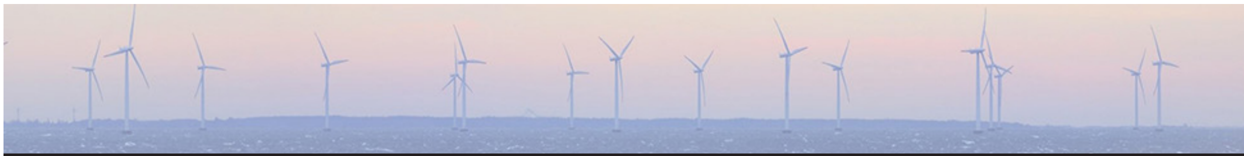
POWER SYSTEM PLANNING TO DEFINE ELECTRICAL REQUIREMENTS FOR ENERGY HUBS

October 2021



Introduction

Offshore wind power has seen significant growth in the past decade, particularly in Europe and China, with projected growth in the coming years as a result of reductions in capital and financing costs, government policies to support wind power deployment, and the large resource potential in various offshore regions that are sufficiently close to the load. Given the nature of offshore wind, offshore wind plants have been growing in size over the past number of years from tens of megawatts (MW) to hundreds of MW, and potentially even gigawatts (GW) scale. The increase in plant size is driven by a number of factors, including economies of scale, the ability to situate where resources are better, and the availability of larger turbines and ambitious decarbonization goals. This has prompted a re-evaluation of how to improve the connections between offshore wind and the main electrical grid. The concept of a renewable energy hub presents a potential solution. Such a hub would serve to connect multiple power sources, typically totaling several to tens of GW, as well as providing a location to enable other services such as energy storage or a conversion to other energy carriers such as hydrogen (Figure 1). Presently, most renewable plants offshore or onshore (and including hybrid plants with more than one source of energy) have been connected to the power network as individual units with radial connections. However, in the future, deploying newer plants and connecting them to one or multiple energy hubs can help increase the transfer of renewable power by a significant margin. Electrical infrastructure for the transmission of power from the energy hub, such as converter stations, substation transformers, switchgear, and even battery energy storage, can be housed within the energy hub—reducing costs and increasing redundancy for a single renewable plant to produce power to the main grid.

An example is the Danish offshore energy island concept that plans to integrate 5 GW of offshore wind from energy islands to the onshore grid by 2030.[1] Energy hubs don't need to be limited to offshore applications, and the same approach can be taken onshore to integrate remote renewable resources to the main grid.

A major challenge for any energy hub is determining how to specify the initial requirements for the electrical system, especially in the case where the energy hub is DC-connected to the external grids as it will be electrically decoupled from the main power grid. In this case, the system becomes an extreme version of a 100% renewable power system where the system stability is governed by the controls on each connected device within the hub. The challenge is to design a system for which there is no previous experience, which must be stable, reliable, expandable, and cost-effective.

An initial starting point might be to list the high-level functional requirements for a renewable energy hub:

- Resiliency and redundancy
- Stable operation of the energy hubs
- Transfer capability between hub and connected systems
- Power control
- Energy storage
- Power to gas and sector coupling

A Generalized Approach to Energy Hub Design Electrical Planning

This white paper will focus on the questions that need to be addressed and/or answered before the energy hub designer develops the system design specification.

The high-level objectives of renewable energy hub electrical design are to:

- Enable a staged implementation of renewable energy and grid connections without unnecessary technical operational barriers
- Define functional requirements and specifications for an electrical offshore system based on 100% converter interfaced resources

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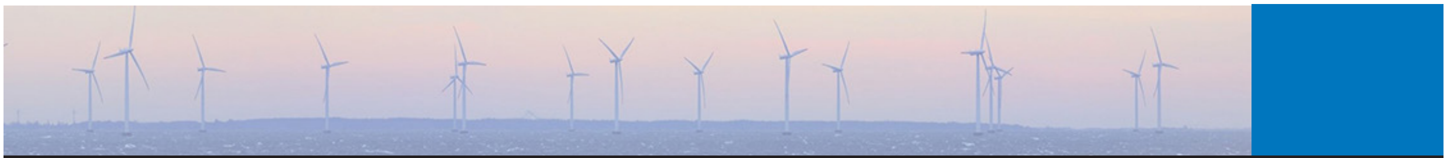
This white paper was prepared by EPRI.

