Deliverable 7.11
Cost-benefit analysis methodology for offshore grids

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
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This result is part of a project that has received funding form the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

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Content

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EXECUTIVE SUMMARY

To understand the economic and social consequences of undertaking an offshore grid development in a particular region, it is necessary to perform a cost benefit analysis to assess the value and costs of the meshed offshore grid to society. In order to perform this cost-benefit analysis, a CBA methodology should be employed that sets out a clear set of guidelines to ensure a thorough assessment and comparison of alternative offshore grid solutions.

Existing methodologies are mostly incomplete when assessing complex systems, such as offshore grids. Therefore, there is a need to develop a CBA methodology within the scope of PROMOTioN, to assess the value of offshore grid alternatives to society. This deliverable provides a set of guidelines to follow when performing a societal CBA analysis for offshore grids. The presented methodology aims to enable the comparison of alternative offshore grid configurations in a certain geographical area, given developments in offshore wind capacity in the researched area. The CBA methodology will set out the criteria and guidelines for the assessment of the costs and benefits of a complex project, i.e. an offshore energy system. A common set of indicators (KPIs) will be used to compare all project alternatives in a transparent manner.

An offshore grid is defined in the context of the CBA methodology as a configuration of offshore infrastructure assets that enables:

(i) the connection and evacuation of foreseen offshore wind energy in a defined offshore area to surrounding onshore grids, and

(ii) the increase of market integration through offshore cross-border interconnections.[1]

The “best” offshore grid topology will be identified through the societal CBA methodology. The “best” configuration of an offshore grid is defined as the “project alternative” that will derive the greatest value to society. This will be determined by the KPIs.

The societal CBA methodology developed in this deliverable will provide guidelines on the choices and options for comparing offshore grid solutions, the KPIs to value alternative offshore grid configurations and the assessment framework that will be used for calculating the final CBA. Throughout this deliverable both an ideal and a practical CBA methodology will be developed. The ideal methodology will provide a more accurate reflection of the costs and benefits but will be more time consuming and onerous to collect the data. There is also a risk that a large number of the data points for the ideal CBA do not exist. The ideal methodology encompasses more complexity and levels of detail. To fit within the scope of the PROMOTioN project, a practical CBA methodology is additionally described to enable the assessment within the scope and time constraints. This practical CBA methodology will be used within WP 12.2.

[1] Within the PROMOTioN project, the researched area will be the Northern Seas and evacuation of offshore wind to the surrounding countries.

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1 INTRODUCTION

1.1 OVERVIEW

To understand the economic and social consequences of undertaking an offshore grid development in a particular region, it is necessary to perform a cost benefit analysis to assess the value and costs of the meshed offshore grid to society. In order to perform this cost-benefit analysis, a CBA methodology should be employed that sets out a clear set of guidelines to ensure a thorough assessment and comparison of alternative offshore grid solutions.

Various CBA methodologies have already been developed for specific types of projects and sectors. Generic guidelines to perform societal CBA analyses have been described in literature. However, existing methodologies are mostly incomplete when assessing complex systems, such as offshore grids. Therefore, there is a need to develop a CBA methodology within the scope of PROMOTioN, which can assess the value of offshore grid alternatives to society.

Departing from generic guidelines for societal CBAs and a literature review of existing CBA methodologies, this document provides a set of guidelines to follow when performing a societal CBA analysis for offshore grids.

1.2 AIM AND SCOPE OF THE CBA METHODOLOGY

The aim of this document is to develop and present a methodology for a societal CBA (SCBA) that is able to assess the value to society of future offshore energy systems. The presented methodology aims to enable the comparison of alternative offshore grid configurations in a certain geographical area, given developments of offshore wind capacity in the researched area. The developed SCBA methodology is intended for application in the context of offshore infrastructure. The CBA methodology will set out the criteria and guidelines for the assessment of the costs and benefits of a complex project, i.e. an offshore energy system. A common set of indicators (KPIs) will be used to compare all project alternatives in a transparent manner. An offshore grid is defined in the context of the CBA methodology as a configuration of offshore infrastructure assets that enables:

(iii) the connection and evacuation of foreseen offshore wind energy in a defined offshore area to surrounding onshore grids, and

(iv) the increase of market integration through offshore cross-border interconnections.[2]

The developed societal CBA methodology for offshore grids regards the *energy network* or *evacuation network* for offshore wind, combined with interconnections, evaluated under multiple scenarios of on- and offshore developments. The main objectives of the offshore grid are:

- to evacuate and connect offshore wind energy, and

[2] Within the PROMOTioN project, the researched area will be the Northern Seas and evacuation of offshore wind to the surrounding countries.

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- to increase market integration between the countries connected to the meshed offshore grid.

