North Sea
Wind Power Hub
Programme

Regulatory & market design

Cost Benefit Analyses for Offshore Hybrid Infrastructure projects

Challenges and opportunities for understanding the socio-economic impact of hybrid interconnections on the European energy system

Discussion paper

#2

Co-financed by the Connecting Europe Facility of the European Union

Table of Contents

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About this paper

Background

Offshore wind power is one of the large renewable energy sources (next to onshore wind and solar power) which are foreseen to ensure the green transition of the European Energy system and support the goal of net zero greenhouse gas emissions by 2050.

The European Commission has set a target of 300 GW of offshore wind capacity to be installed in the European Union by 2050 and ENTSO-E's system scenarios show between 400 and 440 GW in all of Europe.

The North Sea Wind Power hub works with Hubs-and-Spokes concepts to facilitate the integration of large amounts of offshore wind. The Hubs-and-Spokes concept combines the deployment of offshore wind with energy exchange options, by constructing cross-border electricity grids, and potentially hydrogen pipelines and offshore hydrogen production. The aim is to provide a more flexible energy system, better utilise multiple assets, and ultimately ensure cost-efficient integration of offshore wind.

The Hubs-and-Spokes concept is expected to add more value to the energy system, compared to a situation in which a traditional approach with e.g., connecting single offshore sites radially to shore. The design of offshore infrastructure and transmission of offshore wind electricity to land in combination with possible production and transmission of hydrogen will also impact how the onshore energy system should be designed to ideally take advantage of the Hubs-and-Spokes concept. At the same time, options and costs for development of the onshore system will significantly impact the value of the offshore system.

On this backdrop, one of the main goals of the NSWPH is to assess the societal costs and benefits of the Hubs-and-Spokes concept to support planning and decision-making on a European energy system level. Adequate evaluation of Hubs-and-Spokes concepts compared to relevant alternatives is key for understanding the potential societal benefits of different offshore grid buildouts or Hubs-and-Spokes design options.

A Cost and Benefit Analysis (CBA) is a generally accepted approach for reviewing energy infrastructure projects and is an important tool for communication to stakeholders and policymakers. CBAs for infrastructure assets are frequently performed on the basis of simplified market model simulations, disregarding long-term impacts on the surrounding energy infrastructure and details of the physical energy grid layouts.

In NSWPH's recent work it has become apparent, that the complexity, size and potential impact of the installation of a Hubs-and-Spokes concept on the surrounding energy system, means **that traditional applications of CBA methodologies are not suitable for the prospective Hubs-and-Spokes infrastructure** and therefore cannot adequately assess all costs and benefits. A major reason for this is that a traditional CBA often limits the analysis to assess the same overall system with and without a given project and compare the results based on operational changes. Such an approach does not capture the potential high impacts of a Hubs-and-Spokes project on the structure of the overall energy system.

Since investment needs for Hubs-and-Spokes concepts are high, traditional CBA approaches bear the risk of negative evaluation with the potential to favour radial offshore wind deployment and hinder optimal future grid buildout for power and hydrogen.

Important aspects for assessment of Hubs-and-Spokes projects include:

- The large size of a Hubs-and-Spokes system will impact the long-term development of the surrounding energy system and subsequently investments.
- The physical grid layout can significantly impact realisable energy flows (of power and hydrogen), which current applications of CBA methodologies based purely on market setups and large bidding zones, do not capture.
- Calculation of impacts of infrastructure investments on producers, consumers and TSOs deliver important insights for political decision making. The current market setup distinguishing between Day-Ahead markets and subsequent redispatch measures, have implications for individual stakeholders, which are hard to cover without reflecting this process in the modelling setup.

Why read this paper?

The current paper summarizes the NSWPH's experience and **recommendations** for working with CBA analyses of Hubs-and-Spokes concepts.

- The paper builds upon previous learnings and relevant literature and herewith proposes recommendations to ensure the value of future CBA analyses which strive to enable policy makers to make informed decisions.
- The paper is thereby highly relevant for stakeholders working with and using CBAs of Hubs-and-Spokes concepts. This includes e.g., policy makers in the European Union, funding organizations as CINEA (European Climate, Infrastructure and Environment Executive Agency), as well as implementing institutions carrying out CBAs on hybrid projects, i.e. the ENTSO-E, ENTSOG and NSWPH.
- This paper intends to describe key shortcomings of traditional CBAs and suggests alternative approaches. Well-considered CBA methodologies are vital for a meaningful evaluation of large infrastructure projects such as the Hubs-and-Spokes concept.
- This paper aims to provide insights into appropriate CBA frameworks, which can be applied to assess Hubs-and-Spokes concepts, as well as describe options and choices to be taken for implementing different CBA methodologies.
- Finally, the paper gives **recommendations** on how to improve CBAs for Hubs-and-Spokes projects.

The discussion paper is based on a previous discussion paper as published by the North Sea Wind Power Hub[1], key learnings from Cost Benefit Analyses performed so far, as well as other relevant literature related to this topic.

[1] CBA framework for Hubs-and-Spokes projects, Discussion paper #1, NSWPH April 2021.

Structure of the paper

Key aspects and conclusions are summarized in the executive summary. The introduction describes the relevance of Hubs-and-Spokes concepts and key learnings from NSWPH's previous work. The NSWPH perspectives section discusses different approaches that the NSWPH applies for evaluating Hubs-and-Spokes concepts, while the specific challenges of these approaches are described in the section that follows on the methodological challenges.

In the final chapter on CBA setup and execution, we discuss how to setup and execute future CBA studies for Hubs-and-Spokes concepts based on theoretical discussions in the previous chapters. The chapter focuses on the practical aspects of such CBA studies and breaks down the process into several pieces: exogenous variables, model setup, modelling approaches, relevant indicators to monitor and stakeholder inclusion.

Structure of the discussion paper

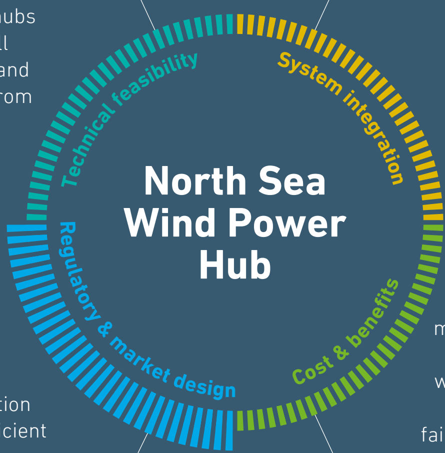
The big picture

The North Sea is a powerhouse of wind energy. Harnessing this power requires us to cooperate across countries and borders to build an efficient network. To show that a solution can be achieved in a cost-effective and secure manner, the North Sea Wind Power Hub is working within four key areas.

This discussion paper explores key topics within system integration.

How to design and build the physical hubs and spokes that will collect, transform and distribute energy from the North Sea.

How to adapt the energy systems in Northern Europe to integrate a large volume of offshore wind from the North Sea.



How to ensure a stable and reliable investment climate by adapting regulation and creating an efficient market design.

How to ensure that the chosen solution maximises benefits for society and climate while minimising costs and distributing them fairly between countries and stakeholders.

Executive summary

Introduction

The current paper summarizes NSWPH's experience and recommendations for working with CBA analyses of Hubs-and-Spokes configurations ensuring adequate evaluation of large infrastructure projects involving generation and transmission of power and hydrogen.

Many of the evaluations and issues in this paper focus on the power system. This approach has been chosen for illustrative purposes. The conclusions and recommendations may as well be applied for the combined power and hydrogen generation and transmission system.

Some concepts as "Market modelling", "NTC", "Flow based market coupling (FBMC)", and "Grid models" are used in the executive summary and are further explained in the Introduction section.

Perspectives on CBA

Hubs-and-Spokes configurations provide an alternative option to connect offshore wind to the surrounding energy system, compared to the traditional radial connection applied in today's offshore wind projects.

CBAs for electricity infrastructure projects are frequently performed on the basis of simplified market model simulations, disregarding long-term impacts on the surrounding energy system, other energy sectors and details of the physical energy grid designs. As such, the assessments of infrastructure projects in ENTSO-E's Ten Year Network Development Plan (TYNDP) focus mainly on estimates of the impact on bidding zone level electricity dispatch using Net Transfer Capacity (NTC)-based market simulations, although ENTSO-E's CBA guidelines[2] also allow for considering a wide range of other factors. As such, changes in grid losses, redispatch volumes and cost, etc. are also reflected. Therefore, ENTSO-E's guidelines cover options to include a large extent of the methodologies and indicators suggested in this paper, but many CBA assessments in the TYNDP do not apply those options.

In NSWPH's recent work, it has become apparent, that traditional applications of CBA methodologies cannot adequately assess all costs and benefits of large Hubs-and-Spokes projects due to their complexity, size and potential impact on the surrounding energy system.

Since investment needs are high, pragmatic CBA approaches bear the risk of negative socio- and economic evaluation of Hubs-and-Spokes configurations with the potential to favour radial offshore wind deployment and hinder optimal future grid buildout.

The current paper aims to provide insights into appropriate CBA frameworks, which can be applied to assess Hubs-and-Spokes concepts, as well as insights into options and choices to be taken for implementing different CBA methodologies.

Improving CBA-methodologies

Text box 1: Recommendations for improving CBAs

To capture the full aspects of Hubs-and-Spokes systems, CBAs should include assessments of:

- Impacts on investment needs in the surrounding energy system
- Realizable market flows and internal grid congestions
- Impact of the current regulatory setup on stakeholder analyses

[2] Latest version is the draft for the 4th ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects, version 4.1, April 2023.

The NSWPH has identified a number of topics, which are important to take into account when performing CBA of Hubs-and-Spokes projects. The findings are based on previous CBAs of different Hubs-and-Spokes configurations carried out in the period from 2020 to 2023, as well as through methodological considerations.

Investments needs

Investments needs in the surrounding systems driven by Hubs-and-Spokes projects must be compared to impacts of alternative solutions (e.g., radial connections to shore).

Assessing the improvement (regarding flexibility and possible congestions) that the interconnectors (in a Hubs-and-Spokes configuration) allow, naturally requires a good understanding and modelling of the shortcomings of the future grid infrastructure. In an unlimited and uncongested grid setup, new grid infrastructure would have no immediate measurable benefit.

Hubs-and-Spokes concepts can impact the need for other investments in grid infrastructure or other options to alleviate congestions. Both costs and options for realizing these investments can have significant importance.

As an example, if the surrounding system has ample options to reinforce the transmission system at reasonable cost, the potential savings from adding the Hubs-and-Spokes concept are limited. On the other hand, if the maximum realizable interconnection capacity in the surrounding system is limited or costs are high, the benefits from Hubs-and-Spokes in alleviating grid buildout can be substantial compared to a traditional alternative of radial connection.

An assessment of investment needs in the energy system is therefore important when evaluating Hubs-and-Spokes projects.

Realizable market flows and internal grid congestions

As a result of ambitious targets for offshore wind deployment, large energy transport needs will arise, and grid congestions are to be expected in close to shore areas. The standard NTC-based market simulations, which often provide basis for the assessment of infrastructure projects, are not able to cover and reflect the interdependency of flows in an AC grid or cover internal grid congestions.

Additionally, NSWPH's analyses show, that internal grid congestions and reinforcement needs can be an important driver for the socio-economic value of Hubs-and-Spokes configurations, highlighting the need for its inclusion.

There are several ways to better reflect the physical constraints in model simulations. When choosing between different simulation options, there are two main considerations:

- How well are they able to reflect actual physical conditions and thus estimate realistic power flows?
- How well do they reflect the current market setup?

The first consideration is key to ensure a realistic estimate of total socio-economic welfare. Though, when choosing the second option, deviating from the current market setup will complicate or even prevent the assessment of impacts for individual stakeholders in the current market setup.

Current European Day-Ahead markets are to an increasing extent applying flow-based market coupling to better represent the physical grid and avoid unrealistic market results. Implementation of flow-based market coupling (FBMC) in market models for CBAs holds the potential to improve representation of the physical flow options and will thus improve the understanding of the impact of Hubs-and-Spokes configurations on market flows. At the same time, introduction of FBMC can improve the link between market and grid models, facilitating subsequent redispatch simulations and assessments.

Therefore, flow-based market simulations are recommended in CBAs of Hubs-and-Spokes projects.

Impact of the current regulatory market setup on stakeholder analyses

In the current regulatory market setup, stakeholders (TSOs, producers, consumers) are to an increasing extent affected by not only Day-Ahead market results, but also subsequent needs for redispatch, which correct the lack of considerations of internal grid congestions in the Day-Ahead market.

It is possible to take internal grid congestions in market models into account with adequate input from grid models, but only a **combination** of a FBMC-based market simulation with grid model based estimations for redispatch will be able to reflect realistic, market-based dispatch, realizable power flows after redispatching as well as resulting stakeholder impacts of both.

Attempting to include detailed internal grid congestions in one single model will complicate or even prevent correct assessment of impacts on individual stakeholders. Current methodologies applied in ENTSO-E's TYNDP largely disregard the impact on stakeholders originating from redispatch needs.

Therefore, it is recommended that redispatch needs and impacts of regulatory market setup are evaluated as part of CBAs for Hubs-and-Spokes projects.

CBA setup and execution

This paper **recommends** working with the analyses of Hubs-and-Spokes configurations at three different levels, of which the two latter can be applied in project specific assessments comparable to those performed in ENTSO-E's TYNDP.

The recommended three levels:

- **System studies** – analysing the general tendencies and long-term energy system pathways with and without options for Hubs-and-Spokes configurations, from a purely energy optimal perspective
- **Pragmatic CBA** – analyses of potential overall design of promising Hubs-and-Spokes configurations with a focus on assessing the socio-economic value
- **Advanced CBA** – assessing the socio-economic value of configurations, by taking into account both regulatory market setup and impacts on the detailed physical grid (grid modelling of redispatch and/or need for grid upgrade) – especially within bidding zones.

The different stages have different purposes and focus areas, ranging from the broadest view in system studies to the most detailed in the advanced CBA. However, study topics are interlinked and as such, the outcomes of one level affect the next.

System studies assess the overall potential pathways for the system and the prospects of Hubs-and-Spokes within those system. The pragmatic CBAs result in a preliminary evaluation, which can support the decision on which configurations deliver promising CBA-results. These configurations can be further explored in advanced CBAs.

The pragmatic CBA is suggested to take into account bidding zone internal grid congestions in a simplified manner, e.g. by being based on FBMC-based market models to limit computational efforts and model iterations. The advanced CBA should increase the detail on grid assessments. For this purpose it can be based on a combination of both FBMC-based market simulations and grid model simulations of redispatch and internal grid upgrade needs. Only the advanced CBA will be able to include all of the suggested improvements for CBA analyses, and we recommend to carry out this work in order to understand all relevant aspects of Hubs-and-Spokes configurations. Pragmatic CBAs will still be able to show indicative assessments but should be improved compared to current practices by including the aspects of investment needs and bidding zone internal grid congestions described in this paper.

To fully illustrate the impact of the suggested modelling methodologies the paper **recommends** using a new list of indicators for CBA assessments, including the distinguishment between market and grid impacts as well as illustration of impact on investment needs.

Stakeholder inclusion

We recommend a strong stakeholder engagement: It starts in the conception phase and has critical importance for the success of the CBA. Discussion of the CBA framework including scope, configurations and indicators, clear understanding of the modelling consequences and distribution of welfare are important for conducting a CBA study. This process can ensure a CBA, which is not only relevant and interesting, but also provides understandable and accepted results, ensuring momentum for further steps into realization.