[1] https://en.energinet.dk/Green-Transition/Energy-Islands



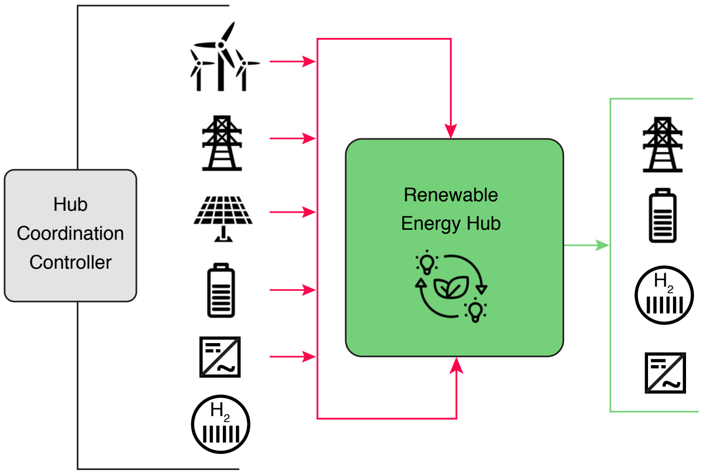


Figure 1. A renewable energy hub connecting a number of sources (wind, solar, battery storage), hydrogen production, and the main AC grid(s)

- Comply with existing applicable connection requirements while improving the design of the energy hub for renewable energy source integration
- Maintain the robustness and stability of the energy hub
- Design a hub that integrates with the existing infrastructure and grid transmission assets
- Avoid overspecifying or underspecifying the requirements, limiting innovative solutions

Unlike most other energy projects, there is usually no existing infrastructure, so the entire system must be designed from the ground up. This is challenging as there now are many degrees of freedom to the design, while there also exists a tendency to incorporate conservative design margins due to the many unknowns of such a novel approach.

The operation and control of the energy hub's internal AC grid and any associated high voltage direct current (HVDC) links to the external grids are governed by the controller design and parameterization of the elements within the hub. Due to their complexity and to bring about seamless vendor agnostic scalability, these individual controllers might benefit from an overarching centralized hub controller to coordinate operation and control. However, the design of the hub controller needs significant work to ensure that it can deliver a stable operating performance while also being flexible to future hub expansion. One of the first decisions to make in the process is to choose topologies and connection technologies, as described in the following sections.

Feasibility Planning

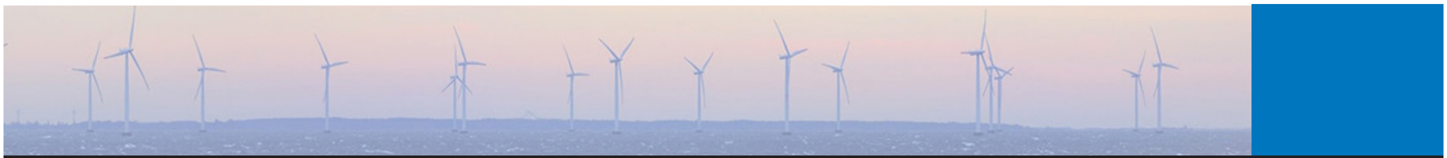
Feasibility planning aims to identify what the overall approach to the hub might look like. An initial step in this planning phase would be to split the hub's ultimate planned capacity into planned stages, based on a reasonable expectation of power park construction and energization timelines, and to study these stages incrementally. For example, each stage could consider additional power parks in the range of 800–1200 MW being commissioned every two to three years, potentially with increasing size as wind plant sizes increase.

The next step in the planning phase would be to identify credible connection point(s) to external AC grids based on available or likely-to-be-available transmission grid capacity: Class each connection point based on whether it is reachable with a high voltage alternating current (HVAC) connection or requires an HVDC. (Note that, in some cases, it might be possible to leverage existing power parks and associated AC or DC assets into the hub design to increase hub capacity, utilization, and resilience.)

An initial hub reliability and resilience assessment would then be carried out for the energy hub. The following considerations should be included:

- Define component level sizing for each stage.
- Define cable outage rates and repair time based on available data and previous experience.
- Define contingency/maintenance capacity or requirement for the energy hub.
- Perform production cost simulations to assess basic reliability, resilience, and economic aspects. (Transmission technology [AC or DC] is undecided at this point, and the focus is only on power flows and costs of energy not delivered.)
- Define applicable largest single infeed loss and required level of redundancy.

The result of the feasibility planning phase will provide the energy hub designer with an initial assessment on the infrastructure needed (number of links, and so forth), the initial reliability requirements, and an overview of the economics of the studied options.



Topology Selection

Figure 2 shows three conceptual layouts for connecting an energy hub to one or more transmission grids. The availability of topology and technology options will depend on site-specific characteristics such as proximity to both offshore wind sites and suitable transmission grid connections. Technology selection is based on screening out those that do not meet fundamental requirements and a cost-benefit analysis of the viable options.