The “best” offshore grid topology from a set of defined alternative topologies/concepts (hereafter also referred to as “project alternatives” or “alternatives”) will be identified through the developed societal CBA methodology. The “best” configuration of an offshore grid is defined as the “project alternative” that will derive the greatest value to society. The value to society will be evaluated through various key performance indicators (KPIs) as detailed in Chapter 6.

The remainder of this document is divided into five Chapters. Chapter 2 gives an overview of definitions of terminology used throughout the document. In Chapter 3 a generic structure of CBA methodologies consisting of several dimensions has been identified from a literature review. This structure is replicated for the remaining chapters. Chapter 4 provides an overview of the requirements of offshore grids based on a gap analysis of literature. Proposed solutions to the gaps identified in Chapter 4 will be discussed in Chapter 5. Further Chapter 5 details the specific decisions for the CBA methodology for offshore grids for each dimension for an ideal and practical CBA. The selection and methodologies for valuation of the key performance indicators (KPIs) enable this report to assess the costs and benefits of each project alternative as discussed in Chapter 6. Finally, a summary and list of references conclude this deliverable.

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2 DEFINITIONS

Cost benefit analyses tend to use an array of complex terminology that can be difficult to understand if undefined. This chapter defines the meaning of various terms used throughout this report.

2.1 CONCEPTUAL DEFINITIONS

2.1.1 COST BENEFIT ANALYSIS (CBA) EXECUTION VERSUS METHODOLOGY

Clarification is required on the distinction between the cost benefit *analysis* and the cost benefit *analysis methodology* to execute a CBA.

A Cost-Benefit Analysis (CBA) is an assessment of the costs and benefits of an investment decision in order to assess the welfare change attributable to it.[3] Such an assessment can be used as a tool to judge the advantages and disadvantages of the investment decision. The aim of a CBA is to assign a value to the benefits expected from the project[4] and compare these to the costs, which are expected to be incurred by developing the project. If the benefit exceeds the cost, there is justification for the project to go ahead. Often an appraisal is performed in comparison to a reference 'business-as-usual' case, i.e. an estimation of the costs and benefits that will continue to arise if the project is not carried out.

A CBA methodology provides a set of guidelines on how to perform a CBA. The methodology describes how to ensure a robust and consistent analysis of multiple projects. This is achieved through: guidelines on establishing a common input dataset, common reference sources, common indicators, a common time horizon, and common discount rates to be applied. The CBA methodology should outline also the methodology for the sensitivity analysis.

A CBA methodology should be:

- able to encompass and compare a wide range of considered alternative projects;
- project and scenario[5] independent (impartial);
- a single methodology to assess alternatives on equal footing.

[3] European Commission. "Guide to Cost-Benefit Analysis of Investment Projects", 2014.

[4] A *project* is defined as a cluster of investments that are expected to be in similar development stages. Note that sometimes a project is just a single investment or a full offshore system. (see also Section 2.1.3 and 2.3).

[5] A scenario is a set of assumptions that describes a possible future development of the region where the researched system or project alternative will be developed and operated. Scenarios illustrate future uncertainties, in this report this includes renewable energy capacity, generation portfolio, load growth, energy prices, CO_2-prices, regulatory framework, etc. See also Section 2.2.4.

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A CBA methodology defines:

- the scope and boundaries of the CBA:
    - whether it regards national or cross-national infrastructure;
    - whether it regards a project value or the value to society.
- the project alternatives;
- the scenarios and sensitivities to analyse at a minimum, and
- the indicators and KPIs to measure the impact of project alternatives.

Figure 2-1 shows the relation between CBA methodology and execution.

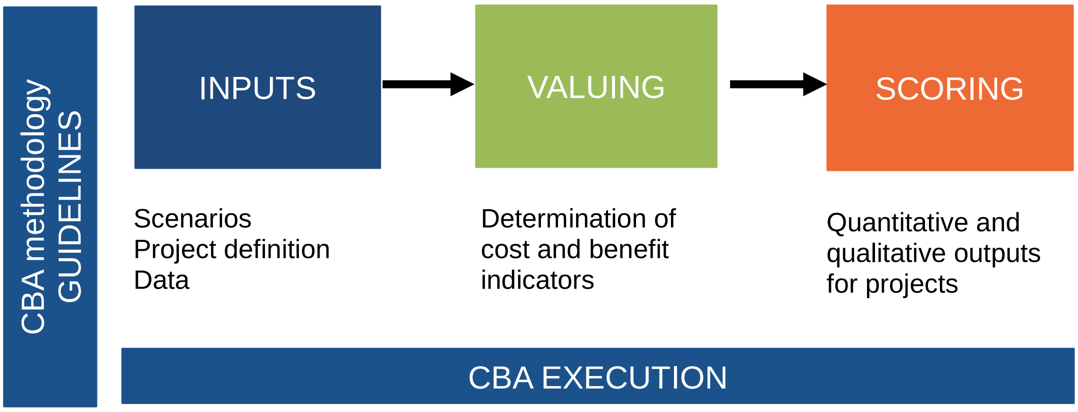

Figure 2-1: Overview of the interaction between a CBA methodology and execution.

