensure compatibility across different vendors. To achieve this, a standardised approach rooted in current industry practices is essential. This approach outlines the design, development phases, and evolution of offshore energy hubs. Existing offshore projects, which fall below the baseline of this plan, are excluded from this roadmap. Key elements include standardised grid codes, electrical interfaces, and adaptable requirements from TSOs. Additionally, leveraging real-time digital twin models can help test control strategies and ensure the hubs are reliable, scalable, and interoperable.

Offshore Wind: Significant cost savings can be achieved by customising wind turbines for the specific needs of offshore energy hubs. Because offshore energy hubs-grids operate independently as isolated AC systems with no direct consumers, turbine requirements can be simplified, focusing grid compliance efforts on the DC converters that deliver power to shore. Turbine control systems will vary depending on the offshore energy hubs setup. For island-mode operation, which can also be applied in non-island settings, specialised hardware and software will be necessary. Turbines designed to support electrolysis may need entirely new configurations, while hybrid turbines could serve both power grids and hydrogen production. To enhance efficiency and reduce wear, wake effects - where wind turbulence lowers output and increases turbine strain - should be carefully modeled to optimise turbine placement and reduce impacts on nearby wind farms. Finally, the interplay between turbines and new components from the energy hub environment will require new cyber security standards to be developed.

Power-to-X & Green Fuels: Power-to-X facilities require power and water and can supply by-products like oxygen and heat, making their placement fundamental. Advanced modeling and analysis are essential to optimise their location. Research must balance the cost advantages of producing Power-to-X molecules offshore - where transport is cheaper - against the operational and maintenance challenges compared to onshore production, which incurs higher costs for power transport. Directly linking wind turbines to electrolysis presents unique challenges due to fluctuating wind energy, requiring Power-to-X systems to operate efficiently under variable conditions without relying on a stable power grid. Addressing this variability is key to achieving reliable performance. Offshore hydrogen production also requires robust infrastructure to connect production sites to demand centers. Coordinating infrastructure development across projects is crucial to maximise socioeconomic benefits and support a smooth energy transition.



Society & Environment: Offshore Energy Hubs will have far-reaching economic, social, and environmental impacts. To support sustainable development, comprehensive assessments must examine macroeconomic outcomes, job creation, community involvement, and environmental effects. Engaging local communities early is essential to ensure projects align with regional priorities, drive local economic growth, and create jobs. A key concept here is identifying and supporting the values in local communities so that OEHs can be part of a European ambition to foster regional growth, especially in rural areas. The central question is how OEH projects can collaborate with local partners to ensure community engagement, adapt projects to local conditions, promote local employment, and support community values.

OEHs will also affect marine ecosystems, necessitating studies on biodiversity, habitat changes, and ecosystem services. Efforts should aim to balance stakeholder interests while mitigating harm and exploring opportunities to enhance benefits, such as restoring biodiversity. The full environmental impact of OEH construction and operation remains uncertain. To address this, more detailed Life Cycle Assessments are needed, using accurate data on resource use and emissions throughout the project's lifecycle to support sustainable and responsible decision-making.

Regulation: Investing in Offshore Energy Hubs carries higher risks compared to traditional offshore wind projects due to the market structure of offshore bidding zones. While this structure enhances efficiency, it also creates uncertainties and raises risk premiums, which could discourage investment. To attract investors, these risks must be thoroughly analysed and mitigated. Financing offshore energy hubs is particularly complex, requiring substantial funding to benefit a wide range of stakeholders, including TSOs, wind energy producers, and society at large - often spanning multiple regions. Socioeconomic models are crucial to evaluate cross-border impacts, such as economic, social, and environmental benefits. Coordinated regional planning can optimise seabed use, garner broad support, and prevent inefficiencies associated with isolated projects. Establishing a cohesive EU framework for offshore energy hub development can further reduce regulatory risks and encourage private investments that are heavily required, as evidenced by the recent report from Mario Draghi on European competitiveness.

Power & Energy Systems

- *Focus area* **1** – Design and operation of GW-scale zero-inertia isolated AC systems
- *Focus area* **2** – Enable offshore energy hub modular build-out
- *Focus area* **3** – System integration of offshore energy hubs
- *Focus area* **4** – Computational platforms for a meshed offshore power systems including offshore energy hubs

Offshore Wind

- *Focus area* **1** – Wind Turbine level
- *Focus area* **2** – Wind Farm level
- *Focus area* **3** – Offshore Energy Hub level

Power-to-X & Green Fuels

- *Focus area* **1** – Offshore Power-to-X Plant and Testing
- *Focus area* **2** – Wind/Power-to-X-Plant Dynamic Interaction
- *Focus area* **3** – Offshore Infrastructure for Power-to-X & Green Fuels

Society & Environment

- *Focus area* **1** – Societal acceptability and citizen engagement through supporting values
- *Focus area* **2** – Biodiversity standards for energy islands
- *Focus area* **3** – Life cycle assessment for Offshore Energy Hubs

Regulation

- *Focus area* **1** – Investable offshore wind at offshore energy hubs
- *Focus area* **2** – Efficient Financing Instruments to Support TSO Engagement and Investments
- *Focus area* **3** – Flexibility to encourage innovation
- *Focus area* **4** – Planning

Power & Energy Systems

Challenge Operating an electrical system almost without inertia, as will be the case for Offshore Energy Hubs, 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. Additionally, further experimentation with the offshore energy hubs regarding a modular structure and expansions regarding Power-to-X is needed.