Other factors influencing the choice of topology that need to be considered are listed for AC and DC options:

Partially or fully AC-interconnected

- Cost of reactive power compensation
- Cost of harmonic filter banks if required offshore (Passive low-frequency filter banks can require large components, but if a STATCOM is used for compensation, it could potentially provide active harmonic filtering.)
- Conventional components with long lifetimes
- Scalability
- Construction time and risks
- Possibility of future conversion to DC if required

DC-interconnected

- Point-to-point and/or multi-terminal
- Cost of converters, impact on hub footprint
- Lifetime cost considering
- Scalability
- Construction time and risks

Associate specific links to each phase of hub development

- Lowest risk/fastest construction for earlier hub phases
- Links with technology or construction risks for later hub phases

The reliability and resilience assessment should determine the number of links required to export the power from the energy hub. After the requirements from the reliability and resilience assessment have been understood, an initial decision on AC versus DC transmission can be made. This decision is generally based on economics, reliability, and the transmission distances. However, it might also need to take into account some other factors as the definition of the energy hub technical requirements progresses. Each technology (AC or DC or a mix of both) contributes differently to the technical requirements of the system. Beyond a straightforward cost comparison, a qualitative comparison of the options might reveal less easily observed benefits or challenges for one technology over the other. Table 1 contains a non-exhaustive list of some of the qualitative considerations when comparing the different options to connect to shore.

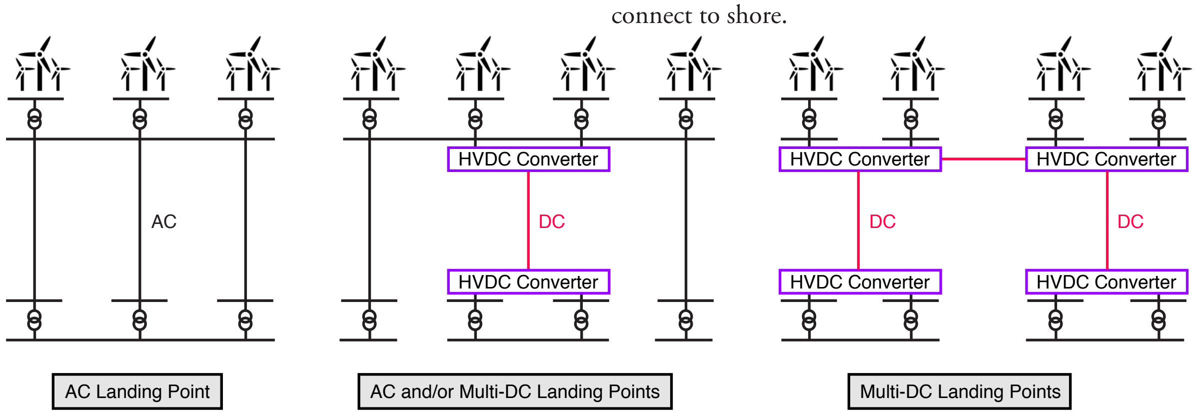


Figure 2. Three main options for connection of the energy hub to the main grid

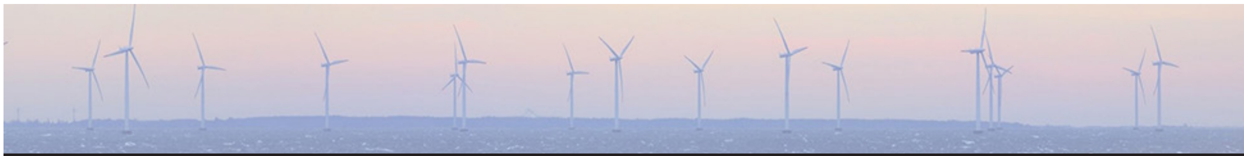
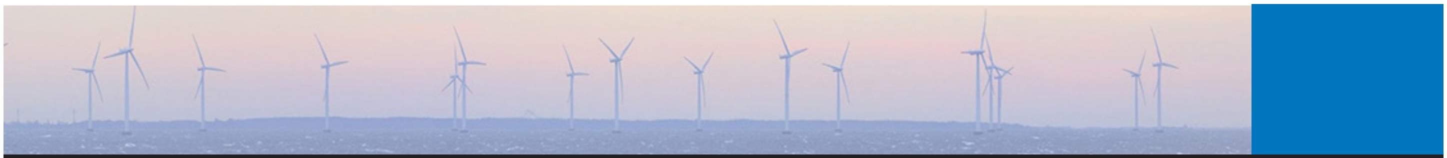