The CBA assessment follows the described steps of the methodology to perform a full assessment of socio-economic, technical, environmental and residual impact categories of a project. These impacts have been identified and translated into indicators in the methodology. The assessment will determine the value of each defined indicator for each alternative project. By comparing the indicator values of alternative projects, the assessment can then perform a scoring of, or comparison between project alternatives.

2.1.2 SOCIETAL VERSUS FINANCIAL CBA

A distinction needs to be made between societal CBAs and project/financial CBAs.
A **project or financial CBA** typically analyses the direct cash flows of the costs and revenues related to the proposed project alternative and will determine the financial investment decisions of the stakeholders directly responsible for the implementation of the project. A project CBA requires full monetisation of the costs and benefits of project alternatives. The selected costs and benefits are those considered relevant by the project promotor, who can furthermore choose to (arbitrarily) monetise the non-monetary indicators for the purpose of performing their own assessment and (internal) decision-making. A net present value (NPV) can be determined from the monetised cost and benefits.

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A **societal CBA** or SCBA not only looks at valuing the direct costs and revenues related to the project, but at valuing all costs and effects to society due to the project. An SCBA is an information tool that systematically presents and assesses the advantages and disadvantages of an investment from the perspective of society. In a societal CBA (SCBA), the wider societal and economic welfare implications of the investment decision are depicted to all relevant parties in society (not only the party implementing the project). Ideally, all identified effects and costs to society would be monetised to perform an NPV calculation of each project. However, in practice not all effects to society can be (meaningfully) monetised or even quantified, or they may not be accepted by all involved stakeholders (see also Section 5.6). This is particularly difficult in the event that indicators which are non-monetary in itself are at some point monetised (according to a certain agreed-upon key) for the purpose of performing a CBA. It is therefore, in a SCBA, not the purpose to monetise and perform a full NPV calculation of all costs and benefits, but to monetise as much as meaningfully possible. An NPV can then be determined from the monetised key performance indicators (KPIs). Monetised KPIs (see also Section 6) are however not the only factor in deciding whether a project is beneficial to society, so the NPV alone is rarely the sole basis for decision-making in an SCBA. Other measures could also be accounted for, this could include a reduction in CO_2 emissions or improved market integration between countries.

2.1.3 A PROJECT AND PROJECT ALTERNATIVES

A project (or ‘investment’ in the ENTSO-E CBA definition) can be defined as “*the smallest set of assets that together can be used to transmit electric power and that effectively add capacity to the transmission infrastructure*”[6], i.e. a combination of infrastructure components that are developed close in time and that together fulfil a single purpose (the set of assets need the full set of components to be fully operational). In the scope of the PROMOTioN project, this definition will be reviewed to accommodate offshore grids and offshore energy infrastructure more generally, as discussed in Chapter 5.

A project that is evaluated through a CBA can take on various forms. A “**single project**”, consists of a (limited) combination of assets that is required for the project to be operational. Offshore grids, on the contrary, fulfil multiple purposes, as highlighted in Chapter 5, but only operate to their full potential when a large number of assets are in place that are built over a longer timeframe. Hence, an offshore grid will usually consist of a **cluster** of single projects (or: "investments"), which together fulfil a desired purpose. Additionally, offshore grids are likely to be in continuous development during their lifetime. The offshore grid envisaged in the PROMOTioN project is a **complex system** that consists of a cluster of multiple, interacting “single projects/investments” that are needed for the offshore grid to become operational.

Project alternatives are choices made within the project, i.e. different alternatives that will be assessed with the CBA methodology. For example, different project alternatives could include different network configurations (radial, meshed, hybrid, …) and technologies (AC, HVDC, …) of an offshore grid. Project alternatives are

[6] ENTSO-E, „2nd ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects“ (draft for review by European Commission), 6 September 2017.

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different ways to fulfil a purpose, e.g. evacuating offshore wind energy. All project alternatives need to be evaluated with the same methodology to ensure objective comparison of alternatives.

2.1.4 SUMMARY

Several CBA methodologies exist to perform a financial or societal CBA for single projects (see Chapter 4). The aim within PROMOTioN is to assess the value of the complex meshed offshore grid in the North Sea. Since meshed offshore project alternatives are still being considered and researched, an initial assessment will be made to evaluate the value to society of these project alternatives rather than focusing on a financial assessment. Figure 2-2 gives an overview of the scope of the CBA methodology within this deliverable.