While stakeholder involvement processes are key to the NSWPHs internal processes, they also apply in a more general context, because active stakeholder involvement serves as a quality check and ensures that concerns are heard, and the results understood.

1 Introduction

Project characteristics

Offshore wind is foreseen to play an important role in the green transition of the European Energy system and to ensuring sufficient resources to enable decarbonization of the power system as well as other sectors within the industry, heating, and transport.

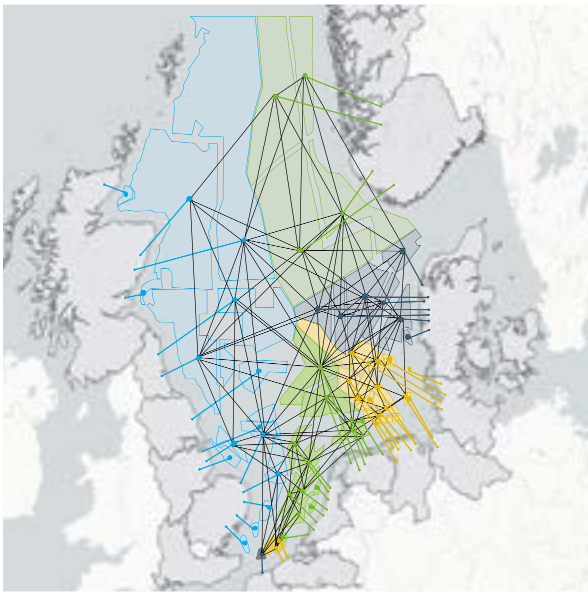
While the pure electricity generation cost of offshore wind is – depending on the actual site conditions – presumably higher compared to onshore wind and solar power, potentials of offshore wind are large and implementation does not face the same competition on land use and societal acceptance, which may set an upper limit on deployment of onshore wind and solar power within Europe.

The European Commission has set a vision of 300 GW offshore wind within the European Union by 2050, ENTSO-E's scenarios towards 2050 show between 400 and 440 GW within Europe and Belgium, Denmark, Germany, and the Netherlands have declared a common target of 150 GW of offshore wind, of which the major share is expected to be placed in the North Sea.

All of these targets underline the importance of offshore wind deployment, and specifically deployment in the North Sea. At the same time, several system studies show, that efficient implementation of an increasing share of variable renewable generation – accounting for 70-80% of all generation in 2050 in ENTSO-E's scenarios – require a flexible energy system and a strong transmission grid.

Hubs-and-Spokes concepts aim at combining the deployment of offshore wind with cross border electricity transmission, and potentially cross-border hydrogen pipelines and offshore hydrogen production, thus providing both energy supply and system flexibility.

Figure 1: Illustration of offshore deployment options and potential interconnections in the North Sea. Each color represents offshore areas of North Sea countries according to the maritime borders. Retrieved from NSWPH program.



The potential size of both generation capacities and interconnectors is large. As an example, the NSWPH is by far the largest transmission project in ENSTO-E's TYNDP 2022, interconnecting 14 GW of offshore wind using 18 GW of interconnectors. The second largest projects are 4 GW DC projects reinforcing the internal German grid. Also, in terms of investment needs, the estimated CAPEX of around 19.5 B€ is almost twice the size of the second-largest project.

Highlight
NSWPH is the largest transmission project in ENSTO-E's TYNDP 2022, interconnecting 14 GW of offshore wind.

The size of the projects, combined with the interconnection of various countries and bidding zones, mean, that a traditional CBA focusing on dispatch impacts in the power system on a bidding zone level, will risk excluding important elements and hinder proper evaluation.

The NSWPH has worked with CBA-studies of different Hubs-and-Spokes configurations over the past years and can draw important learnings from this experience.

Lessons learned

The NSWPH has undertaken several CBA studies with varying scopes in terms of Hubs-and-Spokes configuration, methodologies, and indicators. The quantitative key results are published separately, but the qualitative takeaway is summarized here.

Depending on the approaches taken and factors included in the different analyses, the evaluation of Hubs-and-Spokes concepts has proven to vary from resulting in additional socio-economic costs to enabling system savings.

Short term economic impact

The investments needed to realize Hubs-and-Spokes concepts are large and given that global experience with multiterminal HVDC and offshore electrolysis is limited – and has not been deployed in an offshore context to date – cost uncertainties are also large.

Compared to radial connections of offshore wind (meaning that produced energy by a wind farm is directly connected to onshore grid) Hubs-and-Spokes concepts likely require higher investments – regardless of whether the radial alternative uses HVDC technology or could be realized at closer-to-shore sites with AC-technology.

Based on a number of modelling studies, it is unlikely, that these additional investments costs for Hubs-and-Spokes can be recovered relying solely on savings from more efficient dispatch in the surrounding energy system's bidding zones. These studies imply that only if the surrounding systems are assumed to have very limited ability to absorb additional radial offshore wind, the Hubs-and-Spokes concept might spur high enough dispatch savings.

Highlight
It is unlikely, that Hubs-and-Spokes can be recovered relying solely on savings from more efficient dispatch.

Long term economic impact

Assessing the improvement that the Hubs-and-Spokes concept's interconnectors allow, naturally requires a good understanding and modelling of the shortcomings of the future grid infrastructure.

However, the interconnectors of the Hubs-and-Spokes concept need to be judged against other options for improving grid conditions meaning that alternative measures of lifting grid congestions need to be priced to compare the solutions.

For example, offshore hydrogen infrastructure could facilitate the roll-out of the offshore electricity grid by increasing the electricity grids' utilisation: Producing hydrogen during times of high wind production and using the electricity infrastructure at higher capacity by transporting additional electricity to the electrolysers in times of low wind production. However, this brings in other considerations such as conversion losses and requirement of analyzing an integrated energy system when assessing the economic impact of a Hubs-and-Spokes system. This is needed for designing the 'optimal' system.

Investments in Hubs-and-Spokes systems can impact the surrounding energy system investment needs in several ways:

- Need for transmission investments
- Need for flexibility measures (electricity and hydrogen storage, hydrogen based power backup capacity, electrolyzers,...) and even load
- Investments in renewable generation

These long-term impacts on the surrounding energy system should be considered, when assessing the socio-economic benefit of Hubs-and-Spokes concept.

Highlight
Recent CBAs suggest, that roughly half of the benefit of an interconnector can be attributed to savings in the investment needs in the surrounding transmission system.

As Hubs-and-Spokes can impact the above-mentioned investments, both costs and options for realizing the potential alternatives can have significant importance. As an example, if the surrounding system has ample options to reinforce the transmission system at reasonable cost, the potential savings from adding the Hubs-and-Spokes concept are limited. On the other hand, if the realizable interconnection capacity in the surrounding system is limited or costs are high, e.g., due to a need to deploy expensive underground DC cables, the benefits from Hubs-and-Spokes can be substantial.

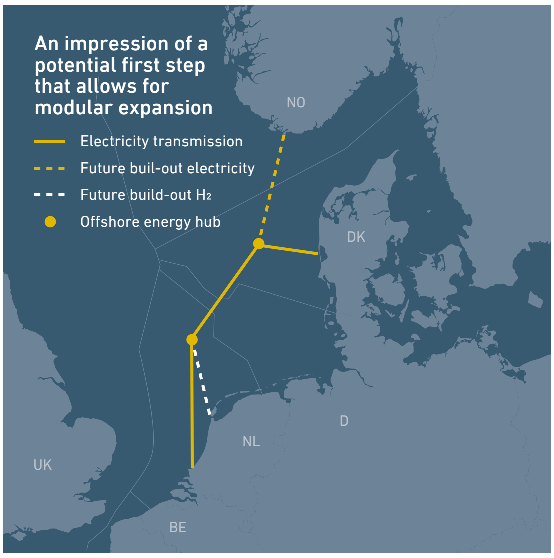
Recent CBAs suggest, that roughly half of the benefit of an interconnector (in a Hubs-and-Spokes project) can be attributed to savings in the investment needs in the surrounding transmission system.

Hubs-and-Spokes design

The optimal design of the Hubs-and-Spokes system is not independent of its interconnection. While this finding sounds trivial, it is important to note, that the amount of offshore wind which can be economically beneficial, is likely higher when the Hubs-and-Spokes system is deployed compared to radial connection – even if total transmission capacity to shore remains unchanged. This is due to the higher flexibility of transporting power along different routes in the Hubs-and-Spokes system. Same holds true when offshore electrolysis (including required offshore hydrogen transmission infrastructure) is added. Such hydrogen capacities could also be regarded as 'interconnector capacity' fulfilling similar purposes as electricity transmission infrastructure. The economic optimal sum of such 'interconnectors' might not equal the sum of connected offshore wind.

Highlight
The amount of offshore wind which can be economically beneficial, is likely higher when the Hubs-and-Spokes system is deployed compared to radial connection.

Figure 2: An indicative design option for Hubs-and-Spokes concept.



Grid congestions

The impact of Hubs-and-Spokes interconnectors on potential savings on alternative trade capacity investments can be assessed in traditional market models using assumptions on net available trade capacity (NTC) between bidding zones. However, this modelling will not cover the full impact on the physical grid, nor the subsequent needs for redispatch measures.

Previous studies have identified a number of preliminary findings, but foremost identified additional methodological development needs:

- Congestions are to be expected in the electric grid close to the onshore connection points of the North Sea's Hubs-and-Spokes systems. Ambitious deployment targets for offshore wind exaggerate this topic.
- Up to one third of the impacts on grid investments in the surrounding system can be attributed to zone-internal reinforcements, which cannot be fully captured by bidding-zone level market analyses (see an example of estimated substation-level grid investments on Figure 3).
- Translating market level trade capacity investments to investment needs in the physical grid is not trivial and a grid level assessment can lead to identification of both: Higher investments needs (grid congestions not captured by market) or lower investment needs (targeted investments in selected grid assets unlock additional capacities in the surrounding system).
- Implementation of flow-based market coupling in market models holds the potential to improve the link between market and grid models. The actual implementation has an important consideration:
    - Current regulation requires TSOs to make at least 70% of the capacity on grid elements available to the market (70% rule[3]). This rule enforces high levels of redispatch, since much of the information on actual available RAM will be ignored.
    - Alternative modelling approaches can improve the representation of internal congestions, but will not be as close to the actual current Day-

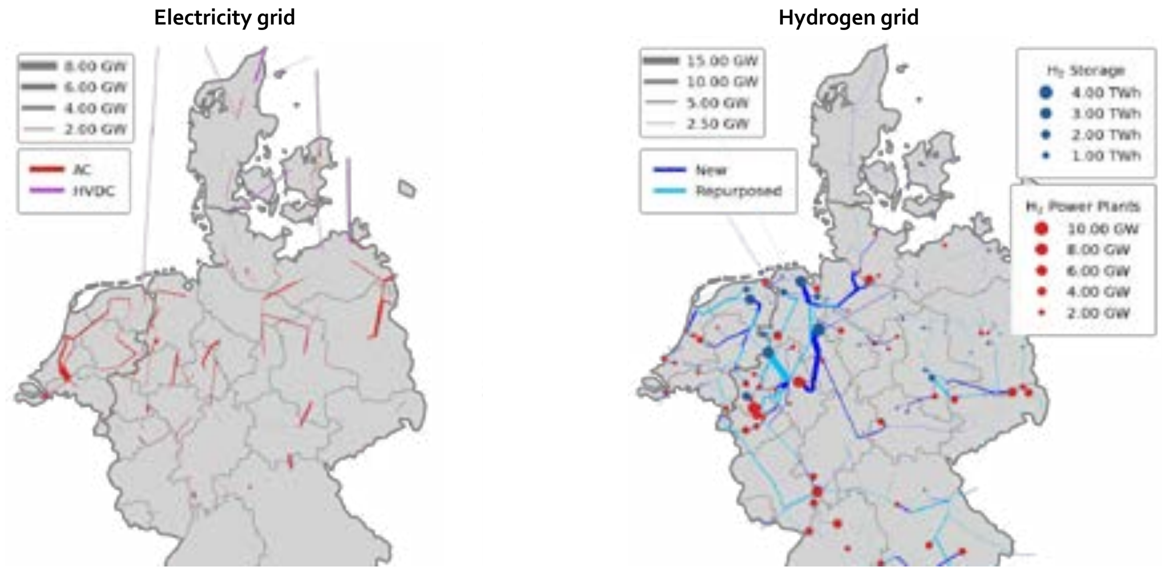
Highlight
Implementation of flow-based market coupling in market models holds the potential to improve the link between market and grid models.

[3] Europe's Clean Energy Package (CEP) has set a binding minimum 70% target for electricity interconnector capacity for cross-zonal trading (the "minimum 70% target"). The reason is that the lack of sufficient cross-zonal capacity is one of the main barriers to the integration of electricity markets, and market integration is key to deliver on Europe's energy goals.

Ahead market setup, by e.g. ignoring the 70%-rule and apply the actual available RAM.

- Alternative options to represent internal grid congestions includes splitting current bidding zones into smaller zone, which again will deviate from the current market setup.

Figure 3: Example of estimated substation-level investments in the electricity and hydrogen grid expansion in 2035 compared to 2030 shown in maps.



Other factors

Other factors impacting the assessment of Hubs-and-Spokes include the impact of topics, not covered in a standard simulation for a normal year.

These variations include fuel and CO_2-price variations as well as weather year variations and can impact the value of Hubs-and-Spokes, as the additional provided flexibility of such a project can have higher value in out-of-normal year characterized by e.g., higher fuel prices or lower generation from renewables.

2 NSWPH Perspective on CBA

Three stages

The NSWPH is working with the design and perspective of Hubs-and-Spokes configurations at three stages:

- The Pathway study – analysing the general tendencies and long-term energy system pathways with and without the option for hubs-and-spoke configurations, attempting to identify optimal techno-economic system designs.
- Pragmatic CBA – analysis of potential overall design of promising Hubs-and-Spokes configurations with a focus on assessing the socio-economic value of certain configurations.
- Advanced CBA – assessing the socio-economic value of configurations, by taking into account both the regulatory setup and impacts on the detailed physical grid, especially within bidding zones.

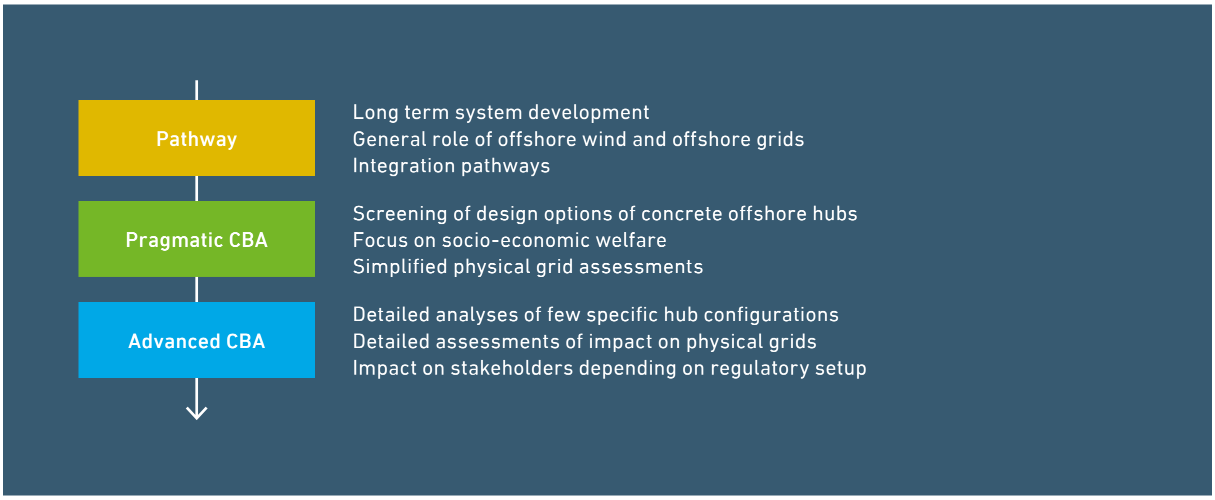
The different stages have different purposes and focus areas, ranging from the broadest view in the Pathway study to the most detailed in the advanced CBA. However, study topics are interlinked and as such, the outcomes of one level affect the next.