Table 1. Qualitative assessment of different connection options

Metric	AC Only	AC & DC	DC Only
Offshore grid stability	Stability is determined by both offshore devices and transmission grid strength and nearby generators and inverters that can change over time.	Stability is determined by both offshore devices and transmission grid strength and nearby generators and inverters that can change over time and the parallel HVDC design and control. This requires detailed study and understanding.	Stability is decoupled, so offshore design and stability are more closely intertwined with HVDC design. But increased coordination of control across elements is required.
Onshore reactive power control	Long AC cables require significant reactive power compensation. STATCOMs are usually installed to regulate voltage.	Long AC cables require significant reactive power compensation. STATCOMs are usually installed to regulate voltage. Appropriately rated VSC HVDC enables independent control of P and Q, which could partially or fully offset the AC cable compensation requirements.	Assuming a voltage source converter (VSC) HVDC is used with independent control of P and Q, then onshore converters can contribute.
Onshore grid stability	Long AC cables can introduce low-frequency harmonic resonance. Filters or controller redesigns could be required to prevent inverter harmonic instability. In all cases, inertia will be reduced due to connection of inverters.	Long AC cables can introduce low-frequency harmonic resonance. Filters or controller redesigns could be required to prevent inverter harmonic instability. Local onshore converter control can contribute.	Local onshore converter control can contribute to stability. Potential control interaction/instability between nearby HVDC.
Ancillary services (oscillation damping, frequency support, reactive power)	All services can be provided by hub energy sources via AC cables.	Hub energy sources can provide all services via AC cable. HVDC can additionally also provide oscillation damping and frequency support if headroom is available.	HVDC can provide oscillation damping and frequency support if headroom is available.
Black start/restoration	Black start from wind power plants is possible, but industry only at very early stages of field trials. Battery energy storage could be used if energy is kept in reserve, but energizing AC cables, transformers, and voltage regulation can present challenges.	Black start from wind power plants is possible, but industry only at early stages of field trials. Battery energy storage could be used if energy is kept in reserve, but energizing AC cables, transformers, and voltage regulation can present challenges. With appropriate controller designs, restoration via HVDC might be more flexible due to independent F, P, and Q control; however, AC cable and transformer energization challenges can still exist.	Black start from wind power plants is possible, but industry only at early stages of field trials. Battery energy storage could be used if energy is kept in reserve. With appropriate controller designs, restoration via HVDC might be more flexible due to independent F, P, and Q control; however, transformer energization challenges can still exist.
Onshore power quality	Long AC cables can introduce low-frequency harmonic resonance. Filters or controller redesigns could be required to mitigate.	Long AC cables can introduce low-frequency harmonic resonance. Filters or controller redesigns could be required to mitigate. HVDC is not a major source of steady-state harmonics. Filter banks typically are installed. Dynamic reactive power can improve voltage sag severity during nearby faults.	HVDC is not a major source of steady-state harmonics. Filters. Dynamic reactive power can improve voltage sag severity during nearby faults.
Market integration	Flows will fluctuate with wind/solar power plant output and transmission grid demand. Phase-shifting transformers could be used to improve controllability.	Flows on AC cable will fluctuate with net power balance at the hub. Flows on HVDC are fully controllable.	Flows on HVDC are fully controllable assuming energy storage devices are present to help "spill" renewables.



Generalized Approach to Defining Energy Hub Electrical Performance Requirements

To define the performance requirement ranges of the energy hubs, a number of studies will need to be undertaken by the hub designer (Figure 3). These requirements can then be used to develop requests for tenders for suppliers to develop the detailed design and commissioning of the project. The following sections provide an overview of the studies to determine electrical requirements.

Modeling Considerations

To determine the performance specification, flexible models that can reasonably capture the capabilities of the technologies are required, both in electromagnetic transient (EMT) simulations and positive sequence simulations.

Generic models, both in EMT domain and root-mean square domain, can be used for initial feasibility studies to evaluate the overall stability and reliability of the energy hub. An appropriately and suitably parameterized generic model can provide very insightful results about interactions between nearby plants and the rest of the network. The challenge arises in drawing meaningful conclusions about the specifications of the energy hub from studies performed with generic models. Using generic models in an initial study can help define conservative limits or ranges of system operation and reliability, and these results can subsequently be used to obtain specific services from original equipment manufacturers. Generic converter models have a wide variety of use in bulk power system planning studies. However, due to their generic nature, these models also have a set of limitations. It is important to understand these limitations and the realm of applicability. The state of the art of generic model development continues to increase with time and is supported by different standardization activities.