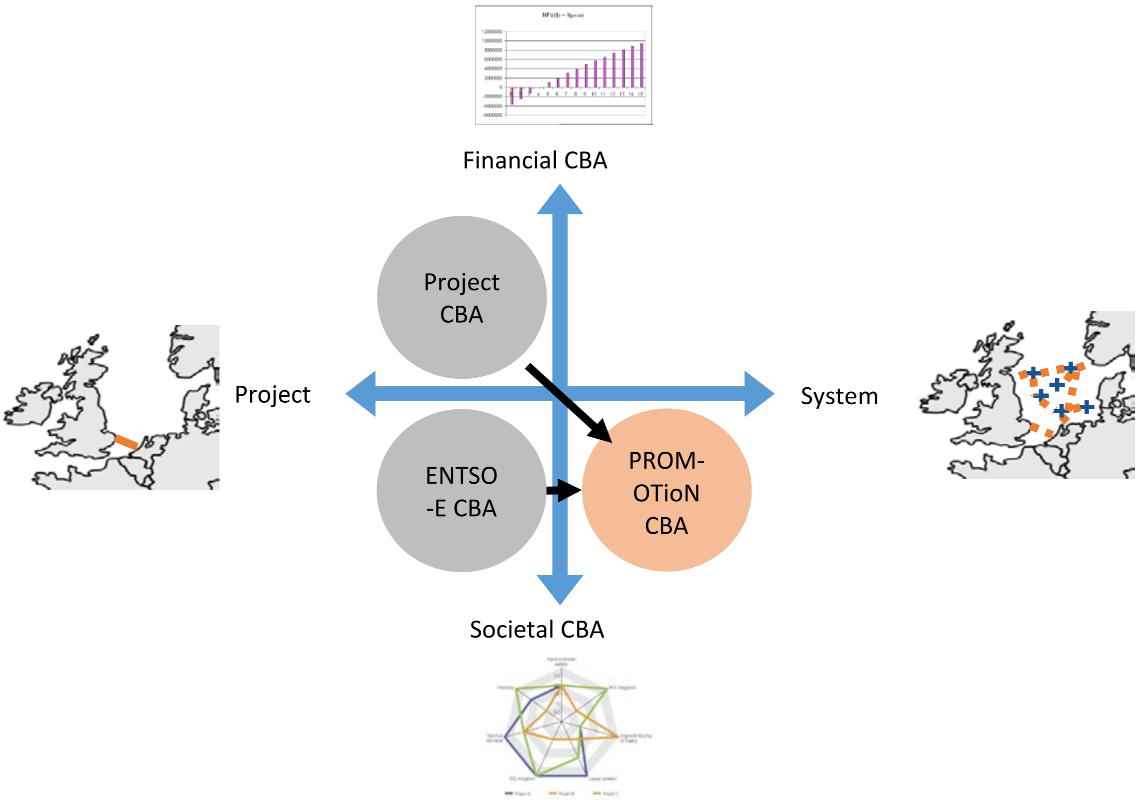

Figure 2-2: Scope of the CBA methodology within PROMOTioN.

2.2 DEFINITIONS OF CBA DIMENSIONS

2.2.1 SCOPE OF THE CBA

The scope of the CBA describes the purpose and boundaries of the analysis. These are further detailed in Section 5.2. The definition of scope and boundaries involves answering the following questions:

- Are we looking at national or cross-national infrastructure?
- Do we need to evaluate the financial or societal value of the project alternatives?

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- Do we incorporate only the offshore or also the onshore grid?
- Does the project aim to facilitate the evacuation of wind energy and/ or facilitate market integration?
- Is the installed offshore wind generation capacity considered part of the 'offshore grid', or is the offshore grid built to connect 'existing' offshore wind?

2.2.2 OFFSHORE GRID

An offshore grid in the context of PROMOTioN connects the offshore wind farms with the connected national onshore power systems. These connections can be radial, hybrid or meshed, with or without power hubs. Additionally, an offshore grid could increase interconnection between European countries. Several alternative topologies of offshore grids will be evaluated with the developed CBA methodology in WP12.

2.2.3 ONSHORE GRID

The onshore grid is the network to which the offshore grid need to connect. Connection of (substantial) wind capacity might require reinforcements of the existing onshore grid. Chapter 5 includes a discussion on whether and how this needs to be included in the CBA methodology.

2.2.4 SCENARIOS

A scenario is a set of assumptions that describes a possible future development of the region where the researched system or project alternative will be developed and operated. Scenarios illustrate future uncertainties, in this report this includes renewable energy capacity, generation portfolio, load growth, energy prices, CO_2-prices, regulatory framework, etc.