The pathway study is delivering first insights on beneficial energy transmission corridors (and possible further changes in the energy system) which are then used to define specific configurations for offshore hubs. Those are then screened with pragmatic CBAs resulting in a preliminary evaluation, which can support the decision on which configurations deliver promising CBA-results. These configurations can be further explored in advanced CBAs.

Highlight

The different stages have different purposes and focus areas, ranging from the broadest view in the Pathway study to the most detailed in the advanced CBA.

Figure 4: The role of different study setups as part of the NSWPH program



Pathway study

The Pathway study encompasses the entire European energy system and analyses how offshore wind can contribute to the decarbonization of the energy system, how offshore wind can be integrated, and which factors impact different integration Pathways.

Highlight

The Pathway study analyses how offshore wind can contribute to the decarbonization of the energy system.

A first Pathway study was carried out from November 2020 to August 2021. The NSWPH is currently working on an updated study, considering the lessons learned and updating system scenarios to reflect increased political ambitions on electrification and renewable energy deployment – not least in the light of the current energy crisis and the increased focus on security of supply.

Results of the updated study are expected in Autumn 2023. The Pathway study does not focus on one specific Hubs-and-Spokes configuration or sites. Instead, it explores how the general concept, deployed across the North Sea, can help integrating offshore wind. Positive assessment of the long-term vision for a broader application of the Hubs-and-Spokes concept is a prerequisite for meaningfully continuing analyses on specific configurations.

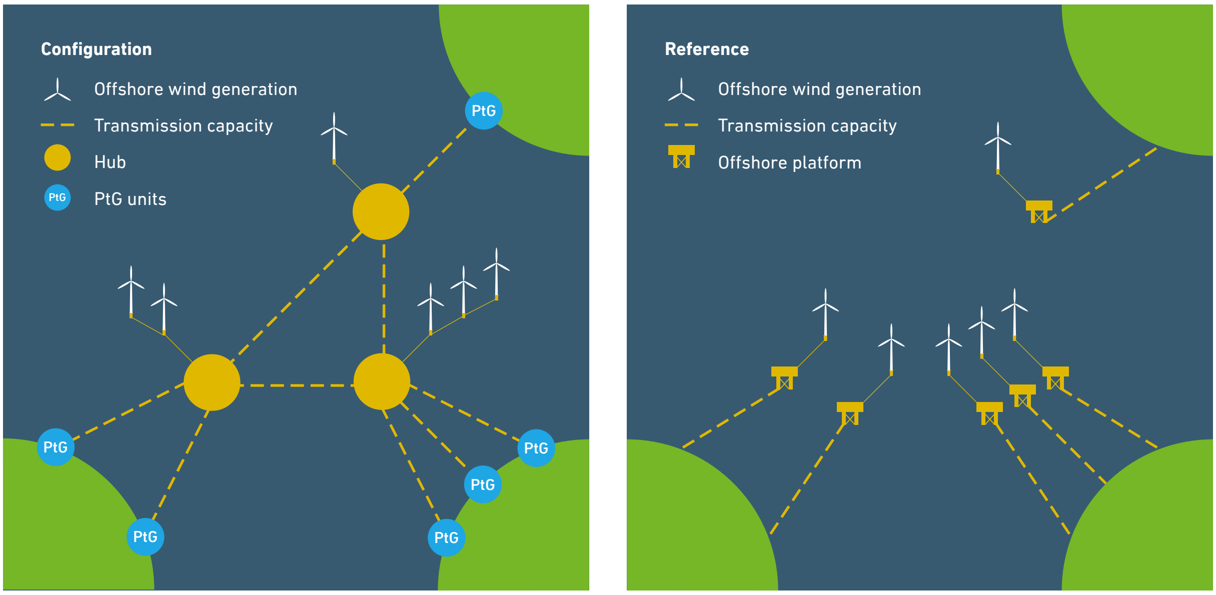
Pragmatic CBAs

Pragmatic CBAs focus on the feasibility of specific Hubs-and-Spokes configurations, which can serve as a first concrete step to realize the visions laid out in the Pathway study. The main topic is not the integration of offshore wind in general but the specific configuration options for Hubs-and-Spokes solutions entailing specific sites.

Over the past two years, the NSWPH has investigated a number of options to interlink offshore wind sites in Danish, Dutch and German waters. The main learnings from those studies are summarized in the introduction section and have led to e.g., possible refining configurations in terms of offshore wind capacity relative to transmission capacities.

Highlight
Pragmatic CBAs focus on the feasibility of specific Hubs-and-Spokes configurations, which can serve as a first concrete step to realize the visions laid out in the Pathway study.

Figure 5: Example of analysed configurations and respective references.



The overall aim of the pragmatic CBA is to explore, screen and define relevant case studies for further evaluation and ensure clear communication with stakeholders on the methodologies behind. For this purpose, the study level needs to be detailed enough to capture the most important aspect, but also efficient enough to facilitate a significant number of configuration evaluations, thus limiting the needs and resources for computational power and analyses.

Application of advanced CBA-methodologies without previous pragmatic CBAs will complicate the important stakeholder involvement processes, as the potential number of factors affecting the results would be higher in this initial phase.

The pragmatic CBAs result in a preliminary evaluation, which can support the decision on which configurations could deliver promising CBA-results. These configurations can be further explored in advanced CBAs. Furthermore, the pragmatic CBAs ensure comparability to other analyses using similar approaches.

Advanced CBA

The advanced CBA will increase the level of detail of the performed pragmatic CBA-study and is intended to follow up on the outcomes of a basic/pragmatic CBA.

The advanced CBA will increase the level of detail on both the impacts for different stakeholders – market participants and grid operators – as well as congestion management in the physical grid within bidding zones.

Highlight
The advanced CBA will increase the level of detail on both the impacts for different stakeholders – market participants and grid operators – as well as congestion management in the physical grid within bidding zones.

For this purpose, both market and grid simulations are part of an enhanced CBA, which deepens the understanding of:

- Market vs. grid driven investments
- Market vs. grid driven dispatch
- Redispatch costs
- Physical grid layouts in the surrounding grid

The NSWPH has carried out advanced CBAs involving grid simulations, proving the potential setup and estimating grid level impacts. However, the results also showed, that linking results from NTC based market simulations to substation level grid simulations is not straight forward and can benefit from further methodological advances, which are discussed in more detail in the following section.

Modelling methodologies

For the three described stages, different modelling methodologies can prove to be the most efficient. We **recommend** the following:

- Pathway study. NTC modelling with increased geographical resolution.
- Pragmatic CBAs. Bidding zone level market model based on FBMC excl. regulatory rules. Thus deriving a market result that respects the limitations of the physical grid to a large extent, limiting redispatch impact as it would not be calculated in this step. Alternatively, an NTC based market model run based on bidding zone level, ideally combined with a subsequent redispatch calculation.
- Advanced CBAs. Bidding zone level market model based on FBMC incl. regulatory rules (i.e. 70% rule) and subsequent redispatch simulations.

Highlight
For the three described stages, different modelling methodologies can prove to be the most efficient.

For long term energy system studies as the Pathway study, the number of potential parameters and optimisations is higher than for project-specific CBAs. It is therefore vital to keep modelling details at a level that still allows reasonable computation time.

For the pragmatic CBAs the details and variations of the surrounding energy system are decreased, and details of Hubs-and-spoke configuration options can be increased.

Applying bidding zone level FBMC will ensure that some considerations about the physical grid are already included in the market results, while keeping the need for iterations between market and grid models at a minimum.

The pure application of FBMC will significantly improve coherence to a potential next step applying advanced CBAs. The advanced CBAs will be able to lay out details, such as impacts from respecting regulatory aspects in a further enhanced manner. With the current market setup full details on stakeholder analyses require the application of both market and grid models. The reason for this is that the modelling must reflect both

- the market setup for estimating the Day-Ahead market outcomes for the stakeholders (market model)
- and the actual physical conditions in the grid including the need for redispatch (grid model)

Details on modelling methodologies as well as suggestions for actual implementation are discussed in the following sections of the paper.

3 Methodological Complexity

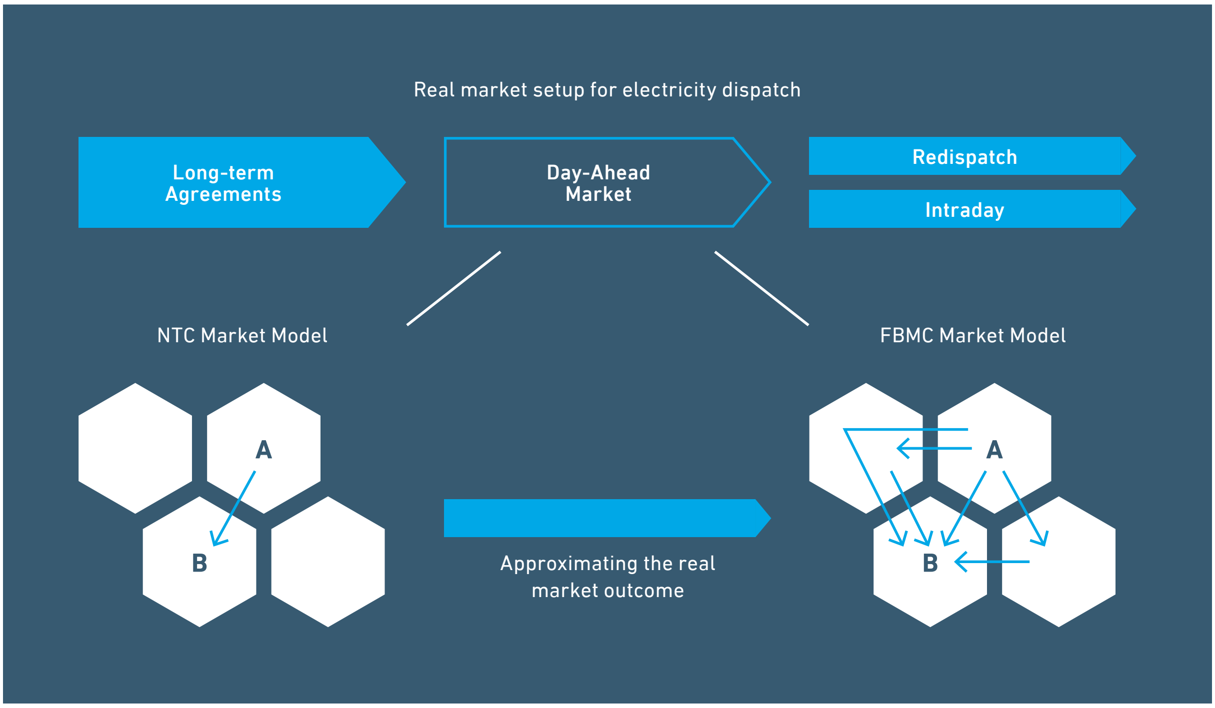
Introduction

This section on methodological complexity is in some subsections technical detailed and assumes knowledge of market and grid modelling subjects. Flow-based Market Coupling and Net Transfer Capacity models are used for electricity grid and market operations, and this section primarily investigates these models and implications of their applications. The more generally interested reader may skip this section and jump to the next following section: "CBA setup and execution".

Market simulations

Market simulations are based on an optimal dispatch approximation. It is important to understand underlying assumptions and their consequences. It will be insightful to elaborate on the "delta" between different options for simulation models and the current market setup for electricity dispatch (FBMC + intraday markets + redispatch). Figure 6 illustrates the overall flow of the current regulatory setup and the main difference between NTC and FBMC market models.

Figure 6: Market modelling approaches: Within the Day-Ahead markets, NTC based constraints limit trades between neighbouring bidding zones. Within FBMC, the constraints take into account all possible trades simultaneously. In the schematic, A and B represent bidding zones, flows are from A to B



Market simulations align closely with the rules of the Day-Ahead (D-1) markets, yet (usually) disregard forecast uncertainties. Within the NTC approximation, trading capacities are constants, one value for each direction per interconnector. Days-Ahead market results are an important reference for the other wholesales markets and hence market simulations may claim to approximate a large share of the total dispatch cost. Congestion management simulation can potentially be done subsequently.

An NTC-based market model disregards most internal congestions within bidding zones. To capture these, a following redispatch simulation is required. For instance, market models based on the NTC approach disregard the North-South transport limitation in Germany since details in the network are – by definition and on purpose – disregarded.

Highlight
An NTC-based market model disregards most internal congestions within bidding zones.

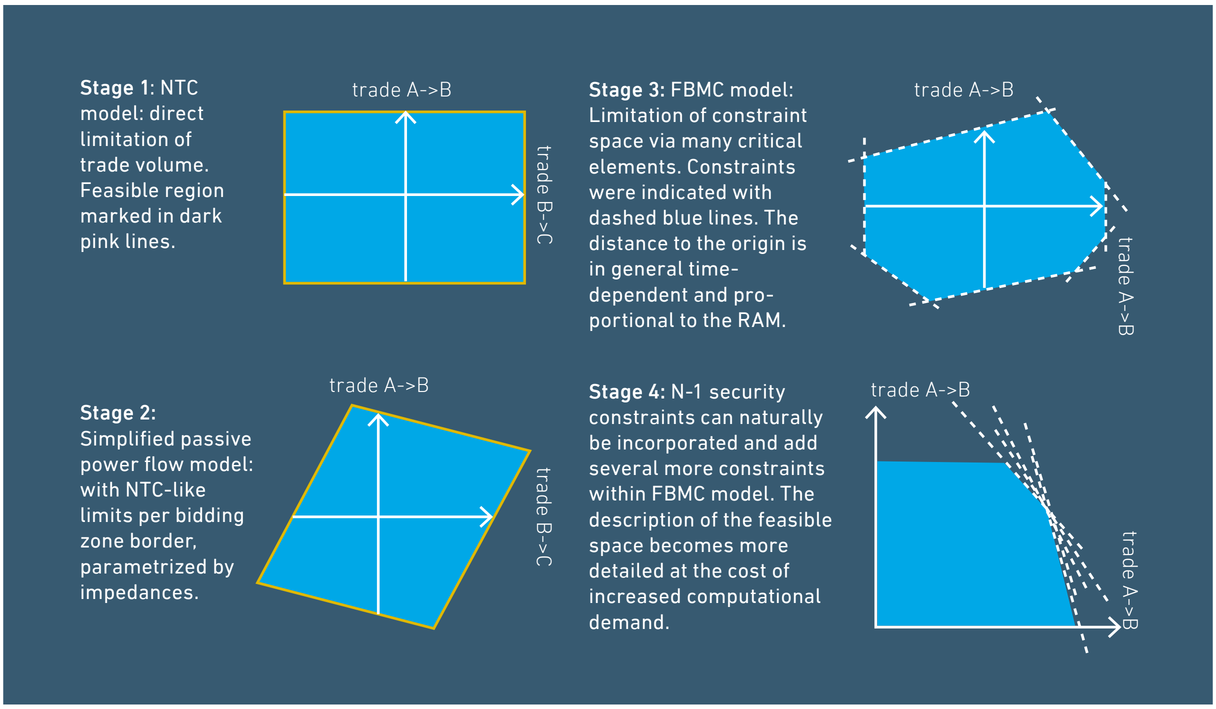
A flow-based approach considers part of the congestion by considering impacts of cross-border trades on critical internal elements, for instance transmission lines for power from North towards South of Germany.