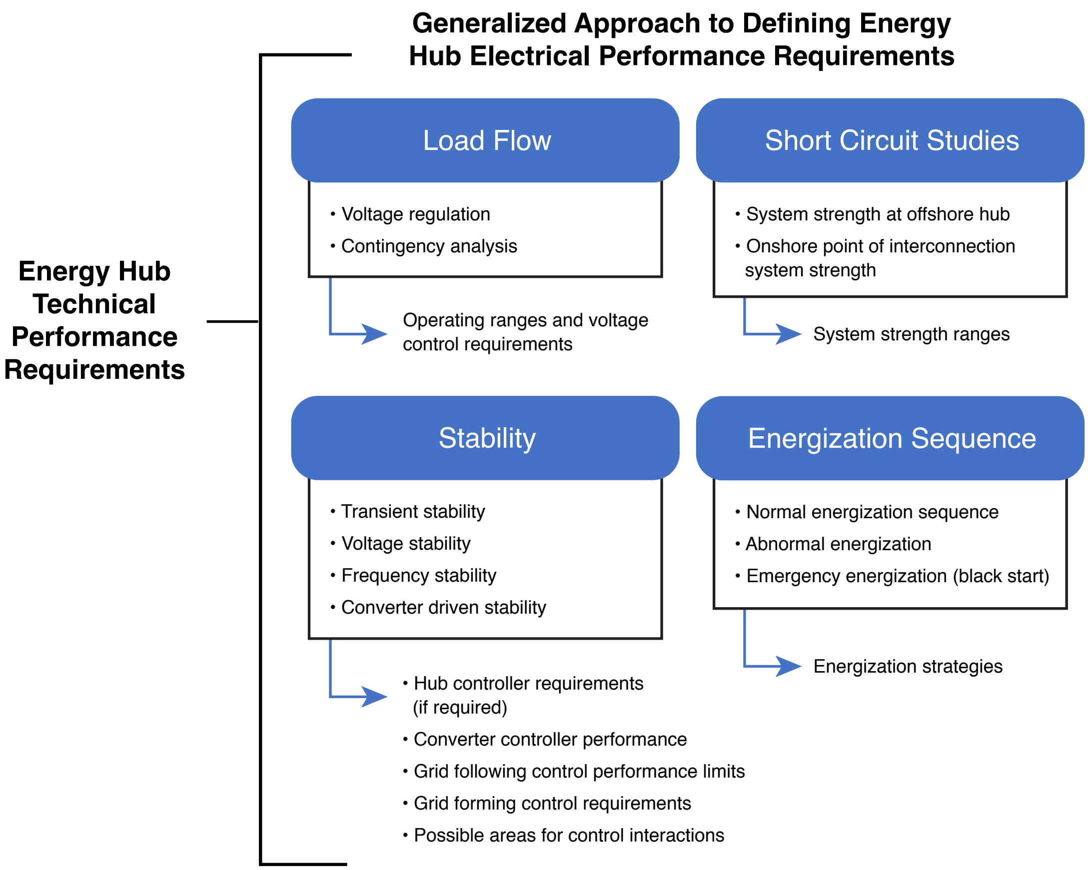
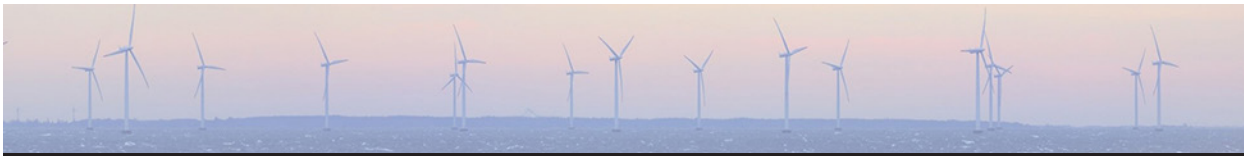


Figure 3. Energy hub technical performance requirements



Defining Grid-Forming Inverters

Grid-forming control might be required in both an AC-coupled scenario and a DC-coupled scenario. The specification studies should determine, at a high level, which resources should provide the functionality to operate in grid-forming mode. The idea of a so-called grid-forming inverter is to try to form its own voltage reference (especially if being called upon to operate as a black-start resource), or at least not be so heavily dependent on the grid-reference to easily lose stability under weak grid scenarios. Many proposed control concepts exist and are continuing to evolve for grid-forming inverters. From the perspective of a transmission system planner/operator, rather than asking how a control structure of an inverter should be implemented, it may be more beneficial to define interconnection requirements from the perspective of the services that are expected to be provided by inverters within the hub with advanced controls, while respecting individual equipment limits. The definition of the point of interconnection (POI) will determine the reference points of applicability of various services, whether the entire energy hub is considered to have one POI at the onshore grid or whether each plant has an individual POI at the energy hub.

Some examples of these services are as follows:

- Ability to create an open-circuit voltage at the POI of the plant. Note that this characteristic is defined at the plant POI and not at the terminal of an individual inverter within the plant. This implicitly assumes that the plant is capable of:
  - Serving its own auxiliary load
  - Operating in the absence of a synchronous machine
- Ability to synchronize and operate in conjunction with other sources of energy (or load) in the hub.
- The inverters within the hub can be expected to contribute toward supporting and balancing the grid, from both frequency and voltage perspectives. This might require ensuring energy headroom and current capacity to respond to events within both the hub and the grids to which the hub is interconnected.
- At a minimum, to not negatively impact the damping of naturally occurring oscillations in the power system following major disturbances: The plant might have the capability to improve the damping of oscillatory mode, with the necessary supplemental controls to facilitate this properly tuned and designed. A supplementary damping controller might employ a control architecture that either detunes the resonant modes by manipulating the impedance seen or directly compensates for active power oscillations using available megawatt capacity in headroom, battery storage controls available on site, or devising supplementary controls on the DC voltage control loop among others.