As a workable definition for scenarios, the content of scenario guidelines from the ENTSO-E CBA methodology is used. This content is described as follows[7]:"

- *Planning scenarios are coherent, comprehensive and internally consistent descriptions of **plausible futures**, (in general composed of several time horizons) built on the imagined interaction of economic key parameters (including economic growth, fuel prices, CO_2 prices, etc.).*
- *A planning scenario is characterised by a **generation portfolio** (capacity forecast, type of generation, etc.), **demand forecast** (impact of efficiency measures, rate of growth, shape of demand curve, etc.), and **exchange patterns** with the systems outside the studied region.*
- *A scenario may be based on trends and/or local specificities (**bottom-up scenarios**) or energy policy targets and/or global optimisation (**top-down scenarios**).*"

[7] ENTSO-E, „2nd ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects“ (draft for review by European Commission), 6 September 2017.

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With the scope of PROMOTioN, distinction will be made between onshore (land) and offshore (sea) scenarios. This is discussed further in Chapter 5. Furthermore, the reference state of the onshore grid should be part of the defined scenarios.

2.2.5 KPIS

Key Performance Indicators (KPIs) are indicators that value the costs and benefits of different project alternatives. Project alternatives will then be compared with each other based on their score on the determined KPIs. To assess the value to society of European energy infrastructure projects, KPIs are based around the objectives of sustainability, affordability and security of supply. KPIs can be defined in qualitative, quantitative or monetised terms (see Chapter 5).

2.3 OTHER DEFINITIONS

- An *investment* is the smallest element that can transport power. For example, a substation without connection to a network is not considered an investment.
- A *cluster* is the smallest group of investments that together are actually useful for the transportation of power in order to meet a target or goal (e.g., enhancing socio-economic welfare, system CO_2 reduction, etc.).
- A *project* is a cluster of investments that are expected to be in similar development stages. Note that sometimes a project is just a single investment or a full offshore system.
- A *topology or configuration* is a set of projects, possibly realised at different moments in time that are part of the same offshore transmission system.
- *Project alternatives* are different configurations of infrastructure that fulfil the same purpose(s) and will be compared through the CBA methodology.
- *Null-alternative* is the reference for comparison between project alternatives. The null-alternative is the reference system, developed using currently established technologies and reflecting a business-as-usual development.
- *Scenarios* are descriptions of external developments of how the energy system could look like. Scenarios represent a set of assumptions for plausible futures wherein the different offshore grid topologies will be evaluated.
- *Sea-scenarios/Offshore scenarios* are scenarios that reflect the considered range of developments in the offshore area, including offshore wind capacity, locations and technologies. The different project alternatives will be evaluated under different scenarios of offshore wind development.
- *Land-scenarios/Onshore scenarios* describe the development in the onshore markets, including demand, fuel prices, capacity mixes and interconnections.

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3 GENERIC STRUCTURE CBA METHOLOGY

3.1 INTRODUCTION

A cost benefit analysis (CBA) is performed to assess the value of each project from a set of alternatives through various indicators (KPIs). Each project alternative in the set should fulfil (a) similar purpose(s). The CBA methodology will enable project promotors to assess “the best” project from the set of alternatives. In order to ensure transparent comparison between project alternatives, a clear set of guidelines has to be defined: the CBA methodology.

Various CBA methodologies exist throughout literature tailored to different types of projects and sectors. Both project and societal CBAs require a methodology to follow. Project CBAs typically monetise all relevant indicators and a full net present value (NPV) for each of the project alternatives is calculated. The guidelines are predominantly based on quantification and monetisation. However, Societal CBAs include non-monetary aspects for the project alternatives. This requires a greater variety of guidelines to ensure transparent project comparison. Although the approach of each CBA differs, a similar structure (similar steps) can be used.

Several theoretical and practical CBA methodologies have been reviewed[8], resulting in a common generic structure of CBA methodologies. The structure is presented in this report through “**dimensions**”, which will be clarified throughout the following paragraphs. In the subsequent Chapters, each of these dimensions will be defined and detailed further.