Focus area **1**

Design and operation of GW-scale zero-inertia isolated AC systems

Focus area **2**

Enable offshore energy hub modular build-out

Focus area **3**

System integration of offshore energy hubs

Focus area **4**

Computational platforms for a meshed offshore power systems including offshore energy hubs

HVDC converter station, Siemens Energy

Design and operation of GW-scale zero-inertia isolated AC systems

Offshore energy hubs provide an advanced solution for integrating offshore renewable energy into power systems, with a fundamentally different operational setup compared to traditional onshore grids. These hubs consist of one or multiple isolated AC networks decoupled from onshore systems through high-voltage direct current (HVDC) converters, which create "zero-inertia" isolated systems. Instead of a stabilising inertia provided by rotating machinery in conventional AC systems, offshore energy hubs rely entirely on converters, and any sources and loads behind these, which demand new design and operational approaches to ensure system stability and flexibility.

A key instrument in managing these hubs is developing standardised grid code requirements. These standards must account for the modular integration of diverse energy technologies, such as wind turbines and energy storage, while specifying voltage, frequency, and power quality standards for onshore bulk AC power network. Ancillary services, including voltage regulation and frequency support, are essential to stabilise offshore energy hubs, so grid codes must define these services for zero-inertia conditions. Control challenges are magnified in zero-inertia offshore energy hubs. Without the natural stabilising effect of rotating-mass, offshore energy hubs require advanced controls like virtual inertia. Because of the natural unpredictability of renewable energy generation, ensuring a balanced and stable operation to the grid through voltage and frequency regulation is essential.

Operating GW-scale zero-inertia AC systems presents specific challenges. The absence of traditional inertia makes offshore energy hubs highly sensitive to disturbances, and scaling to GW capacities demands precise coordination and control among components. To address these demands, optimised system designs for offshore energy hubs prioritise scalable, modular configurations and customised and system-specific configurations of ancillary services for stability. Through these innovative approaches, offshore energy hubs support the integration of offshore renewables, enabling a reliable and adaptable energy future.

Actions

1. Develop robust control solutions for normal and abnormal operation that take component capabilities, system characteristics and zero-inertia into account.

2. Identify functional requirements needed to guarantee system robustness and ancillary services that can optionally be provided to the system and reduce cost-effectiveness.

3. Optimise the electrical design of offshore energy hubs to achieve cost-efficiency while ensuring system robustness and maximising the availability of the connected components.

Enable offshore energy hub modular build-out

Offshore energy hubs as a concept allows them to be centralised nodes for not only wind energy but various kinds of sustainable energy production, conversion, and storage methods. Because its power production might be dependent on how the wind blows it is essential that not all hubs are created from the same schematics with the possibility of modular buildouts and capabilities in its design. The power production priorities of the offshore energy hub might change over time. They might initially be built with a focus of harvesting wind power, but that focus could later shift towards hydrogen production or towards increasing interconnection capacity.

Now, these different capabilities and mixtures of assets are vast and yet to be explored. Further research is needed to develop more insight into these varying setups to determine the optimal ratings and control characteristics of assets to get an idea of the benefits from the offshore energy hubs both now and in the future. When a hub has been constructed it should also allow for modular expansion to avoid locked designs. Because green technologies, like Power-to-X, are relatively new and still under development, it is essential the hubs are planned with future expansions and integration in mind. In the same regard these modules should also be applicable for interoperability both in terms of technologies as well as vendors to allow the modules to operate in sync and in cohesion with each other across borders.

Actions

1. Identify and define modular building blocks of offshore energy hubs considering the potential pathways for offshore energy hub rollout.
2. Define standard interfaces and functionalities of modules to ensure compatibility and interoperability between building blocks in the future.

System integration of offshore energy hubs

The integration of offshore energy hubs into offshore multi-terminal DC networks is pivotal in managing renewable energy across interconnected power systems. Offshore energy hubs, which gather and distribute energy from sources like offshore wind, enable flexible power routing to onshore grids. This interconnected multi-terminal DC network allows for shared reserves, optimising the amount of active power reserves needed across regions and reducing overall system costs. A major advantage is cost savings from relaxed maximum loss of infeed requirements. Traditionally, systems are designed for worst-case single contingencies, requiring large reserves. However, the redundancy provided by multiple offshore energy hubs and DC links reduces this need, potentially cutting costs by minimising expensive DC breakers.

Offshore energy hubs adjust power generation to support onshore frequency regulation, requiring advanced control, communication, and market frameworks for dynamic service provision. Efficient offshore energy hub integration involves close collaboration between Transmission System Operators (TSOs), offshore energy hub operators, and plant operators. Effective control strategies, aligned locally and system-wide, ensure all components operate harmoniously. This new strategy would require reliable communication infrastructure for real-time signal exchange, coordinated control of local and system-wide strategies, and quality information exchange.

Challenges in protection design, control complexity, and regulatory structures require ongoing research and advancements to be achieved. Future developments in communication technology, DC protection schemes, and markets that reward ancillary services will be essential for maximising the benefits of offshore energy hubs in multi-terminal DC networks, ultimately enhancing grid flexibility, reliability, and cost-efficiency. Additionally, further research is needed into the control & protection characteristics of already installed assets, which may need adjustment once the offshore energy hub is expanded.

Actions

1. Mitigate potential adverse interactions between offshore energy hubs, interconnected DC systems and onshore systems.
2. Identify services that can be provided from offshore energy hubs to the onshore systems and establish structures that allow to provide them.
3. Establish robust system-wide control strategies that take into account the need for coordination between many different, independent parties.