Difference between trading domains of NTC and FBMC approaches and stepwise evaluation of the modelling intricacies are illustrated in Figure 6.

Market models with the NTC approximation may differ in the price convergence compared to FBMC approaches since NTC-approaches need to apply lower capacities. The reason is that the NTC simplified model does not include description of the full physics of the electricity flows, but only applies simple continuity constraints for each bidding zone. A lower NTC capacity is a way of avoiding overloading the lines in the simplified market model setup. This limits the quality of hour-specific dispatch solutions and can either increase price differences or increase the need for redispatch.

Regarding studies decades into the future, uncertainties that come from the NTC approximations are likely to increase with increasing renewable generation, fluctuating prices, and flexible dispatch. Time-dependency of generation as well as weather forecast and load forecast can be taken into account in the framework of FBMC, while the NTC value is – within typical simulations – static.

Figure 7: While NTCs limit trades directly, within FBMC the allowed combinations of trades form a complex polytope, described by a multitude of critical element constraints. The coloured volume indicates permitted zone-to-zone trades.



Market simulations, physical realities and socio-economics

The traditional CBA-analysis performed by ENTSO-E for projects in the TYNDP, relies on estimates for the impact of a certain project on the optimal dispatch using NTC-based market simulations.

Therefore, these analyses do not consider some of the following aspects, which are important to evaluate large investment projects, i.e. in offshore grids:

- Changes in need for investments in the surrounding energy system as a consequence of Hubs-and-Spokes projects.
- Changes in need for investments in alternative measures compared to a Hubs-and-Spokes, e.g., transmission infrastructure, flexibility measures.
- Impacts on bidding zone internal grids
  - Changes in investment needs
  - Changes in dispatch needs
  - Changes in redispatch needs.

ENTSO-E's CBA-guidelines acknowledges this shortcoming in both the 3rd ENTSO-E guideline and the current draft for the 4th guideline[4]: *"Assessing projects by only focusing on the impact of transfer capacities across certain international borders can lead to an underestimation of the project-specific benefits"*.

Highlight

"Assessing projects by only focusing on the impact of transfer capacities across certain international borders can lead to an underestimation of the project-specific benefits".

The guidelines describe methods to estimate additional benefits e.g., from redispatch, redispatch reserves or balancing needs. However, to our knowledge those indicators are not currently quantified by ENTSO-E, and have to be provided by the 'project promotor' (typical TSO or project developer or investor).

While in principle, changes in redispatch cost can be included in the main evaluation of socio-economic welfare, a consistent methodology combining both market and redispatch simulations is described, but not implemented in the ENTSO-E proceedings.

The assessment of alternative investment needs as mentioned above is absent in the CBA guidelines. We attempt to propose a methodology for this in section "CBA setup and execution", taking into account the practical realities of modelling needs. The general challenges are discussed in this chapter.

It is widely accepted that NTC-runs are not able to reflect the full physical capabilities of energy infrastructure in reality and thereby do not capture the final operation of the energy system. The shortcomings will affect among others the estimates of cross-border flow.

There are several ways to better reflect the physical constraints depending on the specific research question of a study, confer the noncomprehensive list of options listed in Table 1.

[4] 3rd ENTSO-E Guideline for cost benefit analysis of grid development projects, ENTSO-E, 19 October 2022 and 4th ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects, Draft version 4.0, ENTSO-E, December 2022.

Table 1: Options of selection of models and their geographical resolutions

	Models	Geographical resolution
1	Market model	Bidding zone
2	Market model (NTC)	Sub-bidding zone resolution[5]
3	Market model (NTC) / Grid model	Bidding zone / substation
4	Market model	Sub-bidding zone resolution
5	Market model (FBMC)	Bidding zone
6	Market model (FBMC) / grid model	Bidding zone / substation

When choosing between different options, there are two main considerations:

- How well are they able to reflect actual physical options and thus estimate realistic dispatch and flows?
- How well do they reflect the current market setup?

The first consideration is key to ensure a realistic estimate of total socio-economic welfare. However, deviating from the current market setup will complicate or even prevent the assessment of impacts for individual stakeholders and e.g., the separation of impacts on market levels impacts and redispatch level impacts.

While the assessment of these factors can entail significant benefits in terms of stakeholder involvement and illustration of results, it is also important to note that the market setup for dispatch optimisations reaching towards 2050 is unknown.

NTC-approaches will not cover the uncontrollability of power flows in AC-grids and while higher resolution of market zones will increase the representation of internal congestions, it does not reflect the market setup and requires assessments of NTC-capacities for several new "zones" in a grid model.

A simplified representation of AC-flows, using DC-approximation combined with either bidding zones or higher geographical resolution in market models would solve some of the NTC-calculation disadvantages, but introduce a new market simulation methodology which is not in accordance with the current market setup in Europe.

Flow based market coupling (FBMC) in a market model would – depending on the implementation of FBMC – be able to respect all relevant physical boundaries (option 5 in table 1).

However, Europe's Clean Energy Package (CEP) has set a binding minimum 70% target for electricity interconnector capacity for cross-zonal trading (the "minimum 70% target"). The reason for this is that the lack of sufficient cross-zonal capacity is one of the main barriers to the integration of electricity markets, and market integration is key to deliver on Europe's energy goals.

[5] Sub-bidding zones are higher granularity zones that a "bidding zone" can be divided into.

This rule enforces system operators to make 70% of the cross-zonal capacity available to the market, even though potential use of this capacity by the market would result in overloading of some grid elements if they were already highly loaded due to internal flows.

From this follows the conclusion that only a combination of a FBMC-based market simulation with grid model based estimates for redispatch will be able to both reflect realistic dispatch and power flows as well as stakeholder impacts according to the current market setup (option 6 in Table 1).

Highlight
A combination of a FBMC-based market simulation with grid model based estimates for redispatch will be able to both reflect realistic dispatch and power flows.

This approach requires significantly higher modelling efforts and data requirements than option 5 in table 1.

Grid representation and grid buildout: NTC approximation

The NTC approximation within market models is so far common and still widely accepted for CBA studies and the methodology is currently often applied in ENTSO-E's market simulation for the TYNDP.

This may appear surprising at first, given that the resulting power trading constraints are equivalent to a model with perfect control over power flows – while an AC system (without FACTS[6] elements such as e.g., phase shifters) is passive and uncontrollable. From this follows that the optimization of the market model often will result in solutions with discrepancy between simulated energy trades and realistic power flows[7].

Applying FBMC with its alternative setup of trading capacities, would in turn change the market outcome, and with that the final price convergence between the bidding zones. The deviation between NTC and FBMC approach would mostly arise in regions where several bidding zones share borders.

It should be noted that phase shift transformers and HVDC lines offer a certain amount of controllability. Notably the PSTs in the Netherlands allow a targeted control over electricity flows already today. Especially, when assessing large "Hubs-and-Spokes" projects HVDC controllable transmission lines will be prominent. The value of this flexibility can be assessed in a model with grid description.

Despite its deficits, a couple of factors speak in favor of using the NTC approximation depending on the research question in focus. Contrary to full grid models with thousands of lines which are needed to estimate data for a flow-based (FB) approach, there are consolidated datasets publicly available for NTC values of the current European grid based on the current market setup.

Highlight
As there are consolidated datasets publicly available for NTC values of the current European grid based on the current market setup.

Crucially, this makes CBAs of different authors easily comparable and offers a more transparent basis on which further scenario assumptions can be compared. It especially diminishes the complexity of infrastructure buildout[8] – cost assumptions are better comparable and transparent. From a practical view-

[6] A flexible alternating current transmission system (FACTS) is a system composed of static equipment used for the alternating current (AC) transmission of electrical energy. It is meant to enhance controllability and increase power transfer capability of the network.
[7] However, as these discrepancies may be the same in 'project case' and in 'reference' they may cancel each other out.
[8] Infrastructure build-out refers to the additions to the current grid for approximating to a future grid which can accommodate future power system needs. Announced projects are used as building blocks, however there is a large room of interpretation for future grid outlook.

point, a simplified grid representation via market trading capacities also allows for fast simulation time compared to FBMC.

The (historical) NTC values are a compromise, trying to account for the capacity of multiple interconnectors, N-1 security, and factors such as weather. It is therefore not surprising that FBMC needs many more parameters to describe allowed trade capacities between zones. This underlines once again the trade-off between complexity and accuracy.

Grid representation and grid buildout: FBMC/Redispatch

FBMC is already in effect in countries connected to the offshore wind power hubs in the NSWPH-studies and is likely to extend beyond to include the entire Core[9] region by the end of 2025.

Highlight
FBMC is already in effect in countries connected to the offshore wind power hubs in the NSWPH-studies.

There are reports of TSOs, as well as peer-reviewed scientific articles, on the impact of changing from NTC to FB methodology for the adapting countries. The determination of the available transfer capacities have a profound impact on the outcome of the power markets, such as fuel mix, price convergence and emissions to name the most evident. The reports further offer insights into why and where the grid constraints restrict exchanges.

The trading constraints of FBMC (without the 70% rule) have similarities to nodal dispatch[10] on a passive AC grid, yet disregard internal congestion. The constraints are created on the basis of a full nodal grid model, aggregated in suitable manner over whole bidding zones, and filtered such that only the most binding constraints remain (critical network elements).

This high level of accuracy comes at the cost of representing the complete European network, considering grid buildout as well as planned onshore and offshore HVDC buildout. On top, the effect of phase shift transformers might need to be considered. While various sources are being made publicly available (national buildout plans, ENTSO-E map), the data quality is naturally less consistent (mainly due to the high number of parameters) compared to the simplified NTC data sets. Not only is an accurate representation of the current grid necessary, but also necessary buildout approaches need to be detailed. Table 2 provides a comparative list of main influencing factors for NTC and RAM calculations.

[9] The Core region comprises of 13 Member States: Austria, Belgium, Czech Republic, Croatia, France, Germany, Hungary, Luxembourg, the Netherlands, Poland, Romania, Slovakia, and Slovenia.

[10] Nodal dispatch considers a much more granular system than a zonal dispatch. It is based on a system divided into many "nodes" (often substations in the grid) with individual prices.

Table 2: Influencing factors of available capacity, either between bidding zones (NTC values) or on critical elements (remaining available margin, RAM). The NTC value takes some influencing factors indirectly into account, yet statically rather than dynamically.

<table>
<tr><th>Input Group</th><th>Net Transfer Capacity (NTC modelling)</th><th>Remaining Available Margin (FMBC modelling)</th></tr>
<tr><td rowspan="2">Forecast</td><td colspan="2">Weather Forecast</td></tr>
<tr><td></td><td>Load Forecast
Producer Behaviour</td></tr>
<tr><td rowspan="2">Topology</td><td colspan="2">Grid Infrastructure
Contingencies N-1
Controllable HVDC</td></tr>
<tr><td></td><td>Trade Interdependency</td></tr>
<tr><td>Regulation</td><td></td><td>Regulatory Adaption
(70% Rule)</td></tr>
</table>

Is FBMC relevant to the Hubs-and-Spokes concept?

While the effects are unclear a priori, a couple of factors suggest that a more detailed grid representation would have substantial influence on the approximation of the socio-economic benefit of the Hubs-and-Spokes concept.

The NTC approximation of controllable flows is challenged when multiple shared borders coincide. In cases where this is important, a joint calculation of available trading capacities should be considered since any trade influences multiple zones. The hubs are by nature at the border of multiple of such bidding zones and are explicitly expected to facilitate and moderate trades between many market entities.

The benefits of interconnected hubs come from increased control and mediation of power flows. A large part of the benefit relates to the option to route energy flows to where they are needed the most. Without interconnected hubs, additional buildouts of the onshore grid might be necessary. Due to the importance of flow options to several different onshore grids and the potential internal congestions herein, adequate network representation is vital. This can only be approximated to a certain extent with market models based on the NTC approach.

Highlight
The benefits of interconnected hubs come from increased control and mediation of power flows to route energy flows to where they are needed the most.

70% rule

Europe's Clean Energy Package (CEP) has set a binding minimum 70% target for electricity interconnector capacity for cross-zonal trading (the "minimum 70% target").

This rule in the current market setup enforces minimum capacities for trading between zones, and largely disregards internal congestion. When fully implemented, the regulation may massively influence and expand trading capacities in cases where the internal grid cannot sustain increased amounts of inter-zonal trade. The discrepancy between market flows and realizable flows will increase, and so will the need for subsequent congestion management.

Larger minimum trading capacities between zones allow higher amounts of trades and will contribute to the price convergence.

The full consequences of the 70% rule is not yet to be judged as the rule is not overall fully implemented. It is expected to have a major impact on cost distribution between the different actors, bidding zones and respective TSOs.

Is redispatch relevant to the Hubs-and-Spokes concept?

The need for redispatch arises from

- an overestimation of trading capacity in the NTC approximation
- regulatory expansion of the allowed trading capacity via the 70% rule
- restricted internal grid capacity
- forecast uncertainty
- contingencies
- foreseeable and unforeseeable outages

Hubs-and-Spokes concepts have (depending on the configurations) the potential to massively influence scheduled market flows and redispatch needs.

Highlight
Hubs-and-Spokes concepts have the potential to influence scheduled market flows and redispatch needs.

Whether or not the need for redispatch adds cost or benefits to the Hubs-and-Spokes setup depends on the specific configuration and cannot be determined a priori.

Implementation routes for flow based simulations

The concept of simplification is inherent to explorative studies of the future energy landscape. Full implementation of today's Day-Ahead market application of FBMC on the other hand increases complexity of simulations and therefore poses challenges to computation and simplicity of results.

The FBMC-implementation in today's Day-Ahead market includes operational aspects which do not have the same importance in long term energy system studies. Therefore, the relevant question becomes which parts of FBMC could be carried over to an approach that approximates the effects of FBMC in sufficient detail.

Highlight
The relevant question becomes which parts of FBMC could be carried over that approximates the effects of FBMC in sufficient detail.

Having discussed a variety of setups, we recommend a number of potential setups that may allow the approximation of flow-based coupling in a simplified manner.

Passive interconnected Flows

Flow-based approaches are based on a linearized model of passive AC flows in an interconnected grid, while NTC approaches assume controllability of flows.

In order to assess the sensitivity of a CBA with respect to FBMC/NTC, the controllability of load flows between bidding zones can in a first step be lifted and converted to a strongly simplified grid model of AC flows, e.g., by only taking main transmission lines into consideration.

Every NTC connection becomes an AC line with capacity according to the NTC value, and impedance proportional to length over capacity. The impedance is hereby a rather crude approximation to realistic power flows but can be obtained at limited effort.

The desired outcome is an interdependency of trades between neighbouring bidding zones (as depicted in figure 7, second plot). Trades may need to be balanced out due to unavoidable loop flows[11].

Implementation of DC load flow in a market model is a shortcut to achieve some of the benefits of a full FBMC-implementation in a simpler way. This can be an approach to assess the sensitivity of a CBA with respect to FBMC/NTC, where the FBMC is approximated with the DC solution.