3.2 GENERIC STRUCTURE OF A CBA METHODOLOGY

The common generic structure of CBA methodologies includes steps (i) to understand the project, (ii) to understand the costs and benefits, and (iii) to communicate the results. This structure is defined in this report through seven “dimensions”, as indicated in Figure 3-1:

I. **Scope** of the project and CBA methodology

[8] Guidelines for Cost Benefit Analysis of Smart meter deployment, EUR Joint Research Centre, 2012.; Methodological approach for Estimating the Benefits and Costs of Smart Grid Demonstration Projects, EPRI, 2010.; Several guidelines for Societal Cost Benefit Analyses, CPB Netherlands Bureau for Economic Policy Analysis & PBL Netherlands Environmental Assessment Agency, 2013.: I. Gadjjic, N. Tidemand, Y. Yang. “Full Cost and Benefit Calculation - methodology”, NorthSeaGrid Offshore Electricity Grid Implementation in the North Sea D4.3, 2014.; European Commission. “Guide to Cost-Benefit Analysis of Investment Projects”, 2014.; North Sea Grid – Offshore Electricity grid implementation in the North Sea. “Final report”, 2015.; 1st ENTSO-E Guideline for Cost Benefit Analysis of grid development projects; 2nd ENTSO-E Guideline for Cost Benefit Analysis of grid development projects and consultation reviews of EASE and ACER (ENTSO-E CBA for electricity infrastructure); European Investment Bank. “The economic appraisal of Investment Projects at the EIB”, 2013.

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II. **Scenarios** of market development

III. **Project alternatives**

IV. **KPI** definition / identification

V. **Assessment** framework

VI. Use of **tools**

VII. **KPI assessment** and **scoring** of projects

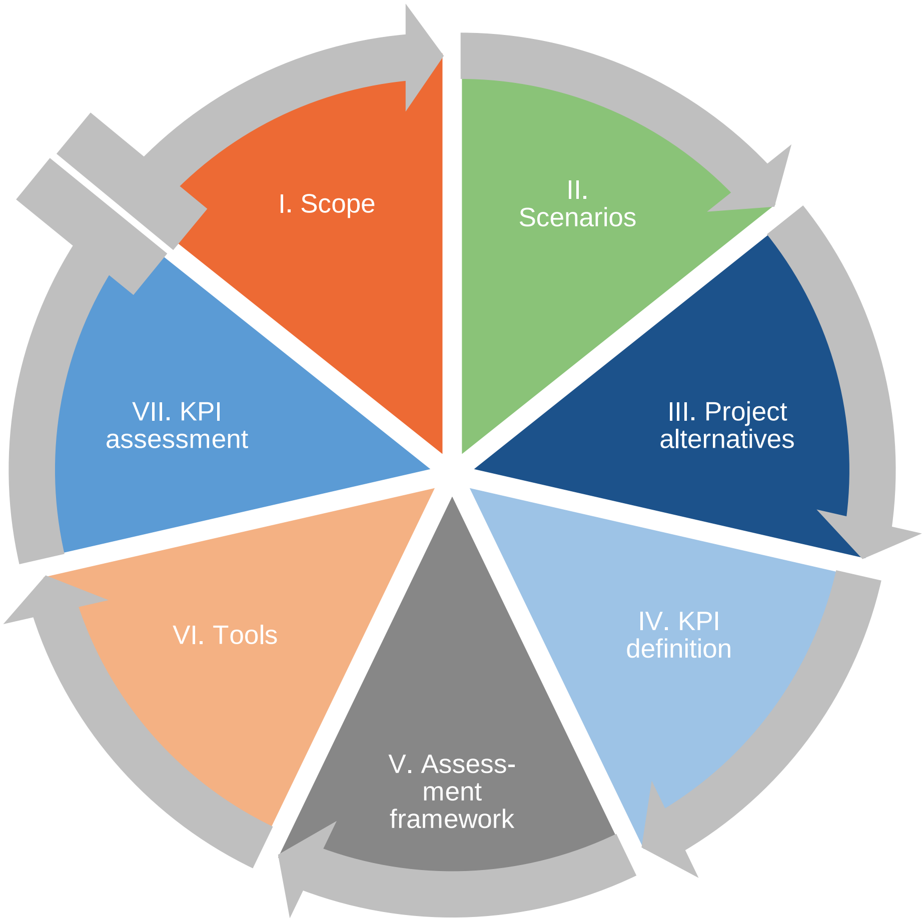

Figure 3-1: Dimensions of CBA methodologies.

Each of the dimensions encompasses distinct steps:

I. Scope of the project and CBA methodology

The first dimension of a CBA methodology involves defining the purpose and scope of analysis and the projects that are assessed. A CBA methodology can be used to assess the costs and revenues of a project (project CBA) or to assess the value to society of a project (societal CBA) (see Chapter 2.1). Additionally, the purpose of the CBA should be clarified: what would qualify as "the best" alternative? What common purpose(s) should each

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project alternative fulfil? For example, alternative offshore grid topologies could have a common purpose to evacuate offshore wind energy. The scope of the project should also be defined to understand how project alternatives should be developed in dimension III of the methodology. A project could namely be a single project or a complex multi-purpose system.