Computational platforms for a meshed offshore power system including offshore energy hubs

As part of designing robust and reliable offshore energy hubs with multiple onshore grid connections, it is crucial that relevant simulation platforms are available, that can simulate the various electrical components in a multi-vendor simulation environment. The simulation platform shall be able to accurately reflect component characteristics to ensure interoperability and verify that the overall control design and control strategies are stable and robust. Relevant simulation studies include steady state and transient time-domain simulation and frequency-domain simulations. Additionally, the number of facilities that are capable of performing these types of simulation will need to increase with the number of projects in the pipeline as this could lead to potential bottlenecks.

The simulation platform shall be able to support usage of original equipment manufacturers and generic simulation models and should support the integration of control and protection system replicas when needed. Generic simulation models are mainly used for designing the overall control concept for the offshore energy hub. Where the original equipment manufacturers specific simulation models are mandatory for assessing any control interoperability issues and securing a robust and stable operation of the offshore energy hubs during steady state and transient conditions. Simulation models shall be maintainable in the lifetime of the offshore energy hub.

It's important that the simulation platform supports a multi-vendor original equipment manufacturers model setup where confidentiality can be maintained and secured. Methods to support this can be with the usage of a real time simulation platform based in a dedicated lab environment or with the usage of a cloud-based simulation solution where model and simulation access rights can be controlled in a way that supports confidentiality. These cloud-based simulation solutions are not commercially available and will require further development.

Some simulation and assessment methods can be borrowed from well-established best-practices used in today's connection of HVDC-renewables. Yet, offshore energy hubs bring not only new challenges to technical performance of interconnected assets, but also a particularly high concentration of power electronic converters with associated control & protection in a unique operating environment. This is likely to intensify the need for agreed standards and efficient simulation platforms for offshore energy hubs.

Actions

1. Kickstarting the development of offshore energy hub digital twins, potentially through a joint collaboration between industry and research partners.

2. Coordination to allow for multi-vendor model setup as well as modular build out.

3. Ensuring reliable data for the complex equipment working in the harsh offshore conditions to ensure realistic and reliable simulations.

Offshore Wind

Challenge Given the unique characteristics of the power grid at an Offshore Energy Hub, there is potential to develop new types of wind turbines specifically designed for offshore energy hubs, enhancing their cost-effectiveness and cooperation in different settings.

Focus area **1**
Wind Turbine level

Focus area **2**
Wind Farm level

Focus area **3**
Offshore Energy Hub level

Wind turbine technicians at work, Ørsted

Scenarios and potentials

Given that the wind power sector is ever evolving and highly innovative it's likely in the future that we will see offshore wind turbines being designed for much more than just producing power. Three potential scenarios are expected to unfold over the short-, medium-, and long-term.

On the short-term, we are most likely to see electricity-producing wind turbines in wind farms connected to a hub as the main focus. These turbines will generate and export electricity exclusively, similar to current systems. Hybrid-type wind turbines, producing electricity and/or hydrogen, may be a likely scenario in years to come. This setup will enable the export of either electricity, hydrogen or both. Hydrogen production could occur either at the wind turbine or as a centralised solution, while at least some turbines produce electricity only. In the long-term scenario, the majority of wind turbines may produce hydrogen most of the time, while a minority of turbines may produce power most of the time. Flexibility is key in the renewable-based energy system. Achieving these scenarios will require extensive research, innovation, testing, and demonstration at the levels of individual turbines, wind farms, and offshore energy hubs. Additionally, developments with regards to the turbines and the interplay with new offshore energy hub components, new cyber security standards need to be developed to maintain the security and mitigating crippling of critical infrastructure.

Table 1: Energy hub complexity increases over time as new technology is developed

	1 **Short-term:** Electricity producing wind turbines with a hub connecting the wind farms, exporting electricity only.	2 **Medium-term:** Electricity and hydrogen producing wind turbines connected to a hub. Exporting electricity, hydrogen or a mix of both. Hydrogen to be produced either at the wind turbine or at a substation.	3 **Long-term:** Hydrogen producing wind turbines connected to a hub, exporting hydrogen only. Hydrogen to be produced either at the wind turbine or at a substation.
Wind Turbine level	• Reduced converter capacity at wind turbine level	• Hardware and software components for island mode operation • Reduced converter capacity at wind turbine level • Hybrid/hydrogen producing turbine	• Hardware and software components for island mode operation • Reduced converter capacity at wind turbine level • Hybrid/hydrogen producing turbine
Wind Farm level	• Grid requirements to be fulfilled in common point of coupling and not at wind turbine level • Wake optimisation	• Grid requirements to be fulfilled in common point of coupling and not at wind turbine level • Optimisation of infrastructure between electricity and hydrogen producing turbines • Wake optimisation	• Hardware and software components for island mode operation • Optimisation of infrastructure between electricity and hydrogen producing turbines • Wake optimisation
Energy Hub level	• Grid requirements to be fulfilled in common point of coupling and not at wind turbine level • Enhanced cybersecurity in the controls and software • Wake optimisation	• Grid requirements to be fulfilled in common point of coupling and not at wind turbine level • Optimisation between wind farms between hydrogen and/or electricity • Enhanced cybersecurity in the controls and software • Wake optimisation	• Hardware and software components for island mode operation • Optimisation between wind farms between hydrogen and/or electricity • Enhanced cybersecurity in the controls and software • Wake optimisation

Wind Turbine level

Optimising current wind turbine designs holds considerable promise for reducing costs and improving efficiency. The unique configuration of offshore energy hubs, which operate an independent alternating current (AC) network disconnected from direct consumer grids allows for a more flexible approach to turbine design. Unlike traditional systems, where turbines must adhere to rigorous grid-connection standards, offshore turbines within an energy hub can prioritise compliance specifically for the converters at the large direct current (DC) connections used to transmit power to shore.