Disregarding RAM

A large portion of the FBMC framework deals with assessing the "remaining available margin (RAM)" on various grid elements before any allowed trades. It is largely influenced by internal production and consumption in the bidding zone.

The mentioned and explained 70% rule requires a large share of the capacity of elements to be available for inter-zonal trade.

The 70% rule is today largely violated, and not yet fully enforced. Exemptions from the rule will gradually be phased out, and for scenarios as late as 2035 no further exemptions are foreseen.

A simplified entry, and intermediate step towards a full FBMC market simulation could be to disregard the RAM calculation and assume 70% of its thermal capacity on each element. This would underestimate the allowed flow in some cases, but may be an acceptable approximation, utilizing the logic of the 70% rule.

Highlight
A simplified entry could be to assume 70% of its thermal capacity on each element.

Technically, this approach can be seen as emulating AC flows in the undisturbed full network and is thus an improvement of the simplified AC flow using primitive line assumptions described above.

FBMC with RAM from pre-run

Deriving time-dependent RAM values is considerable effort, and usually requires an estimate of the flows at every hour, taking into account the behaviour of market participants. A common way to approximate this is to utilize an "NTC pre-run". After mapping the pre-run market result to the grid, the line load of all elements can be evaluated, and remaining margins for trades can be allocated. Concerning sources of uncertainty it should be noted that in reality load and weather forecast uncertainty are likely to dominate; whereas for the NTC pre-run the quality of the NTC approximation is decisive.

[11] Circular flows, referred occasionally as loop flows, are observed when trades within a single bidding zone flow through the neighbouring zones. This occurs because the grid is meshed and physical flows are governed by law of physics (Kirchhoffs laws) which may not be included in the market model. Loop flows are very difficult to control.

RAM estimation via dispatch variables

Alternatively, the RAM calculation on elements can be approximated as a linear expression of dispatch variables of the market model. This linear approximation can be either evaluated based on a pre-run (which is commonly done) or can be put into the constraint expressions directly in the market model (without applying the 70% rule). This would lead to a market result that largely respects the limitations of the grid, and the resulting dispatch cost can be regarded as an approximation to a market run plus subsequent congestion management. It should be noted that this approach is close to a simplified nodal dispatch.

Socio-economic FBMC on bidding zone level

One of the motivations of implementing FBMC is to be able to replicate the correct future market setup, enabling stakeholder analyses and prepare more closely for CBCA (Cross Border Cost Allocation) analyses subsequent to the CBA-study.

A market model with FBMC setup has an intrinsic representation of the accurate physical flows within the underlying grid. Thus, a FBMC-base market model also holds the potential to increase the likelihood of estimating scheduled flows, which would be compatible with the physical grid. The advantage of such an approach is that more realistic flows can be calculated, even without iteration with a dedicated grid model (which however still is needed for estimating FBMC-parameters).

To allow for this, several assumptions have to be taken, which will result in larger differences to actual market outcomes, thus limiting the applicability for direct stakeholder analyses and the option to divide results into market and redispatch results.

However, the approach could be useful in a screening phase, as it limits the need for model iteration and complexity. The following assumptions could be considered:

- Ignoring the 70% rule
- Implementing RAM estimates via dispatch variables
- Including internal lines as critical network elements

Ignoring the 70% rule will violate foreseen regulations but ensure a better grid-compatibility of estimated flows.

Implementation of RAM estimates via dispatch variables will mean that the value of generation from different assets will vary within the same bidding zone, depending on their geographical location. The effect is a resemblance of nodal pricing, which can be interpretated as including the redispatch needs in the market run. Again, current regulations would be violated, but the scheduled flows will be closer to the physical reality.

Finally, TSOs today do not necessarily nominate internal lines and the potential congestions to the market algorithm. Including a higher amount of critical network elements in the FBMC-calculation in combination with dispatch dependent RAM estimates will enable the market simulations to also take into account congestions due to conditions within a bidding zone and thus be an additional step towards more realistic flow estimates.

4 CBA Setup and Execution

Model setup

The practical application of the study defines the usefulness of CBA studies for stakeholders and the practical implications of obtained insights. It is therefore absolutely vital to perform following actions for the model setup:

- Define a relevant system baseline
- Define relevant **project cases** for the Hubs-and-Spokes configurations, which must be compared to their relevant **references** (comparable solutions without Hubs-and-Spokes)
- Ensure sufficient level of detail while ensuring realistic complexity in the modelling setup.

Conventional CBA frameworks for energy infrastructure projects focus on single projects in single energy sectors. The NSWPH project has the unique features of being transnational[12], cross-sectoral[13] and hybrid[14].

Highlight
The NSWPH project has the unique features of being transnational, cross-sectoral and hybrid.

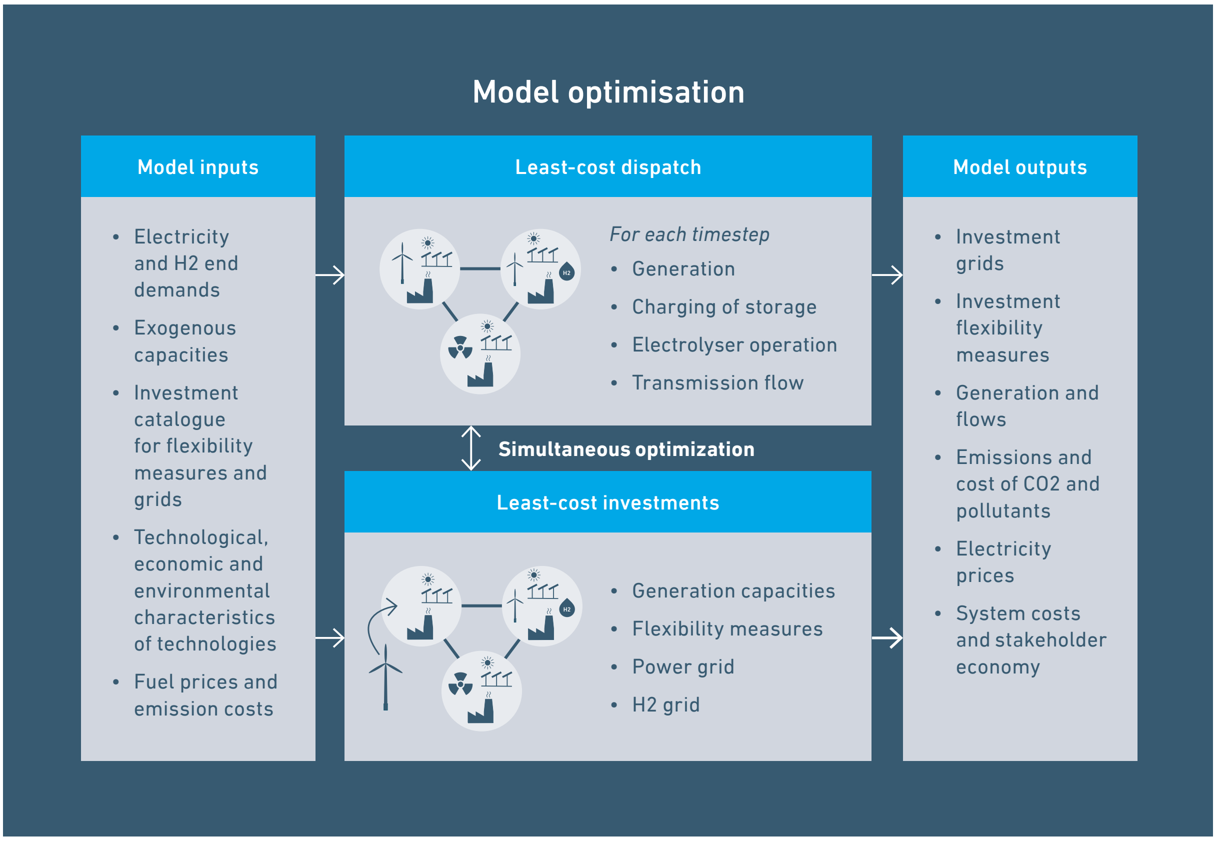
These features provide a large spectrum for the CBA framework in consideration of alternative references, scenarios, geographical coverage options available and correspondingly wide cost-benefit-analysis criteria. A stepwise approach is therefore suggested to identify the best configurations and cases for a CBA assessment.

The suggested CBA approach for the pragmatic and advanced CBA sounds appealing and simple at first sight. However, the actual implementation requires numerous decisions and assumptions, especially regarding the interplay between different models or model add-ons.

Basic inputs to, optimization by and output from market models are illustrated on Figure 8. The usefulness of the analyses depends on the applicability of the input. Input data relates to demand forecasts, dispatch cost (fuel, emissions, O&M), the start-grids. Based on the optimization of investments and dispatch, generation patterns, electricity prices, system costs and stakeholders economy are available as output.

[12] Transnational: Connecting multiple countries through a Hubs-and-Spokes concept.
[13] Cross-sectoral: Integrating electricity and hydrogen sectors.
[14] Hybrid: Co-functioning of lines for connection of offshore wind and system interconnection.

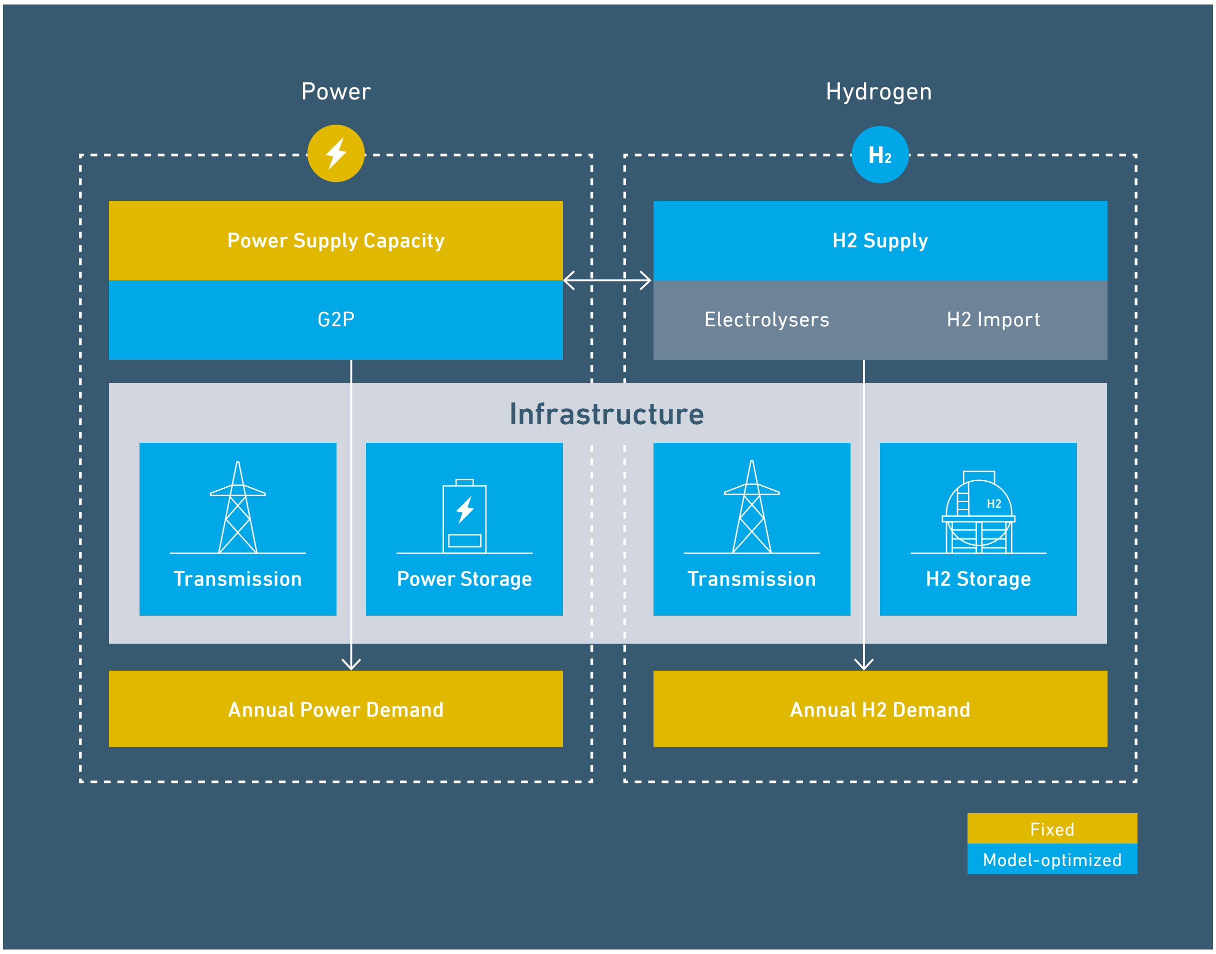
Figure 8: **High-level representation of the market model: Input, optimisation and output**



Depending on the scope of the optimisation, some inputs are not needed. The suggested scope of optimization is illustrated on Figure 9. The main supply system is to be defined on the input side (e.g. wind and solar generation capacities), while only parts of the supply system (flexibility measures) will be optimized by the model and therefore require adequate cost data. The effects are evaluated within different scenarios for the development of the power system in terms of generation capacity and electricity and hydrogen demand.

In the following text we discuss the decision areas and options for model setup, we examine the status (literature, industry standards etc.) and introduce the NSWPH CBA approach to realize central implementation questions in both the pragmatic and advanced CBA.

Figure 9: Optimisation scope and fixed inputs. Assets subjected to optimisation: Power supply, power transmission, power storage, Hydrogen based power generation, electrolysers, Hydrogen transmission and Hydrogen storage.



Model types

The essence of CBAs is to estimate and compare costs of system operation between scenarios. Simulations are used to come as close as possible to realistic results, ultimately reflecting also the impact of market outcomes for market participants. We assume markets to be perfect and that market participants act according to their marginal costs and that this will lead to socio economic optimum.

The Day-Ahead market, covering the largest volume of both electricity and trading value, is designed such that market participants do not need to consider grid limitations within the bidding zones. Markets across bidding zones are coupled and flows of electricity is allowed and encouraged, leading to overall optimal socio-economic solutions.

With the growing penetration of fluctuating renewables in the systems – commonly put at locations with favourable natural resources rather than aligning with demand centres – this clear separation of undisturbed "copperplate" markets and subsequent, previously cheap congestion management has become more and more challenging. Congestions are not any longer cheap. It should be noted that combined hydrogen production from electrolysers can be a measure of relieving congestions in the power grid.

Highlight

To capture the full impact of Hubs-and-Spokes, both market and grid models need to be applied at different stages.

Substantial cost and additional CO2 emissions are caused by insufficient transmission capacity of electricity already today. Changes in redispatch costs are part of the socio-economic impact. To capture the full impact of Hubs-and-Spokes, both market and grid models need to be applied at different stages.

Market models

In transmission planning, a market model refers to a mathematical representation of energy markets. The model is used to simulate the market and thereby analyse the economic impacts of potential transmission projects. This applies both to electricity and hydrogen.

Highlight

A better representation of the grid gives a better chance of optimizing the utilization of the scarce transmission capacity.

The market model takes into account the supply and demand within a specific geographic region, as well as the costs associated with generating, transmitting, and distributing energy. It also considers the behaviour of market participants, such as producers and consumers, and how they interact with one another in a competitive market.