II. Scenarios of market development

The second dimension of a CBA methodology involves defining guidelines regarding the number, scope and setup of the scenarios under which to assess the costs and benefits of each project alternative. The guidelines provide an agreement on how system development scenarios should be set. Scenarios represent major future uncertainties including renewable energy capacity, generation portfolio, load growth, energy prices, CO_2-prices, regulatory framework, etc. For each scenario, the methodology defines the required set of parameters. These parameters will then need to be specified in the execution phase of the CBA. The selected scenarios represent a set of future visions for the development of the onshore and offshore system in which project alternatives will operate. Alternatives may have different costs and benefits depending on the scenario under which they are evaluated. The project alternatives under consideration thus need to be assessed under multiple scenarios to avoid any bias and to ensure robustness of the result of the CBA under uncertainty. Clear and transparent guidelines on how to select and determine scenarios, and how to ensure an appropriate range of scenarios are therefore paramount to mitigate bias towards a certain alternative and facilitate a valuable comparison between project alternatives. Potentially, guidelines regarding sensitivity analyses within scenarios and dealing with uncertainty could be provided.

III. Project alternatives

The third dimension of a CBA methodology defines the number of project alternatives that need to be assessed and how project alternatives should be developed. This allows the study to compare alternative strategic or technical solutions for the proposed infrastructure. Each project alternative requires a definition and information on the assets' functionality and characteristics. This includes guidelines on (i) the purpose(s) or function(s) of the project, and thus of each project alternative, (ii) the scope of variation between project alternatives, and (iii) the scope of services and technologies that could/should be included in scope of project alternatives. Additionally, guidelines should be provided on how to define the reference project or "null-alternative" that will serve as the point of comparison. Along with guidelines regarding the scope of project alternatives, guidelines should be provided regarding the project boundaries; what defines "a project"?; which assets can be combined/clustered?: where does the project begin and end both in physical terms and in time?

IV. KPI definition / identification

The fourth dimension of a CBA methodology defines the different key performance indicators (KPIs) to assess for each project alternative. Each KPI will be valued (calculation or valuation method) through qualification, quantification or monetisation. This choice will affect the assessment framework. The KPIs will be set through understanding the cost and benefit impacts of the researched project alternatives. These impacts will be based on the different assets that make up each project alternative and the functionality and purpose of each project alternative.

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V. Assessment framework

After the definition of the KPIs, the fifth dimension of the CBA methodology will define the assessment framework. The assessment framework will depend on, and also define, the level of monetisation of the KPIs. The following must also be defined: the evaluation period of each project alternative and the method to evaluate costs and benefits over time. The assessment could include a financial analysis (NPV calculation), an economic analysis (monetization), a project scoring or a multi-criteria analysis.[9] In addition, guidelines could be provided regarding risk and sensitivity analyses, or guidelines on how to allocate costs and benefits of project alternatives to stakeholders involved. Guidelines on the interest rate and economic life, to be used for project comparison, could also be provided. The ENTSO-E methodology, for example, compares each project against one of two extreme baselines or reference grids. Projects can be included in the reference grid (and are subsequently assessed following the "take one out at a time", or TOOT principle), or excluded in the reference grid (and are assessed following the "put one in at a time", or PINT principle).

VI. Use of Tools

The sixth dimension of a CBA methodology consists of defining the tools with which the different KPIs will be determined. Guidelines should be provided regarding the type of models and calculation tools required and how to set up and develop models. These models could, for example, be network or market models for projects in the energy sector. The CBA methodology should clarify critical assumptions and implementation approaches to ensure all project alternatives will be evaluated under the same conditions.

VII. KPI assessment and scoring of projects

When all dimensions of the CBA methodology are defined, the CBA can be executed following the described guidelines. Within the assessment step, the KPIs will be determined for the various project alternatives. The obtained KPI values will result in a score for each project alternative for each KPI. A comparison of the different project alternatives can subsequently be performed based on a combination of the results of the KPI assessment. The CBA execution in PROMOTioN is part of WP12.2.

In the following chapters, the different dimensions of the CBA methodology will be defined and detailed with respect to a societal assessment of offshore grids.

[9] European Commission. “Guide to Cost-Benefit Analysis of Investment Projects”, 2014.

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4 REQUIREMENTS FOR A SOCIETAL CBA METHODOLOGY FOR OFFSHORE GRIDS

4.1 INTRODUCTION

The scope of the CBA methodology developed in this deliverable is indicated in Figure 4-1. Current established CBA methodologies mainly focus on the financial or societal CBA assessment of a "single project". Knowledge from existing CBA methodologies is used to develop a societal CBA methodology to model the complexity of an offshore grid system.