By focusing on these critical components rather than the broader grid requirements, significant savings can be achieved in turbine production, deployment, and operation. This streamlined approach also simplifies the engineering and manufacturing processes, reducing complexity while maintaining performance. Additionally, these cost reductions can accelerate the scalability and modular build out for hydrogen and Power-to-X of offshore energy hubs, making renewable energy more accessible and competitive. As the offshore wind sector continues to innovate, this flexibility in design and operation could play a key role in driving the next generation of cost-efficient renewable energy solutions. Furthermore, as wind turbines are critical infrastructure, they are also a potential target for an attack, especially a cyber-attack. The interplay between wind turbines and the new components in an energy hub needs to be carefully managed in terms of cyber security. New standards are therefore likely to be developed.

Actions

1. The potential for reduced converter capacity and cost-effective designs should be explored when connected to an OEH decoupled from AC systems on land with HVDC connections.
2. Investigate integrating advanced capabilities - such as producing hydrogen or other Power-to-X outputs directly - and evaluate the enhanced functionality.
3. Investigate solutions for ensuring reliable energy availability and maximising resource utilisation, e.g., by incorporating solar panels and battery backups.
4. Development of secure controls and software for the individual turbines and connected components to ensure stable operation and supply of power and fend off cyber-attacks.

Wind Farm level

Wind farms interact with the atmospheric boundary layer, generating wake effects that propagate downstream and create zones of reduced wind speed and increased turbulence. These wakes can significantly impact wind farm performance, leading to lower power output, accelerated turbine fatigue, and reduced overall operating efficiency. As offshore energy hubs bring together multiple wind farms in close proximity, the potential for wake interactions increases. These effects should be addressed through advanced modelling, and strategic planning should be applied in the early phase.

By accurately modelling wake dynamics and considering these interactions during the layout and placement of wind turbines, planners can optimise energy capture while reducing mechanical stress on the turbines. This not only improves the efficiency and longevity of individual wind farms but also minimises the adverse impacts on neighbouring installations. Furthermore, integrating wake management strategies, such as turbine-specific control settings or adaptive layouts, can help balance the performance of the entire network of wind farms within an offshore energy hub.

Effective planning that takes wake interactions into consideration enhances the overall reliability and sustainability at wind farm level. This as well ensures consistent power generation and an optimisation of the feasibility to operate at peak efficiency for the long term. Such approaches also support better collaboration between developers, operators, and regulators by addressing the shared challenges of turbine interactions in densely utilised offshore spaces.

As for the individual wind turbines, entire wind farms are also vulnerable to cyber-attacks. The interplay between wind turbines and the new components at a wind farm level needs to be carefully managed in terms of cyber security and new standards are therefore needed.

Actions

1. Research and testing are required to optimise wake control.
2. Investigate the benefits of fulfilling grid requirements at the common point of coupling rather than at the turbine level.
3. Investigate solutions for ensuring reliable energy availability and maximising resource utilisation, e.g., by incorporating solar panels, and hydrogen - and battery backups at offshore substation level.
4. Development of secure controls and software of the wind farms to ensure stable operation and supply of power and fend of cyber-attacks.

Offshore Energy Hub level

Offshore energy hubs typically integrate multiple wind farms and along with other facilities, they can create a diverse renewable energy system. However, this arrangement can lead to interactions between the wind and PV systems, such as variability in energy generation, requiring careful control and optimisation. To minimise interference and ensure efficient operation, advanced management strategies are needed to balance energy contributions from both systems. For example, leveraging their complementary generation profiles - wind energy peaking during certain conditions and solar during daylight - can maximise output, while energy storage solutions help stabilise fluctuations and enhance overall hub efficiency. All levels of the offshore energy hubs are vulnerable to cyber-attacks through the interplay of its many components. New standards for the cyber security of the hubs need development before the hubs are launched.

Actions

1. Research, innovation, testing, and demonstration should prioritise optimising wake effects to minimise impacts on neighbouring wind farms, as well as reducing operations and maintenance (O&M) costs across multiple farms.
2. Investigating diverse power supply solutions - including wind, solar, and battery systems - is essential to support interconnectors and converter stations, alongside integrating hydrogen-powered backup solutions.
3. Development efforts must also focus on enabling hubs to operate in “island mode” while ensuring that grid requirements are met at the common point of coupling, rather than at the individual turbine level, to enhance infrastructure efficiency.
4. Collaboration with developers in the hydrogen and Power-to-X industries is crucial for seamlessly integrating these technologies into the offshore energy hub framework.
5. Development of secure controls and software of the offshore hubs to ensure stable operation and supply of power and fend of cyber-attacks.

Power-to-X & Green Fuels

Challenge Power-to-X technology is poised to become a cornerstone of offshore energy hubs. In various scenarios, Power-to-X will either balance electricity production or serve as the main product. Regardless of its role, Power-to-X has the potential to enhance the economic viability of offshore energy hubs. The successful implementation of Power-to-X on offshore energy hubs necessitates innovative solutions in electrolysis, storage, and other related technologies.