A market model typically has a limited representation of the grid. The market area may be divided into market bidding zones with exchange capacities between bidding zones given as NTC values and representing the bidding zone as a copperplate (ignoring internal grid issues). NTC stands for "Net Transfer Capacity" and is a term used in transmission planning to refer to the maximum amount of power that can be transferred over a specific transmission line or interconnection point without exceeding system limits. However, NTCs are not able to capture the interdependency of flows across the system.

The motivation behind introducing the so-called FB (Flow Based) approach, is that the FB approach has the potential to better take into account the physical flow and constraints compared to the NTC method. FBMC (Flow based market coupling) is already in effect in large parts of Europe and is likely to extend beyond the current scope to include the entire Core[15] region by the end of 2025.

A better representation of the grid gives a better chance of optimizing the utilization of the scarce transmission capacity, which leads to better dispatch solutions and more accurate price signals.

Remaining Available Margin (RAM) in the context of Flow Based Market Coupling (FBMC) refers to the amount of transmission capacity – on a specific grid element – that is available for trades between bidding zones in the market after other necessary allocations of capacity have been made.

Grid models

A grid model is a mathematical representation of the transmission system used to simulate and analyse the behaviour of the electrical grid and take into account the laws of physics for transport.

For electricity the grid model provides a detailed description of the electrical components of the transmission system, including generators, transformers, transmission lines, and other equipment.

[15] The Core region comprises of 13 Member States: Austria, Belgium, Czech Republic, Croatia, France, Germany, Hungary, Luxembourg, the Netherlands, Poland, Romania, Slovakia, and Slovenia.

Electrical grid models are used for computing FBMC parameters, which in turn are used in the flow-based market models. Besides that, they are used for simulating redispatch needs with the aim of finding new/updated and optimal dispatch solutions which comply with the grid constraints that are not handled in the market setup.

Highlight
For electricity the grid model provides a detailed description of the electrical components. Hydrogen grid models are represented in a simpler way using entry and exit capacities between market zones.

Hydrogen grid models are – in the methodologies discussed in this paper – represented in a simpler and are more a less similar way to the market models for hydrogen using entry and exit capacities between market zones.

Scope

In the CBA context, scope refers to the boundaries of the analysis in terms of geographical and sectoral coverage as well as which technological, economic, and political aspects are included in the assessment.

The scope has a direct impact on the establishment of the references and scenarios for the analysis, as they need to define assumptions on the applicable level of detail and coverage. The challenge is to ensure a balance between the need to capture all relevant impacts on one hand and on the other hand too high level of detail or coverage, increasing complexity and leading to risks of high computational and analytical burdens.

Highlight
The challenge is to ensure a balance between the need to capture all relevant impacts on one hand and on the other hand too high level of detail or coverage, increasing complexity and leading to risks of high computational and analytical burdens.

Too much complexity would diminish focus and clarity, while a too simple approach runs the risk of delivering an insufficient assessment. The level of detail per CBA assessment should be wisely determined based on the research question and intended outcome of a CBA assessment.

ENTSO-E and ENTSO-G published a methodology report -The Interlinked Model Investigation[16]– developed for making project CBA assessments including scenarios and infrastructure with an interlinkage between gas and electricity sectors.

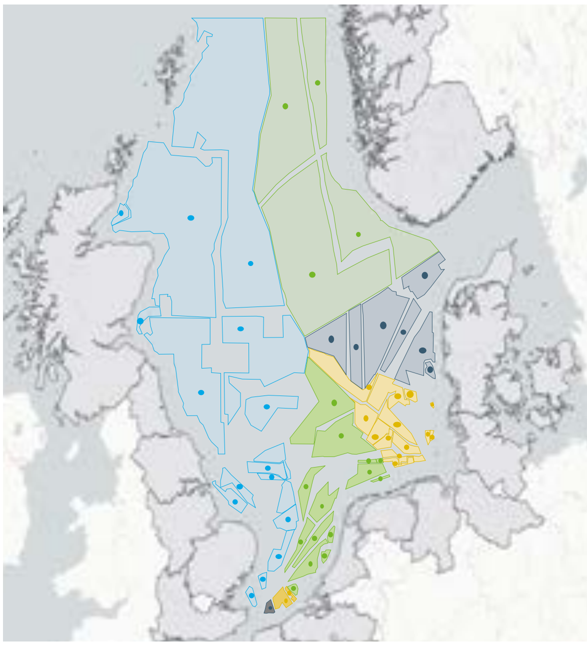
The methodology suggests using the geographical perimeter of member countries and TYNDP covering the EU-28 countries as well as Switzerland, Bosnia and Herzegovina, Serbia and the Republic of North Macedonia.

ENTSO-E's CBA guideline[17] suggests covering all member states and the third countries on whose territory the project is planned to be built and all directly neighbouring member states. The scope of the European Energy System should be reflected, since the prospective Hubs-and-Spokes project connects large quantities of offshore wind capacity with shore and herewith impacting the trade and infrastructure at a wide area.

However, the level of detail for the geographical region can differ, as e.g., the spatial resolution for the applied data. Previous NSWPH-analyses have shown little impact from Hubs-and-Spokes configurations on the system in more distant countries (see the map in Figure 10[18] below for previously applied modelling scope).

[16] Interlinked Model Investigation, May 2021, ENTSO-E and ENTSO-G
[17] 3rd ENTSO-E Guideline for cost benefit analysis of grid development projects, ENTSO-E, 19 October 2022 and 4th ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects, Draft version 4.0, ENTSO-E, December 2022
[18] The geographical layout and granularity (NUTS-1) was used in the Pathway Study. In a traditional CBA the model footprint would include all of Europe.

Figure 10: Modelling scope with geographical resolution (NUTS-1 for core region) applied in previous NSWPH CBA analyses.



In order to allow for dedicated grid analyses the spatial resolution for the countries directly connected to the Hubs-and-Spokes configuration and for which the physical grid layout will be further analysed, the so-called NUTS-1 resolution as shown in Figure 10 is suggested as a starting point for defining parameters in the market model and as a starting point for further disaggregation to substation level in grid models.

This level ensures both reasonable detail in description of variable renewable energy profiles aggregated to bidding zone level, as well as the option to transfer market-level results to substation-level detail for grid calculations.

Baseline scenario

The baseline scenario describes the general system development. The development should be compatible with the political ambitions, to which the projects in focus are meant to contribute. In the current context, Hubs-and-Spokes configurations are a measure to ensure an efficient pathway towards a European net-zero energy system.

The Baseline scenario should reflect the most updated policy developments and targets, such as RED3 (Renewable Energy Directive III, EU) and REPowerEU[19], which have fundamentally changed the European renewable energy targets and energy security approach.

[19] REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition, EU, May 2022.

Therefore, the baseline scenario should enable such a transition, while system scenarios not supporting that overall development, are less relevant. Potential baseline scenarios should reflect the general developments within:

- Electricity demand
- Hydrogen demand
- Portfolio of generation capacity (wind, solar, hydro, thermal power plants)
- Policies for assets outside of the analysis scope (e.g., coal phaseout, nuclear targets)
- Transmission
- CO_2-policies and pricing
- Fuel prices
- ....

If the CBA approach includes investments and not only dispatch changes then Hubs-and-Spokes driven investments must be compared with impacts of alternative solutions (e.g., radial connections to shore).

Potential sources for defining the baseline scenario are e.g., scenarios from ENTSO-E's TYNDP or the European Commission's impact assessments. As ENTSO-E's scenarios are power system models, the level of detail is compatible with the needs for the suggested CBA-analyses. Further assumptions can help to define the required level of spatial resolution[20].

For the sake of not complicating things unnecessarily the baseline scenario is suggested to be fixed with respect to total generation capacity for renewables including offshore wind, however subject to possible minor changes as a result of Hubs-and-Spokes setup.

Highlight
The baseline scenario is suggested to be fixed with respect to total generation capacity for renewables including offshore wind. Hubs-and-Spokes configurations can be explored in sensitivities.

Potential long term impacts of Hubs-and-Spokes configurations on surrounding system generation capacities (location or level) can be explored in sensitivities or illustrated by analysing captured prices of the different generation technologies.

Potential sensitivities can shed light on the project relevance in systems not supporting a transition to net zero. These analyses can function as risk assessment but are not at the core of the assessment.

Configuration, reference and project case[21]

The configuration of Hubs-and-Spokes setups describe the connections to shore and between offshore sites for both electricity and hydrogen. It is advisable that the connections to be fixed in both the pragmatic and advanced CBA, as they constitute the analysed subject. However, different scenarios can explore different setups, and marginal values can inspire additional setups.

The terminology "Project cases" refers to specific Hubs-and-Spokes configurations to be analyzed, whereas "References" are the configurations which facilitate comparable amounts of offshore capacity development without the Hubs-and-Spokes concept, rather based on radial connections or alternative, relevant configurations.

[20] Unlocking the North Sea as a Green Powerplant, Key Insights into Northern Europe's Green Energy Future, NSWPH 2022.
[21] In the NSWPH Discussion Paper #1, References and Scenarios were previously introduced as Counterfactuals and Factuals, respectively. In sake of simplicity, terminology is updated in this paper.

Depending on the number of project cases and their differences, several references might be needed. Lack of a common reference has the risk of impairing comparability of the different scenarios to each other and consistency of the CBA assessment, however the diversity of the options can necessitate such an approach.

Highlight
The references should reflect the same overall system targets but uses a less integrated and less international approach on deployment for offshore wind.

Design of the references has high importance, as it should reflect the same overall system targets but uses a less integrated and less international approach on deployment for offshore wind.

Project cases describe the complete setup of Hubs-and-Spokes including not only the connections to shore and between hubs, but also offshore wind capacities and potentially offshore electrolysers' capacities.

Offshore wind and electrolyser capacity can be subject to optimization in the Pragmatic CBA, thus enabling an exploration of ideal setups. Accordingly, offshore wind and electrolysers' capacity can differ between project cases and the reference. The cost for establishing additional capacities must be included in the evaluation of the socio-economic welfare.

The advanced CBA on the other hand aims at increasing the level of detail of the impact on the surrounding system and should therefore apply fixed cases of e.g., offshore wind and electrolyser capacity.

Starting grid

The time horizon for the realization of offshore Hubs-and-Spokes is 2030 and beyond. In combination with the large foreseen changes in system composition, defining the starting grid for both electricity and hydrogen surrounding the projects case scope is not trivial, but will impact the evaluation of the value of Hubs-and-Spokes. Options include three principal approaches:

- Exogenous definition of the entire grids. (Corresponding to ENTSO-E's approach in the TYNDP)
- Optimization of surrounding grids according to the reference, but without changes in the cases
- Optimization of surrounding grid in both reference and case calculations.

Highlight
It is advisable to follow the approach of optimization of the surrounding grids in both the reference and the cases.

As potential impacts of Hubs-and-Spokes on the needs for alternative transmission investments in the surrounding energy transmission systems are a key parameter to investigate, it is advisable to follow the approach of optimization of the surrounding grids in both the reference and the cases.

Optimization of the surrounding grids in the reference only will potentially be to the disadvantage of the analysed project, without necessarily showing a more reasonable estimate for the surrounding grid.

Exogenous definition of the surrounding grids will enable the analysed Hubs-and-Spokes to contribute to alleviating sub-optimal grid setups, but the exogenous definition will highly impact CBA results – in either upwards or downwards direction.

When optimizing the surrounding grids, realistic options should be considered regarding both cost and realizable grid capacities, considering the analysed time horizon.

Modelling Approaches

The suggested setup of applying both pragmatic and advanced CBAs is meant to enable both wide and overall analyses in a first step and more detailed specific analyses in a second step. This is often recommended to reduce modelling time and efforts in an early stage, allowing for a higher number of promising configurations to be analysed.

Highlight
Pragmatic and advanced CBAs is meant to enable both wide and overall analyses in a first step and more detailed specific analyses in a second step.

The following description applies to power system CBA. This part of the system will typically be most complex in NSWPH studies because of grid congestions and redispatch which normally will not be an issue in the hydrogen system. Hydrogen grids will be modelled in a more simplified way by using continuity constraints for each node/zone and entry/exit capacities.

Pragmatic CBA

A general overarching question is whether the Pragmatic CBA should attempt to estimate the full socio-economic welfare or rather focus on the market impacts, explicitly excluding additional impacts the project could have in other areas (e.g., redispatch).

The latter would enable recognizable stakeholder analyses and well-known methodologies. However, there is a risk, that the excluded elements would have had important impacts. For this reason, we suggest focusing on the full socio-economic welfare and attempt to include grid related impacts in a simplified manner.

This suggestion makes stakeholder analyses more difficult as the current market setup and thereby market outcomes for stakeholders in the absence of dedicated redispatch simulations cannot be replicated.

However, the suggested model setup, applying FBMC[22] in the market simulation, ensures good transition to the potential advanced CBA.

Advanced CBA

The advanced CBA is meant to replicate the current regulatory setup more closely. As such, FBMC in market simulations is suggested to include the 70% rule and exclude investment options in bidding-zone internal grid elements. In the second step, the dedicated grid model will be applied to optimize internal grid elements, while the interconnection capacities remain fixed.

An overview of different decisions and suggestions regarding the model setup and approaches is illustrated in Table 3.

[22] Another option would be to solely focus on market outcomes and apply a NTC market model and current bidding zones (BZ).

Table 3: Illustration of suggested modelling setup and approaches for pragmatic and advanced CBA studies.

Topic	Pragmatic CBA	Advanced CBA
System scenario	Fixed (Impact explored in sensitivity)	Fixed
Hub configuration	• Transmission fixed • Offshore assets optimised or varied (offshore wind, offshore hydrogen, storage)	• Transmission fixed • Offshore assets fixed (offshore wind, offshore hydrogen, storage)
Surrounding grid (interconnectors)	• Optimised (restrictions apply) • Investments in critical network elements • 70%-rule excluded. Real RAM applied. • Simplified alternative: NTC based interconnection and investments	• Optimised in market simulation • Investments in critical network elements • 70% rule applies (or used directly to define RAM)
Internal grid	• Optimised (restrictions apply) • Part of FBMC formulation • Investments in critical network elements possible	• Optimised as part of the grid model simulations, but fixed in market model simulations
Models	• FBMC market model • (Grid model delivers FBMC parameters)	• FBMC market model • Grid model delivers FBMC parameters and redispatch simulations

Output Handling: Indicators

Quantification and monetization of benefits

The goal of the assessments is to characterize the impact of a project case in comparison to its reference, both in terms of added value for society, as well as associated costs.

The net benefits of the project case and its reference can subsequently be compared, and it can be concluded if the Hubs-and-Spokes project case has precedence.

Indicators are a mean to aggregate large amounts of output data from (various) modelling steps to the lowest possible and meaningful number of (usually numerical) values. These values should then enable the external world to judge on the benefit of a project. The most common approach is a 'delta ' approach where the project values are compared with corresponding values from the reference case. It is important to note that the meaning and quality of each indicator depends on the modelling approach from which it is derived from and the underlaying input date. For example, the delta of CO2 emissions between the project case and reference case is different when comparing CO2 emissions from the market model step and the CO2 emissions after redispatch. Also, the change of the indicator along the model chain could deliver meaningful insights and therefore be an indicator itself.

Each indicator is not equally important, and it is not always possible to reflect all costs and benefits on a single indicator. One way of coming around this problem is to assign an evaluation weight of each indicator. Especially this may help in the evaluation of large infrastructure projects, including different stakeholders across countries and sectors.

Highlight
Indicators are a mean to aggregate large amounts of output data from (various) modelling steps to the lowest possible and meaningful number of (usually numerical) values.