System Security and Services

Power system adequacy will require an evaluation of the available facilities within the hub to fulfill system operational constraints and meet demand, including transmission and distribution facilities required to transport the energy to the load point/consumers.

System security concerns will consider the system's ability to react to transient disturbances, either local and widespread, including failures like abrupt loss of generation or loss of transmission facilities that might lead to voltage and/or frequency instabilities.

Reliability studies will dictate functional requirements and specifications for the energy hub. These studies will be the responsibility of the energy hub owner/operator to perform. The main elements to consider when assessing the stability and functional requirement studies for the energy hub are outlined in Figure 4.

Integrated system studies are required to assess the capability of the onshore AC system to deliver the power provided by the energy hub to the consumer. These studies will be the responsibility of the transmission system operator to perform. The capability of the AC grid to host the HVDC connection point is limited by (1) capacity constraints and (2) stability constraints. This should be considered as part of coordinated expansion planning. Network reinforcements will likely be required to support the hub, and a wide array of solutions could be evaluated, including wired and non-wired alternatives at different levels of the power system to maintain network-wide stability. The decision will be taken by the transmission system organization/operator, and this will be a techno-economic decision. Furthermore, the energy hub itself will be able to provide a host of services (Figure 5) that would serve to support the AC system where required by the system operator. Figure 5 outlines a path to conceiving, designing, and specifying these services.

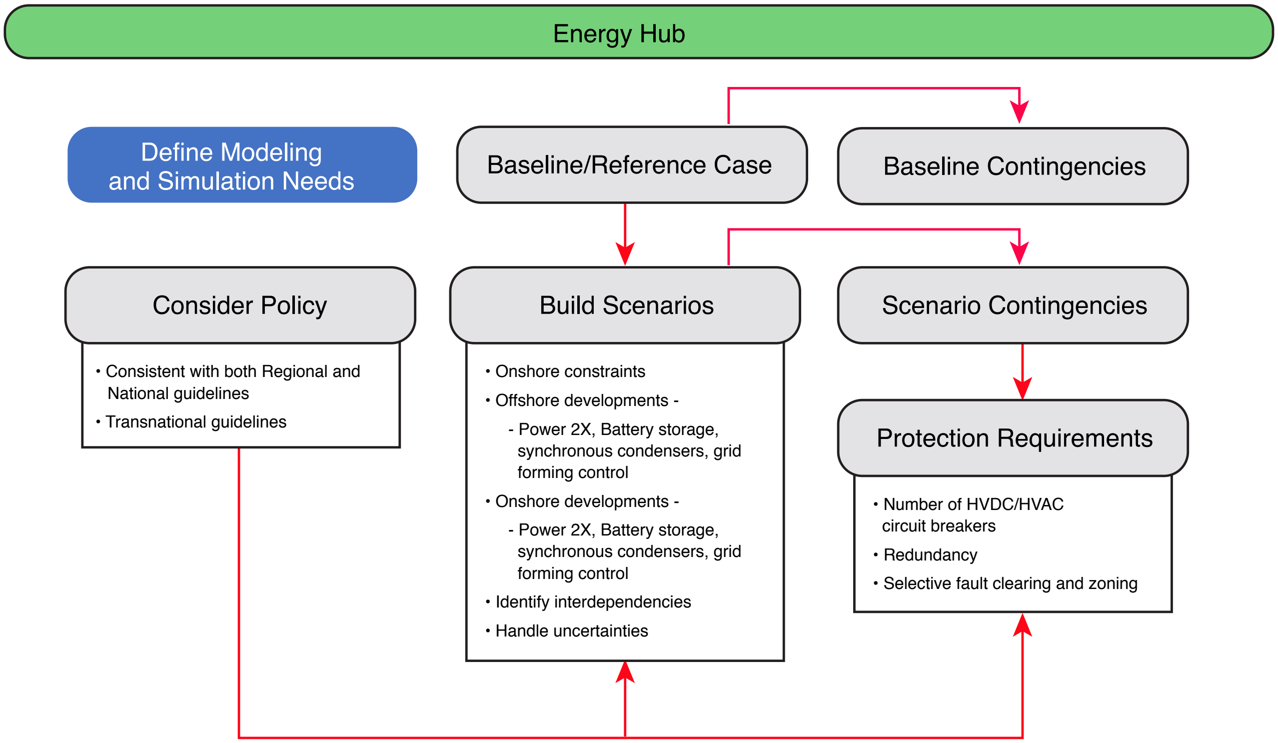


Figure 4. Outline for stability analysis study development

DC Hub Control

In the HVDC connected case, the services described will be delivered through coordinated control of the energy hub elements by a central grid controller. This functionality is summarized in Figure 6. The control architectures best suited to delivering the required functionality must be explored in detail in the specification stages of the project. In the pre-specification stage, the services required must be defined to enable the more detailed design of the hub controllers and the converter control systems.