Focus area **1**

Offshore Power-to-X Plant and Testing

Focus area **2**

Wind/Power-to-X-Plant Dynamic Interaction

Focus area **3**

Offshore Infrastructure for Power-to-X & Green Fuels

Illustration of artificial energy island, Copenhagen Infrastructure Partners

Offshore Power-to-X Plant and Testing

Power-to-X facilities require a reliable supply of power and water and have the potential to provide valuable by-products such as oxygen and heat to consumers. Identifying optimal locations for these facilities involves comprehensive modeling and analysis. Innovative actors to bring forward solutions will play a crucial role in the optimisation of offshore hydrogen production, to enable the most cost-efficient solutions. This includes comparing the advantages and dis-advantages of offshore versus onshore production of Power-to-X molecules. Key considerations include the benefits of reduced transportation costs for Power-to-X molecules against the operational and maintenance challenges posed by offshore environ-ments, as opposed to the higher transportation costs associated with onshore power production.

Actions

1. **Ensure reliable supply:** Secure a consistent and reliable supply of power and water for Power-to-X facilities.
2. **Utilise by-products:** Develop systems to capture and utilise valuable by-products such as oxygen and heat.
3. **Optimal location identification:** Conduct comprehensive modeling and analysis to identify optimal locations for Power-to-X facilities.
4. **Establish offshore design and testing guidelines:** Develop comprehensive design and testing standards for the Power-to-X plant tailored to offshore conditions, ensuring that the plant can meet safety, performance, and durability requirements under extreme weather, corrosive marine environments.
5. **Develop testing facilities for Power-to-X in offshore harsh environments:** Establish dedicated testing facilities to emulate offshore conditions, ensuring the Power-to-X plant design demonstrates resilience and reliability.
6. **Comparative research:** Develop knowledge through comparing the advantages and disadvantages of offshore versus onshore production of Power-to-X molecules. This should be focused on optimising the configuration of offshore vs. onshore hydrogen production, creating the most value to consumers and society.
7. **Cost-benefit analysis:** Evaluate the benefits of reduced transportation costs for Power-to-X molecules against offshore environments' operational and maintenance challenges, compared to the higher transportation costs associated with onshore power production.

Wind/Power-to-X-Plant Dynamic Interaction

Integrating offshore wind energy with Power-to-X conversion processes presents significant technical challenges. Directly coupling wind turbines with electrolysis processes results in transient operations due to the fluctuating nature of wind energy production. In the absence of a balancing power grid to buffer these fluctuations, the variability of wind energy is transferred directly to the Power-to-X process chain. This necessitates the development of robust systems capable of overseeing such variability to ensure efficient and stable Power-to-X production.

Actions

1. **Develop robust systems:** Create systems capable of managing the variability in wind energy to ensure efficient and stable Power-to-X production.
2. **Manage transient operations:** Address the challenges of transient operations resulting from the direct coupling of wind turbines with electrolysis processes.
3. **Buffer energy fluctuations:** Explore solutions to buffer fluctuations in wind energy without a balancing power grid.
4. **Enhance stability:** Implement technologies and strategies to transfer wind energy variability effectively within the Power-to-X process chain.

Offshore Infrastructure for Power-to-X & Green Fuels

The large-scale production of hydrogen and e-fuels through offshore Power-to-X plants necessitates a significant expansion of offshore infrastructure to enable cost-competitive transportation. This infrastructure must facilitate the movement of these energy carriers within a single offshore energy hub, between multiple offshore energy hubs, and connect to onshore demand centres.

Repurposing existing infrastructure: Can existing oil and gas infrastructure be repurposed to transport hydrogen and e-fuels, or are entirely innovative solutions required?

Will there be synergies between hydrogen and CO_2-pipeline infrastructure?

If large-scale CO_2 is to be transferred offshore for storage (or utilisation if fuel production offshore is feasible) and large-scale hydrogen/Offshore Energy Infrastructure is transferred in the opposite direction, this could potentially lead to significant pipeline construction synergies both offshore and onshore.

Innovative systems: Is it feasible to develop innovative systems, such as hybrid hydrogen-electricity pipelines, for both inter-array connections and export-level transmission?

Multi-functional substations: Should offshore substations be transformed into multi-functional modular energy hubs, integrating production, storage, and conversion technologies?

Pipeline as storage: Is large-scale offshore hydrogen storage a realistic option?

With a more technical focus on the pipeline, we should also consider the ability of the pipeline to serve as storage leading to significant improvement in pipeline capacity utilisation and potentially make offshore fuel consumption more realistic.

Hub and Spoke model: Additionally, we need to address the challenge and ability of a pipeline to adopt a hub and spoke model like that used for electricity cables.

Actions

1. **Expand offshore infrastructure:** Develop extensive and optimised infrastructure to support the large-scale offshore production and transportation of hydrogen and e-fuels.

2. **Repurpose existing infrastructure:** Assess the feasibility of repurposing existing oil and gas infrastructure for hydrogen and e-fuels transportation or determine the need for innovative solutions.

3. **Develop innovative systems:** Explore the development of hybrid hydrogen-electricity pipelines for both inter-array connections and export-level transmission.

4. **Transform substations:** Consider transforming offshore substations into multi-functional modular energy hubs that integrate production, storage, and conversion technologies.

5. Develop understanding operating patterns of production of hydrogen (or other Power-to-X products) to ensure optimisation of dimensioning of power and hydrogen transmission systems.