Moreover, the total surplus approach[23] reflecting the overall welfare economic assessment of the project, should then be possible to further dissect to the stakeholders and countries involved. This assessment can form the basis for an allocation of costs between countries, the so called “Cross-Border Cost Allocation” (CBCA). In our cross-sector analyses (power and hydrogen) also attributing and division of costs between sectors may be relevant.

According to ENTSO-E’s CBA guidelines the assessment should be undertaken as a multi-criteria approach enabling to address both qualitative aspects and quantitative, monetized aspects. It is important to lay-out the benefits which cannot be quantified in an objective manner, as these can still be fundamental decision components. This applies to e.g., “system safety” and “environmental impact”.

On one hand, multi-criteria aspect enables inclusion of unquantifiable benefits. On the other hand, the CBA methodology should continuously strive to find solutions to objectively quantify indicators which were previously not quantifiable, as well as define new and accurate ways of quantifications.

In this regard, the accuracy and reliability of the indicators demonstrate a strong correlation with the modelling approach.

Firstly, indicators should capture the strengths of the model for harvesting important information for decision makers. Secondly, indicator result should account for the shortcomings of the model leading to a misleading conclusion. E.g., in case an indicator has high importance for monitoring, yet due to the nature of model cannot be adequately measured, remarks and necessary arguments should be made during the presentation of the indicator results.

Finally, indicators can influence the needed modelling detail and methodology. For example, cost for congestion management in power grids can be one of the largest expenses of electricity-TSOs, but consequently also for grid fee payers. The costs were over €1.5 billion solely in Germany in 2021. Therefore, it has profound importance for decision making. To be able to monitor the impact of a project case on the congestion management in a congested grid, a modelling approach reflecting the physical reality in the grid is needed. A simplified NTC-based market approach model cannot provide insights into this topic.

Highlight
Indicators can influence the needed modelling detail and methodology.

Modelling always aims at making the most effective simplifications, while being aware of the consequences. In case of market coupling methodologies, it is far easier to build a model based on NTC modelling techniques in comparison to FBMC, however this can be at the cost of receiving misleading trade capacities, which further propagates to e.g., economic results.

As explained in the previous section: “Methodological complexity”, a FB methodology not only enables a more accurate estimation of e.g., market dispatch indicators as it reflects the inter-play between the grid and market, but also provides basis for further insights into other indicators such as redispatch cost via grid simulations which cannot be monitored via the NTC approach.

[23] Total Surplus Approach compares producer and consumer surpluses from bidding areas, congestion rents and possibly cross-sector rents based on short-term economic results.

Furthermore, having access to the finer detail in the locational and temporal aspects reveals further quantification opportunities for risk and opportunity assessment.

Both ENTSO-E and ENTSO-G provide guidelines for CBAs of grid development projects based on extensive stakeholder engagement and subjected to the review of the European regulator ACER. These CBA methodologies provide sets of indicators addressing costs and benefits for investigating projects in their own sectors, electricity, and gas, respectively.

However, for projects like NSWPH, some indicators should be refined, redefined or even created to make use of the extended modelling approach, i.e., capture interactions between the sectors. This being said, the indicators suggested by the ENTSOs should be preferred to use as much as possible to ensure consistency and comparability with other single sector projects.

Highlight
For projects like NSWPH, some indicators should be refined, redefined or even created to make use of the extended modelling approach, i.e., capture interactions between the sectors.

For identifying the most relevant indicators, ENTSO methodologies for electricity and gas sectors and bidding zone reviews were analysed, in total addressing more than 40 indicators.

In the context of a Hubs-and-Spokes CBA, all the suggested indicators are relevant and applicable. However, some of these indicators are integral and more global, whereas some are supportive and represent very specific aspects of the projects. The indicators presented in e.g., ENTSO-E's methodology guidelines cover a large number of aspects – but the practical usage in key CBA assessments such as the assessments in the TYNDP are much more limited.

One of the core strengths of the suggested modelling approach is that it enables high degree of detailed analysis of the indicators. The majority of the suggested indicators can be calculated at different stages of the modelling: pre-NTC run, FBMC run and redispatch run. "Deltas" in the indicator evaluations can provide further insights into market and grid dynamics and structures. Table 4 shows the key (K1) and supportive indicators (K1.1-K1.6) in addition to supplementary indicators selected by NSWPH after the mentioned evaluation of more than 40 indicators. Some of the indicators are upgraded from the forementioned sources or were newly introduced to be able capturing additional impacts from the large infrastructure projects analyzed by NSWPH.

Highlight
One of the core strengths of the suggested modelling approach is that it enables high degree of detailed analysis of the indicators.

Socio-economic welfare (K1) is the main indicator which is global and consists of key impacts of the Hubs-and-Spokes projects, whereas the supportive indicators (K1.1 – K1.6) increase understanding by also being reported separately. Stage-wise (pragmatic or advanced CBA) calculation of these indicators can be applied in case the "project case-reference" couples yield similar results at the higher level priority indicator- K1 in Table 4.

The K1 indicator (socio-economic welfare) is a global number for the project case as a whole. It makes sense keeping it as one number.

K1.1. and K1.2 (operation and investments) can in principle be evaluated separately for power and gas even though redispatch may only be relevant for the power system.

Also, K1.3 (avoided grid buildout) can be divided into power and gas while grid losses (K1.6) applies to power.

With regard to the supplementary indicators, then CO2 savings (S1) could be one number. S2 (RES integration) is relevant for the power system, while S3 (security of supply) could apply both to the power and gas system.

Table 4: NSWPH CBA key (global K1 and supportive K1.1-K1.6) and supplementary indicators.

	Indicator	Unit
Key indicators	K1. Socio-Economic Welfare	€/yr
	K1.1.1 Market operation K1.1.2 Market Investments	€/yr
	K1.2.1 Redispatch operation K1.2.2 Redispatch investments	€/yr
	K1.3. Avoided Grid Build-out	€/yr
	K1.4. Avoided H2 Import Costs	€/yr
	K1.5. H2 Operation	€/yr
	K1.6. Grid Losses	€/yr
Supplementary indicators	S1. CO2 Savings	Mt/yr
	S2. RES Integration	MWh/yr
	S3. Security of Supply	MWh/yr
	S4. Grid Utilisation	hours/yr
	S5. Cross-sectoral Flux	-/0/+

Key indicators

K1. Socio-Economic Welfare:

The socio-economic welfare indicator is the most important indicator and widely used for hybrid and electricity system CBAs which estimate the direct impact of the project case on total welfare economics.

The classical approach on the socio-economic welfare described by ENTSO-E includes only the short-run economic surpluses of the consumers, producers and transmission system owners based on the wholesale (Day-Ahead) market outcomes, disregarding the long-term effects.

The proposed modelling methodology enables us to consider the indicator on a wider aspect including additional parameters for capturing the interdependencies between the power and hydrogen systems, as well as tapping into the potential of the grid simulation. Therefore, we suggest including the following impacts in the socio-economic welfare:

- Market driven investment changes (K1.1.2)
- Market driven dispatch changes (K1.1.1)
- Grid driven investments changes (based on redispatch needs) (K1.3)
- Grid driven dispatch changes (based on redispatch needs) (K1.2.1)
- Both dispatch and investment changes should include impact on the hydrogen sector, including the potential changes on hydrogen import needs. (K1.4, K1.5)
- Grid related operational costs (losses and variable costs) (K1.6)

Highlight
The proposed modelling methodology enables to including additional parameters for the interdependencies between the power and hydrogen systems.

Whether or not all inputs are available depends on the level of the CBA analyses. An advanced CBA analysis based on FBMC market simulations and subsequent redispatch simulations allow for a sufficient analysis of the entire energy system, while the suggested pragmatic CBA will enable an estimate of the full coverage without being able to distinguish between market and grid related impacts.

K1.1. Market operation and investments
This indicator details the impact on the (Day-Ahead) market solution. However, compared to the pure short-term analysis traditional used the indicator also includes investment impacts, which can be important for correct assessment of Hubs-and-Spokes projects. Therefore, the indicator is subdivided into K1.1.1 (operation) and K1.1.2 (investments). The K1.1.2 CAPEX indicator is an innovative 'extension' the traditional CBA indicator set.

K1.2. Redispatch operation and investments
The indicator details the impact on redispatch needs and includes both operational costs and investment needs. As for K1.1. this indicator K1.2. is therefore also subdivided into K1.1.1 (operation) and K1.1.2 (investments). This indicator is important as future connection of large amounts of offshore wind are foreseen leading to onshore grid congestions in the neighbourhood of wind connection points. Already today redispatch costs are significant in many countries.

The approach of including investment needs in redispatch (CAPEX redispatch) is an innovative recommendation compared to traditional CBA approach.

Highlight
The approach of including investment needs in redispatch (CAPEX redispatch) is an innovative recommendation compared to traditional CBA approach.

Estimation of this indicator requires a redispatch simulation, which adjusts the dispatch results of the market model by resolving the congestions.

In the CBA methodology of ENTSO-E, the redispatch associated costs are calculated based on the maximum annual redispatch in an hour. We suggest to instead base redispatch calculations on the sum of redispatch costs of the involved individual generation units and include among others fuel cost and annualized capital cost.

For purposes of estimating distributional effects, curtailment costs are suggested to be calculated based on full compensation of the affected units and the power price in the Day-Ahead market.

K1.3. Avoided grid buildout
With a Hubs-and-Spokes project some alternative grid buildout options may be avoided. However, already approved projects should not be affected. Avoided grid buildout for both the hydrogen and electricity grid are highly important, and one of the foreseen investment impacts.

Highlight
With a Hubs-and-Spokes project some alternative grid buildout options may be avoided.

The indicator details the costs of avoided grid buildout from both a market and redispatch point of view. The investment impacts are also a part of K1.1. and K1.2., but explicitly shown here for the grid only.

K1.4. Avoided H2 import costs
The indicator draws a parallel to an ENTSO-G indicator: "reduction in the cost of gas supply", which captures the benefits stemming from project cases reducing the overall European cost of gas supply.

Improvements in connection of offshore wind can lead to both curtailment reductions and higher value of the electricity produced. In the future European Energy system, this will not only impact electricity dispatch, but also the opportunities to deliver cost-competitive hydrogen. The impact on hydrogen production and imports of hydrogen should therefore be reported separately.

Highlight
Improvements in connection of offshore wind will not only impact electricity dispatch, but also the opportunities to deliver cost-competitive hydrogen.

Furthermore, this indicator can be derived to estimate security of supply by comparing the percentage of hydrogen demand covered by hydrogen production within the system borders.

K1.5. H2 Operation
This indicator relates to changes in the operational costs for the hydrogen transmission system, such as electricity demand for compression.

K1.6. Grid Losses
Grid losses in the electricity grid may be quite significant and therefore the indicator has been included. Grid losses is also an indicator in ENTSO-E's CBA guidelines.

Impact of the project cases on the grid losses can be calculated based on the results of the grid model, which takes into account the distance between the production and consumption centres, voltage levels, and load flows. Grid losses should be monetized using the value of electricity in the market simulations.

Supplementary indicators
S1. CO2 savings (variation)
CO2 is at the core of the European energy policy and should therefore be estimated explicitly.

Highlight
CO2 is at the core of the European energy policy and should therefore be estimated explicitly.

The K1 indicator embeds the impact of renewable integration and CO2 emissions inherently based on the change of the fuel mix in both market and redispatch simulations. However, K1 does not explicitly calculate the CO2 variation in terms of annual amounts, which is one of the key monitoring areas for European energy policy.

The indicator is based on the change in CO2 emissions as a consequence of the changes with the implementation of the Hubs-and-Spokes case. Although quantification of the CO2 variation is straight forward, the monetization of the change has a broad aspect in consideration of the damage cost of climate change.

While the monetized impact included in K1 is based on expectations for the ETS price (European Union Emission Trading System price), the indicator can illustrate additional impact deriving from alternative values of CO2. In order to avoid double counting, the indicator should only show the "delta" differences a higher CO2-value would incur compared to the ETS price.

Availability of realistic grid simulations for redispatch is important to acquire realistic estimates because redispatch measures mostly rely on conventional fossil fuelled units with significant CO2-emissions.

S2. RES Integration
RES and RES integration are also at the core of European energy and climate policy. Therefore, RES integration is of course included in the list of indicators.

RES Integration is a well-established indicator, which has been in use since the first publication of the CBA methodologies of ENTSO-E. It defines the ability of the power system to make use of existing and future renewable generation.

There is no need for an upgrade in the calculation methodology of the indicator. However, it should be noted that inclusion of the detailed grid model, corresponding assessment of the curtailments and ability to transfer power, are important for realistic estimation of RES integration.

Highlight
There is an inter-play between gas/hydrogen and electric systems, which can impact integration.

Furthermore, there is an inter-play between gas/hydrogen and electric systems, which can impact integration, and which is part of the suggested modelling setup. The indicator can also be expressed in percentage to provide direct comparability to the EU RES percentage targets.

S3. Security of Supply
Security of supply is evidently important for the energy systems. We have had a supply crisis of gas in winter 2022-23 and at the same time a crisis in the power sector with very high spot prices due to among others high gas prices.

Security of supply is a broad term, especially in projects including both electricity and gas/hydrogen. ENTSO-E addresses the security of supply concept under 3 segments: "system adequacy (for generation and grid)", "system stability" and "system flexibility". ENTSO-G has two separate indicators addressing the issue: "reduction in exposure to curtailed demand" and "remaining supply flexibility".

We suggest building a hybrid indicator illustrating a number of topics for security of supply.

- Energy not served
- Reserve needs
- Import dependency

Highlight
We suggest building a hybrid indicator illustrating a number of topics for security of supply.

Both market and grid models estimate energy not served, although in a simplified manner, as long as no dedicated system adequacy calculations taking into account variations such wheather patterns and outages are taken into account. The grid model will be able to deliver more detailed insights into energy not served as a result of lacking transmission options. Likewise, both models can estimate import dependency and add simplified estimates of reserve needs.

S4. Grid Utilization
Grid utilisation illustrates usage patterns for the grid infrastructure. Ineffective usage of the infrastructure has direct impact on the grid costs.

One part of the indicator addresses the utilization of both electricity and hydrogen grid assets. Another part of the indicator illustrates potential regulatory aspects in FBMC. With the meshed nature of the European power grids, the loop flows (see footnote 11) are unavoidable.

Due to these loop flows, available transfer capacity at the critical elements may be reduced. Thus, e.g., the number of hours with the 70% Rule being violated by loop flows is another part of the grid utilization indicator, which is to be factored in negatively.

S5. Cross-sectoral Flux
Parallel optimization of the hydrogen grid and power grid build-out allows to identify the number and ideal locations for placing electrolysers and hydrogen peakers (hydrogen gas turbines). This indicator is meant to illustrate to what extent hydrogen and electricity sectors are integrated in different locations.

This locality aspect in comparison of different project cases can provide the decision makers with additional information for use in the infrastructural planning.

Project costs

In a "cost benefit analysis" of course the costs must be included as indicator. Besides benefits appropriate monitoring of the costs and fair distribution of costs between the countries and stakeholders are decisive when analysing the stakeholder impact of Hubs-and-Spokes configurations.

Highlight
The main challenges are to set the project boundaries for cost inclusion and deciding which cost should be considered within the scope of direct costs.

Costs of a project case are estimated based on capital investments (CAPEX) and operational costs (OPEX).

The main challenges are to set the project boundaries for cost inclusion and deciding which cost should be considered within the scope of direct costs. Onshore grid reinforcement costs related with the offshore connections and offshore wind farm connection costs are of particular interest for this decision.