Other Factors Affecting Performance Requirements

Grid Codes

Grid codes define the operating range and performance requirements from energy sources and loads connecting to the grid. At present, the European HVDC code 2016/1447[2] defined requirements at the AC connection points in the form

[2] https://www.entsoe.eu/network_codes/hvdc/

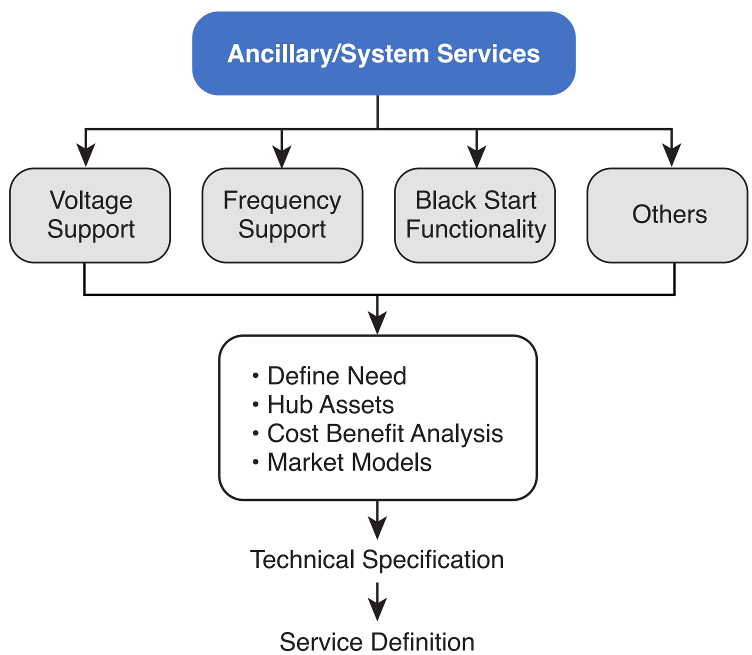


Figure 5. Energy hub services and consideration in their development and specification

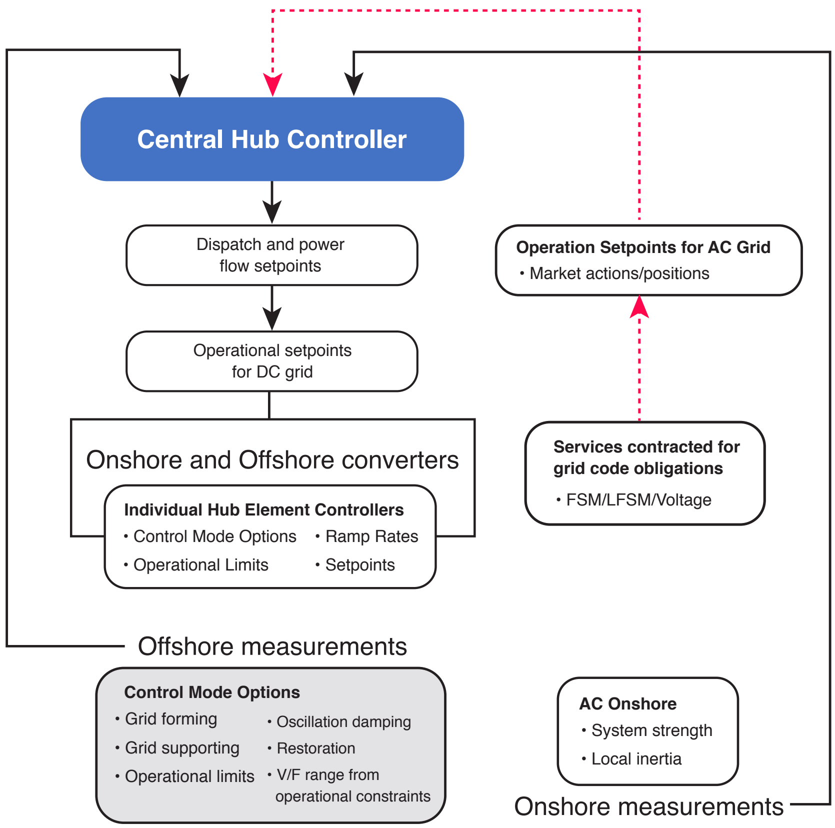


Figure 6. Control architecture for the energy hub

of the frequency sensitive mode (FSM), limited frequency sensitive mode (LFSM) at overfrequency/underfrequency, and voltage ranges for secure operation. Similar requirements could be extended for the energy hub as far as the AC connection point is concerned. A potential gap that currently exists in the context of the energy hub is the technical specifications required for the DC connection point.