6. **Utilise pipelines for storage:** Investigate the potential for pipelines to serve as storage solutions, utilising flexible pressure and other necessary points for storage options.

7. **Implement Hub and Spoke Model:** Address the feasibility and challenges of adopting a hub and spoke model for pipelines, like the model used for electricity cables.

Society & Environment

Challenge The projected scale of Offshore Energy Hubs and their associated wind farms is likely to significantly impact marine ecosystems and biodiversity. Additionally, offshore energy hubs will have profound effects on the welfare of communities, particularly those situated near or on inhabited islands. Deciding whether to locate offshore energy hubs close to communities or far from shore requires balancing economic, environmental, and social factors. Proximity holds potential for local benefits and cost reductions but can cause environmental and community disruptions. Distant locations, far out to sea, reduce local impacts but increase costs and logistical challenges.

Focus area **1**

Societal acceptability and citizen engagement through supporting values

Focus area **2**

Biodiversity standards for energy islands

Focus area **3**

Life cycle assessment for Offshore Energy Hubs


Wind turbine construction site. DTU

Societal Acceptability and Citizen Engagement through Supporting Values

Offshore energy hubs will inevitably influence nearby communities, as these large-scale projects occupy considerable space both offshore and onshore. Consequently, various negative impacts may arise for local residents and their communities. It is essential to identify and address these issues early on to ensure alignment with sustainable development goals and public opinion.

To meet and nurture public opinion, it is crucial to clearly communicate the potential benefits at the national, international, and individual levels of offshore energy projects. For instance, emphasising how offshore energy hubs can promote renewable energy, create job opportunities, or potentially lower electricity bills can resonate strongly with local residents. A key concept here is identifying and supporting the values in local communities so that OEHs can be part of a European ambition to foster regional growth, especially in rural areas. The central question is how OEH projects can collaborate with local partners to ensure community engagement and the adaptation of projects to local conditions, as well as promoting local employment and supporting community values.

In planning the location and construction of these hubs, it is vital to balance potential benefits - such as local economic growth - with challenges like uncertainty during planning, visual or noise disturbances that may affect property values and quality of life. The communities living close to these projects are important to involve. Involving citizens in the decision-making process is critical to ensuring their concerns are adequately addressed.

While the overarching goal of offshore energy hubs is to support renewable energy and sustainability, immediate environmental impacts must also be considered. Both onshore and offshore projects pose risks to local ecosystems, biodiversity, and wildlife, which can influence public opinion. Furthermore, large-scale construction and transportation associated with these projects will generate significant CO_2 emissions, despite the ultimate aim of producing clean energy. However, it is important to note that the energy required to construct a typical offshore wind farm is paid back within approximately six months of operation. This rapid payback period underscores the efficiency and long-term environmental benefits of offshore wind energy, making it a highly sustainable option in the fight against climate change.

To address these concerns, establishing citizen forums early in the planning process can provide a platform for local input and suggestions. These forums could address a range of issues, such as employing local labor, adjusting designs to preserve property values, and incorporating specific environmental safeguards into the project. By empowering the community, these forums can help identify potential problems early on, preventing them from occurring and maintaining public support for offshore energy hubs.

Actions

1. **Identify and address issues early:**
   - **a)** Identify and acknowledge potential negative impacts on local communities.
   - **b)** Align the projects with the sustainable development goals.
   - **c)** Meet and nurture public opinion and local communities.

2. **Communicate potential benefits:**
   - **a)** Clearly convey the benefits of offshore energy projects.
   - **b)** Highlight positive outcomes at national, international, and individual levels.
   - **c)** Emphasise renewable energy promotion job creation, and potential reduction in electricity bills.

3. **Balance benefits and challenges:**
   - **a)** Consider local economic growth alongside challenges like uncertainty.
   - **b)** Ensure the project is seen as a sustainable option in combating climate change.

4. **Establish citizen forums:**
   - **a)** Create forums early in the planning process for local input and suggestions.
   - **b)** Address issues such as employing local labour, preserving property values, and incorporating environmental safeguards.
   - **c)** Empower the communities to identify and prevent potential problems, maintaining public support.

Biodiversity standards for energy islands

The development of offshore energy hubs will inevitably result in some level of disruption to marine and natural environments. The impacts range from short-term effects during construction - such as increased noise, sediment displacement, and habitat disruption - to longer-term alterations in ocean currents, wind patterns, and new sources of artificial light and noise. Such changes can have effects on marine habitats and food chains, potentially disrupting ecosystems both at sea and on land.

It is essential to identify and assess these potential negative impacts before the project begins, allowing time to develop the effective mitigation strategies. While some issues may be straightforward to address, others may require in-depth research, particularly given the unique challenges posed by specific locations. Collaboration with maritime stakeholders, developers, and environmental organisations is essential to find a balance between minimising negative impacts and enhancing positive outcomes, such as restoring and possibly enhancing lost biodiversity.

Simultaneously, it is essential to emphasise the potential of offshore energy hubs to positively impact biodiversity, especially through their ability to create artificial habitats. The structures within the entire setup of offshore energy hubs, including wind farms, can serve as artificial reefs, promoting marine life by providing surfaces for organisms to colonise and enhancing habitat complexity. Additionally, the establishment of No-Take Zones around these hubs which restrict fishing, allows ecosystems to recover and helps protect vulnerable species. It is therefore important to carefully plan and monitor how to balance the ecological impacts of the full offshore energy hub setup. Through careful planning, offshore energy hubs can maximise these benefits while minimising negative impacts.