Stakeholder inclusion

The Hubs-and-Spokes projects are large infrastructural projects; they bring together many stakeholders and also have potentially large societal impact.

Highlight
Stakeholder engagement provides the basis for the CBA results having acceptance.

Stakeholder engagement starting in the conception phase has critical importance for the success of the CBA. Discussion of the CBA framework including scope, configurations and indicators, clear understanding of the modelling consequences and distribution of welfare are important for conducting a CBA study. This process is not only relevant and interesting, but also it provides the basis for the CBA results having acceptance and driving force for further steps into realization. While stakeholder involvement processes are key to the NSWPH's internal processes, they also apply in a more general context, because active stakeholder involvement serves as a quality check and ensures that concerns are heard, and the results understood.

NSWPH internal processes

NSWPH is a large consortium bringing gas and electricity TSOs of Denmark, Germany (in Germany only TenneT) and Netherlands to undertake an extremely complex and expensive infrastructural challenge with technical, economic, environmental, and social components.

Furthermore, due to the energy security and trade aspects, the Hubs-and-Spokes project has a strategic and political significance for the involved and neighbouring countries. Therefore, internal, and external stakeholder engagement is an extremely important process with many influential parties involved including ministries and EU.

Considering both the complexity and magnitude of the project, internal stakeholder structure and decision mechanisms play a key role to propel the project from "Pathway Study" to "Advanced CBA". NSWPH has four work-streams: Energy Systems, Technical Concepts, Market and Regulation, Stakeholder and Communication with each stream having members from all internal stakeholders.

The structure is meant to enable a number of benefits:

- All the aspects of the project are investigated from the perspectives of all the stakeholders and their concerns and interests are represented at all times. This means the suggestions developed by the work-streams are realistic and desirable which are likely to have high acceptance by the authorities.
- Development of the acceptable suggestions (such as project cases and configurations) saves time for the project realization and in meeting greater climate targets.
- Flow of information among the stakeholders is much more fluent and reliable. This reduces the influence of frictions and boosts the cooperation.
- Each stakeholder is well-informed regarding the progress and challenges in front. Solutions to challenges in specific contexts can better be facilitated, and synergies can more easily be created for finding solutions to common problems.

Internal stakeholder engagement is further cultivated via alignment sessions between different work-streams and deep-dive sessions for exploring a theme thoroughly.

Internal stakeholders have consortium representatives from each country being responsible of managing the relations at the governance levels and working in conjunction with the Stakeholder and Communication work-stream.

External stakeholders

Ministries and governments are key stakeholders for the project confirmation of the validity of the configurations and project cases of interest. This also involves identification of critical timelines to be fed into the policy decisions and regulatory designs.

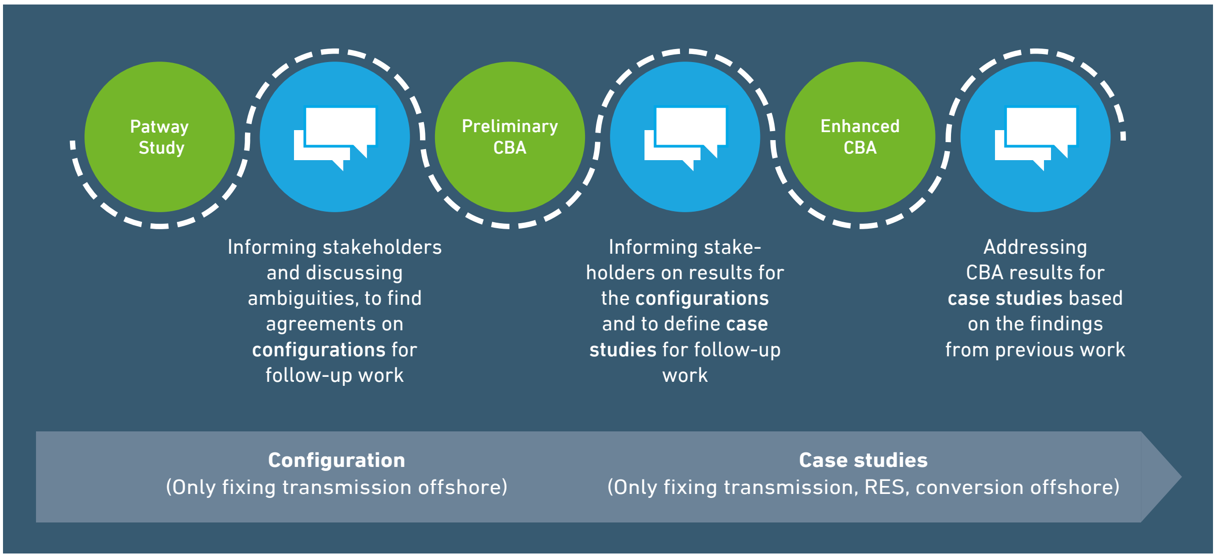
Highlight

Ministries and governments are key stakeholders for the project confirmation of the validity of the configurations and project cases of interest.

Commitment to the project, a coordinated and consistent regulatory framework across the North Sea countries, accompanied with timely implementation of regulatory changes, are critical for project success.

Figure 11 depicts the critical external stakeholder engagement phases with timing of their necessary input in the CBA process.

Figure 11: External stakeholder engagement process of NSWPH's CBA studies



In the entire process of the CBA execution, internal and external stakeholders must be kept onboard in order to move in the right direction.

The external stakeholders are not limited to ministries. Involvement of ENTSO-E/G, EU and other relevant bodies are also important. Different organizations and authorities can be contacted at different phases of the study. It is beneficial to keep the stakeholder group open for new members.

In the North Sea, there are many countries and actors creating initiatives (e.g., Aquaventus and Eurobar) and working in parallel to NSWPH. Consulting with these initiatives for finding the synergies and noticing the potential benefits and risks for technical and commercial success of the project and factoring in such elements in the CBA are important for the resilience of the study.

A large stakeholder engagement is advisable moving from “Pathway Study” to “pragmatic CBA” to receive more input and inspiration for configuration options. Results of the pragmatic CBA should again be shared with the relevant stakeholder groups to define the cases for “Advanced CBA” based on the most promising configurations according to the results of “pragmatic CBA”.

Final results of the “Advanced CBA” are of interest to stakeholders, as well as the broad public in consideration of the size of the project. Therefore, analysis, conclusions and insights should be communicated at various levels and channels with appropriate material.

Highlight

A large stakeholder engagement is advisable moving from “Pathway Study” to “pragmatic CBA” to receive more input and inspiration for configuration options.

5 Conclusions and Perspectives

Conclusions

NSWPH has identified a number of topics which are important to take into account in CBAs for Hubs-and-Spokes projects.

Recommendations for improving CBAs include investigating:
- Impacts on investment needs in the surrounding energy system
- Realizable market flows and internal grid congestions
- Impact of the current regulatory setup on stakeholder analyses

Investments

Investments needs in the surrounding systems driven by Hubs-and-Spokes projects must be compared to impacts of alternative solutions (e.g., radial connections to shore).

Highlight
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Assessing the improvement (regarding flexibility and possible congestions) that the interconnectors (in a Hubs-and-Spokes configuration) allow, naturally requires a good understanding and modelling of the shortcomings of the future grid infrastructure. In an unlimited and uncongested grid setup, new grid infrastructure would have no immediate measurable benefit.

Hubs-and-Spokes concepts can impact the need for other investments in grid infrastructure or other options to alleviate congestions. Both costs and options for realizing these investments can have significant importance.

As an example, if the surrounding system has ample options to reinforce the transmission system at reasonable cost, the potential savings from adding the Hubs-and-Spokes concept are limited. On the other hand, if the maximum realizable interconnection capacity in the surrounding system is limited or costs are high, the benefits from Hubs-and-Spokes in alleviating grid buildout can be substantial compared to a traditional alternative of radial connection.

Flows and regulatory setup

Flow-based market simulations (FB) are recommended in CBAs of Hubs-and-Spokes projects. The reason is that FB better simulate the physical flows in the system.

Highlight
Flow-based market simulations (FB) are recommended in CBAs of Hubs-and-Spokes projects. It is recommended that redispatch needs and impacts of regulatory setup are evaluated as part of CBAs for Hubs-and-Spokes projects.

It is possible to reflect internal grid congestions in market models with given adequate input from grid models, but only a combination of a FBMC-based market simulation with grid model based estimates for redispatch will be able to both reflect realistic dispatch and power flows as well as stakeholder impacts according to the assumed market setup.

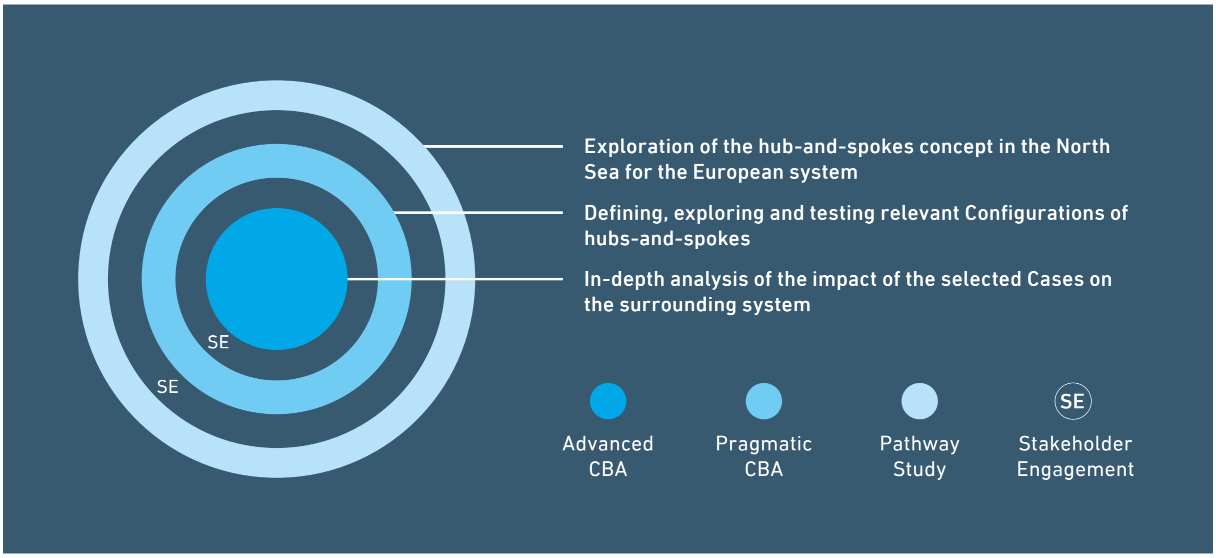
It is recommended that redispatch needs and impacts of regulatory setup are evaluated as part of CBAs for Hubs-and-Spokes projects.

Three different levels of analysis

This paper recommends working with the analyses of Hubs-and-Spokes configurations at three different levels, of which the two latter can be applied in project specific assessments comparable to those performed in ENTSO-E's TYNDP. Figure 12 summarizes the NSWPH approach on the CBA process.

Highlight
NSWPH CBA process: converging process from Pathway Studies toward Advanced CBA.

Figure 12: NSWPH CBA process: converging process from Pathway Studies toward Advanced CBA



The recommended three levels:

- System studies – analysing the general tendencies and long-term energy system pathways with and without options for hubs-and-spoke configurations, from a purely energy optimal perspective
- Pragmatic CBA – analyses of potential overall design of promising Hubs-and-Spokes configurations with a focus on assessing the socio-economic value
- Advanced CBA – assessing the socio-economic value of specific configurations, by taking into account both regulatory market setup and impacts on the detailed physical grid (grid modelling of redispatch and/ or need for grid upgrade) – especially within bidding zones.

CBA execution

To realise CBA at different levels both market and grid models will play an important role. While pragmatic CBA's can be realised with simplified market models (possibly adjusted to take into account internal congestions in a simplified manner), the advanced CBA requires the use of grid model in order to better reflect the physical reality as well as the regulatory setup. The latter will enable stakeholder analyses split up according to e.g. market and redispatch impacts. To fully benefit from this setup, also indicators presenting the results should be able to reflect the applied methodology and corresponding level of detail. For this purpose, the paper suggests additional indicators distinguishing between marked and grid impacts and illustrating the above mentioned impacts on investments needs.

Highlight
To realise CBA at different levels both market and grid models will play an important role.

Stakeholder engagement

A strong stakeholder engagement is recommended. It starts in the conception phase and has critical importance for the success of the CBA.

Highlight
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The discussion of the CBA framework including scope, configurations and indicators, a clear understanding of the modelling consequences and distribution of welfare, are important for conducting a CBA study. This process can ensure a CBA, which is not only relevant and interesting, but also provides understandable and accepted results, ensuring momentum for further steps into realization.

Perspectives on CBA

As the energy systems are transitioning from fossil fuelled to zero carbon integrated systems, the CBA methodologies and guidelines are developing accordingly.

Highlight
As the energy systems are transitioning from fossil fuelled to zero carbon integrated systems, the CBA methodologies and guidelines are developing accordingly.

In the context of European transmission system operators (TSO), the assessment of the power and gas system is continuously the subject of discussion between the ENTSOs, the European regulator (ACER) and the European Commission.

According to the "old" Regulation (EU) No 347/2013, the ENTSOs by end of 2016 had the task of developing a 'consistent and interlinked electricity and gas market and network model including both electricity and gas transmission infrastructure'. The model should be used for CBA assessments

ENTSO-E did deliver an interlinked model that focuses on common scenario building, but ACER took the view that a number of additional aspects should be investigated in more detail. This meant that in the future interlinkage issues between energy sectors must be explicitly assessed in the CBA for power and gas projects in the TYNDPs.

In the meantime, the "old" Regulation (EU) No 347/2013 has been repealed by the new Trans European Network: TEN-E regulation (EU) 2022/869. The previous infrastructure technologies in the Regulation: electricity and gas have been replaced by electricity, hydrogen, renewable gases, electrolysers and CO2. Thus, the new regulation has an updated focus on the EU strategy for future zero carbon emission.

Of special interest for NSWPH, the new TEN-E regulation specifies that ENTSO-E (starting in 2024) as part of future TYNDPs shall develop "high-level strategic integrated offshore network development plans for each sea-basin" in EU including the North Sea.

The offshore network plans shall provide "a high-level outlook on offshore generation capacities potential and resulting offshore grid needs, including the potential needs for interconnectors, hybrid projects, radial connections, reinforcements, and hydrogen infrastructure".

So, in the future, NSWPH can benefit from cooperating with ENTSO-E in offshore grid planning. The cooperation could be facilitated by the TSOs who participate in both ENTSO-E and the NSWPH.

The new regulation (EU) 2022/869 also has an updated focus on CBA:

- The methodologies for cost-benefit analyses developed by the ENTSO-E and ENTSO-G shall be consistent with each other, taking into account sectorial specific issues.
- In 2023, the ENTSOs shall publish their respective consistent single sector draft methodologies.
- In addition, in 2025, ENTSO-E and ENTSO-G shall jointly submit to the Commission and ACER a "consistent and progressively integrated model that will provide consistency between single sector methodologies based on common assumptions including electricity, gas and hydrogen transmission infrastructure as well as storage facilities, liquefied natural gas and electrolysers".

Highlight
in 2025, ENTSO-E and ENTSO-G shall jointly submit to the Commission and ACER a "consistent and progressively integrated model".

Therefore, it follows that also on modelling which forms the basis for CBA analyses, NSWPH and the ENTSOs may have similar or overlapping tasks. A future collaboration may be fruitful.

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