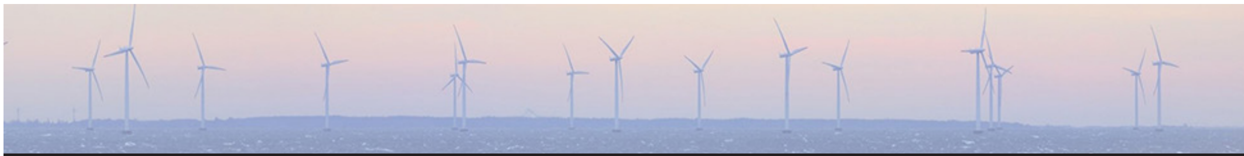
A question to consider is the definition of Pmax (the maximum capacity of the power park module in 2016/1447[3]) for the energy hub. It would be excessive to require the hub to meet the requirements for the full capacity of the hub at each onshore AC connection point. Instead, it would appear appropriate for the capacity of the DC link in question, between the hub spoke and onshore AC network, to serve as the proxy capacity for code compliance to a given AC connection point.

Market Integration

As its own synchronous area, load frequency control is a substantial consideration for the design of energy islands. An energy island that is its own control area requires the capability to minimize cross-border flow schedule deviations and frequency excursions. Within the market scheduling interval, the energy island needs to be capable of mitigating the majority of the forced outages or derating of assets within its territory as well as continuous variability and production uncertainty.

Operating reserves, such as frequency containment reserve, frequency restoration reserves, and replacement reserve, will be required within the control area, in alignment with Europe's SOGL (electricity transmission system operation) and EBGL (electricity balancing). The reserve policy will dictate the quantity of reserves

[3] https://www.entsoe.eu/network_codes/hvdc



required, but the allocation of reserve to resources connected to the energy island affects (and is influenced by) the network design. A sudden drop in production from one block of connected generation (for example, high-speed shutdown, converter failure) necessitates a response from storage or other generators. The relative locations of the HVDC converters and the resources holding the operating reserve might influence the sizing of the converters in either design scenario. An alternative to providing a significant portion of these reserves within the energy island could be to contract for balancing services from other resources on the mainland system. This would depend on the market constructs and the resources available, which are in the grids connected to the energy island.

Energy Hub Expansion

Energy hubs might be expanded to include multiple hubs connected together as more are developed in nearby geographical locations. Electrically connecting multiple energy hubs will need to be planned in advance when specifying the first energy hub. Specifically, in the HVDC connected context, the design of the HVDC control systems will be required to be expandable to incorporate power flow from multiple hubs. The hubs could be connected together either via AC or DC (implying a multi-terminal HVDC system).

Expanding the system from one hub to multiple hubs does not simply scale up the power rating; it extends the system operating range for converter control to coordinate, changes the network impedance/transfer function for control stability evaluation, increases redundancy, and adds to the complexity of analysis. The following are the criteria of analysis required to develop multiple hubs beyond the previous initial studies developed:

- System reconfigurability and remaining power transfer capacity when certain components (for example, converter station, wind parks, HVDC pole) need to be taken out of service for maintenance
- Validity of the control settings for an expanded hub design
- Minimum required changes to both the converter power and voltage control and the master control scheme when expanding the system to include more converters and more hubs

To alleviate some concerns with existing plant and hub control when expanding the hub system, existing components could be designed to have the capability to receive auxiliary signals from a central controller providing hierarchical control to all connected energy hubs. In specifying this capability at the design and build of the first energy hub, future coordination might be easier to achieve.

Conclusions

Building a renewable energy hub at a gigawatts scale is a once in a lifetime event for a power system and should be considered a great opportunity to integrate huge penetrations of renewable energy. Careful consideration should be given to the design of the energy hub in the initial phase, with thought given to a range of scenarios, some of which are outlined in this white paper. The initial power system planning assumptions have a large bearing on the specifications, which are developed for tendering the construction of the system. This white paper has provided a generalized approach to the considerations in the early feasibility planning and early electrical design of the energy hub. Traditional transmission planning considerations, such as reliability planning, transmission topology, modeling, and stability, are discussed and some other concepts specific to the development of an energy hub, such as requirements for grid-forming control on the energy hub, hub control, market integration, and hub expandability, also have a large bearing on the specifications for the system.

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Note

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

EPRI RESOURCE

Jonathan Ruddy, *Senior Project Engineer*
650.855.7904, jruddy@epri.com

Aidan Tuohy, *Program Manager Transmission Operations, Planning and Bulk System VG/DER Integration,*
atuohy@epri.com

Anish Gaikwad, *Program Manager, Transmission Operations and Planning,*
agaikwad@epri.com

Alberto Del Rosso, *Principal Project Manager, Transmission Operations and Planning,*
adelrosso@epri.com

Transmission Planning

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com