Actions

1. **Identify and assess environmental impacts:** Evaluate both short- and long-term impacts on marine and natural environments.
2. **Develop and implement mitigation strategies:** Create and apply strategies to minimise negative impacts, collaborating with stakeholders and conducting necessary research.
3. **Enhance positive biodiversity outcomes:** Promote the creation of artificial habitats and establish No-Take Zones to protect and enhance marine life.

Life cycle assessment for Offshore Energy Hubs

The full environmental impact of an offshore energy hub remains uncertain and may only become evident long after the first hub is constructed. To address this uncertainty, a prospective Life Cycle Assessment (LCA) is crucial for anticipating potential environmental consequences of energy hubs, particularly concerning future development patterns and climate commitments. The most reliable projections for these future scenarios are the Shared Socioeconomic Pathways (SSPs) proposed by the Intergovernmental Panel on Climate Change (IPCC), which provide a structured view of potential development trajectories. By incorporating the SSPs, LCA can more accurately model how different patterns of growth, technology adoption, and climate policy will influence the life cycle of offshore energy hubs, including resource use and emissions. This SSP-based prospective LCA approach allows for more precise modeling of resource consumption, emissions, and environmental impacts throughout the life cycle of offshore energy hubs under different future scenarios. To ensure a comprehensive and future-proof assessment, it is crucial to invest in research and innovation that provides high-quality data, enabling more accurate and forward-looking assessments across the construction, operation, and end-of-life phases.

Actions

1. **Conduct a prospective Life Cycle Assessment (LCA):** Anticipate potential environmental consequences of offshore energy hubs, considering future development patterns and climate commitments.

2. **Utilise shared socioeconomic pathways (SSPs):** Use SSPs proposed by the IPCC to provide structured projections for the future scenarios, aiding in accurate and forward-looking assessments.

3. **Adress uncertainty in environmental impact:** Recognise that the full environmental impact may only become evident after construction, and plan accordingly, to mitigate unforeseen consequences.

Regulation

Challenge Current regulation needs enhancement to fully support the realisation of Offshore Energy Hubs and unlock their potential to significantly contribute to the decarbonisation of Europe. Offshore energy hubs will vary in scope, ownership model and technical layout, which can require different regulatory designs. Offshore energy hubs will in general involve new market structures, higher investment risks, and a broader value distribution. Therefore, an upgraded regulatory framework is essential to facilitate investments in offshore wind at offshore energy hubs and to efficiently handle risks for Transmission System Operators (TSOs) and society regarding infrastructure investments. Further, a new approach to regional planning should be adopted to facilitate realisation of offshore energy hubs.

Focus area **1**

Investable offshore wind at offshore energy hubs

Focus area **2**

Efficient financing instruments to support TSO engagement and investments

Focus area **3**

Flexibility to encourage innovation

Focus area **4**

Planning

European Parliament building in Brussels, European Parliament

Investable offshore wind at offshore energy hubs

Investing in offshore wind at Offshore Energy Hubs with hybrid interconnectors involves additional risks compared to traditional radially connected offshore wind generation. These increased risks stem from the market setup of offshore bidding zones, which seems to be preferred by policymakers and Transmission System Operators (TSOs) due to efficiency gains. However, this market setup requires a thorough analysis of the new risk landscape and a strategy to manage it. Without this, the heightened risks will lead to higher risk premiums, creating barriers for investment in offshore wind.

Offshore bidding zones are typically small and with limited demand. Further, the ability to export generation depends on the availability of interconnectors. This makes revenue generation from offshore wind placed in offshore bidding zones even more sensitive to events in neighbouring bidding zones and events related to connecting infrastructure. These effects are amplified by the limited demand to absorb shocks and the difficulty in managing these risks with traditional market products like Power Purchase Agreements (PPAs), which are challenging to implement across borders. The exacerbated risks in offshore bidding zones include price risks, volume risks, and buildout risks. These risks, which are difficult for offshore wind generation owners to quantify or control, should be managed through a fair and efficient risk allocation model to avoid additional costs from increased risk premiums to ensure investability of offshore wind at offshore energy hubs.

Alternative approaches to risk allocation should be further explored by policy makers. These include capability-based two-sided contracts for difference, transmission access guarantees (TAG), and financial transmission rights, which can address the mentioned risks to varying degrees. Profit-sharing schemes should also be considered to unlock capital. Investing in offshore energy hubs with Power-to-X production at the hub requires sufficient flexibility to optimise the configuration of the hub and surrounding assets. Technology neutral tenders for offshore energy hubs will be important.

Actions

1. **Establish a common EU understanding of risks:** Develop EU Commission guidelines for member states to address the risks associated with offshore hybrids and offshore bidding zones.

2. **Develop regulatory risk management measures:** Create regulatory measures to manage increased risks, thereby enable investments in offshore wind at offshore energy hubs.

3. **Provide guidelines on risk relief instruments:** Issue EU Commission guidelines on instruments for risk relief to support investments in offshore wind.

Efficient financing instruments to support TSO engagement and investments

Financing infrastructure investments related to offshore energy hubs is complex. First, they are massive investments in new technical equipment. Additionally, these investments benefit a wide range of parties, including Transmission System Operators (TSOs), offshore wind generation, and society at large. Further, the benefits are distributed across regions, including countries not directly connected to the offshore energy hubs but still experiencing system benefits. These complex and hence, traditional financing principles are inefficient.

In the near term, investments in offshore energy hubs are anticipatory investments to support future needs and thereby enable materialisation of the electrification needed for the green transition. This poses an additional complexity regarding the fairness of letting current users pay for investments that will benefit later users as well as a question regarding who should cover the risk related to materialisation of the future use of the infrastructure.

The wide range of complexities around the costs, risks and benefits illustrate why a fair and efficient cost and risk allocation mechanism is important for enabling investments in the offshore energy hub infrastructure. Funds to cover costs and inter-temporal tariff reforms can be useful and justified measures as argued in a recent note published by the Florence School of Regulation. As projects have EU relevance, EU financing mechanisms as suggested by Elia and Ørsted in the publication Making Hybrids Happen, are worth investigating further.

Actions

1. **Develop a comprehensive EU financing mechanism:** Create a robust framework to facilitate and streamline funding for infrastructure projects across the EU, including a potential revision of the Cross-Border Cost Allocation (CBCA) mechanism.

2. **Integrate the financing mechanism into EU institutions:** Ensure seamless incorporation of the financing mechanism within existing EU institutional structures to enhance efficiency and accessibility.

Flexibility to encourage innovation

Flexibility regarding the configuration of the offshore energy hub will encourage innovation and enable technical and economic optimisation of the hubs. Flexibility should be provided regarding e.g. capacity size, technology mix between offshore wind assets, Power-to-X production and storage solutions and export solutions including e.g. hydrogen pipelines. Optimal framework design relies on activation and involvement of market participants such as private investors and developers.

Actions

1. Provide flexibility regarding the configuration of the offshore energy hub to encourage innovation, including configuration for offshore wind sites and electrolyser capacity.

2. Activate and involve market participants such as private investors and developers in preparation of offshore energy hub configurations.

Planning

Regional planning of offshore energy hubs is essential to ensure optimal utilisation of seabeds and the successful realisation of concrete projects. A coordinated approach involving a group of projects within a region is more likely to benefit multiple markets and generate broader interest, compared to a project-by-project approach where individual projects may not attract sufficient interest. Elia finds that joint planning across borders and hybrid build-out can save Europe €6.5 billion/year.

Experience with technical solutions and regulatory frameworks for offshore energy hubs is currently limited. Real-world projects are necessary to gain technological and operational expertise and to learn valuable lessons. This practical experience will help optimise future offshore energy hub projects and refine regulatory frameworks before they are implemented on a larger scale.

Visibility and commitment to a tender pipeline is crucial to enable the supply chain to scale up and deliver on these projects. A well-defined and transparent tender pipeline provides suppliers with the necessary foresight to plan and allocate resources effectively. This visibility allows for better coordination among various stakeholders, ensuring that materials, labour, and other essential inputs are available when needed.

Actions

1. **Regional planning:** Promote regional planning, involving TSOs. Governments and industry to ensure the best possible utilisation of seabed and the realisation of beneficial projects.
2. **Proactive planning and investments:** Engage in proactive planning and investments to gain technical and regulatory insights, which will help unlock the potential of future hybrid buildout.
3. **Commitment and visibility on tender pipeline:** Ensure commitment and visibility on the tender pipeline to enable the supply chain to scale up and deliver on projects.

Acknowledgements

Thank you for taking the time to engage with this roadmap. On behalf of Energy Island Forum and all our partners, we hope the outlined actions in each chapter have provided a clear and comprehensive overview of the steps necessary to unlock the full potential of Offshore Energy Hubs. These hubs represent a transformative opportunity for renewable energy, but their realisation requires collaboration, innovation, and determination across industries, sectors, and borders.

This roadmap is the culmination of significant collaborative efforts, and it would not have been possible without the invaluable contributions of our partners. We extend our sincere gratitude to everyone who contributed to the working groups within the five innovation fields, offering their expertise and insight to define challenges, and set the strategic scope. Additionally, we thank the steering committee for their leadership in shaping this roadmap and guiding its direction.

We are especially grateful for the dedication, time, and resources that our partners have invested to bring this vision closer to reality. Your commitment has not only helped to craft this document but also to spread awareness about the immense potential of Offshore Energy Hubs. As we move forward, we look to build on this foundation, continuing to collaborate and innovate to achieve our shared goals. Together, we can turn the vision of Offshore Energy Hubs into a global success story.

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Together we create
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References

For further reading regarding offshore energy hubs, the following articles and documents are suggested.

[1] Energy policy ideas for the next Commission, Leonardo Meeus, EUI – Florence School of Regulation, Oct. 1. 2024

[2] Making Hybrids Happen, Elia Group & Ørsted, March 2024

[3] Going Like The Wind, Elia Group, Oct. 15. 2024

[4] Pathway Study 2.0, North Sea Wind Power Hub Programme, Energinet et. al.

[5] Hubs and spokes – viable beyond theory, North Sea Wind Power Hub Programme, Energinet et. al.

[6] A Mars Mission for the Energy system, N. A. Cutululis et. al., Aalborg Universitet & DTU

[7] Denmark as the Energy Island Pioneer, DTU Sector Development Project, J. Østergaard et. al., DTU

[8] A vision for Europe's energy production and infrastructure in 2050, CIP, September 2024

[9] The future of European competitiveness, Mario Draghi, 9 September 2024

Offshore turbines in Esbjerg, Vestas

Join us

Energy Island Forum

info@balticenergyisland.com

+45 20 48 81 13

Baltic Energy Island

Lille Madsegade 32-34

DK-3700 Rønne