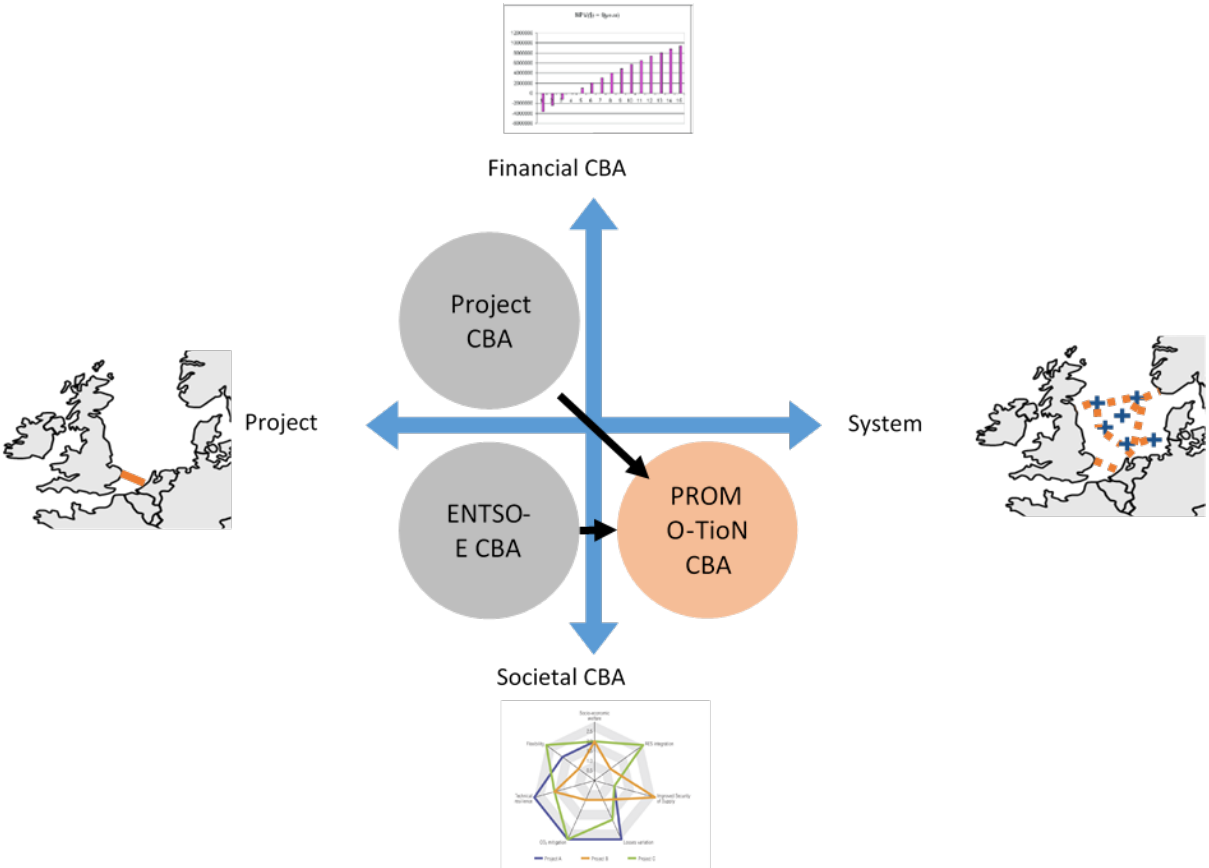

Figure 4-1: Scope of the CBA methodology in comparison with existing CBA methodologies.

Within PROMOTioN a societal CBA is most appropriate since:

- a (meshed) offshore grid is still in a preliminary study phase where the overall benefits and costs to society need to be assessed before moving towards a financial CBA;
- the goal of PROMOTioN is to study the development of societally optimal integration of offshore wind;
- a (meshed) offshore grid comprises cross-national electricity infrastructure of which its value to society needs to be valued before moving on to the specifics of a project CBA;

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- the starting point for the CBA methodology in PROMOTioN is 2nd ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects (6/09/2017) hereafter often referred to as the "ENTSO-E methodology", which is an SCBA.[10]

4.2 STARTING POINT

A literature review has been performed to investigate the requirements of a CBA methodology for offshore grids. The most important documents in this review are (see also References):

- 1st ENTSO-E Guideline for Cost Benefit Analysis of grid development projects and consultation reviews.
- 2nd ENTSO-E Guideline for Cost Benefit Analysis of grid development projects (version September 2017) and consultation reviews.
- ACER. "Opinion of the agency for the cooperation of energy regulators No 05/2017 – on the draft ENTSO-E guideline for cost benefit analysis of grid development projects", 2017.
- European Commission. "Guide to Cost-Benefit Analysis of Investment Projects", 2014.
- PROMOTioN deliverables: D1.3, D1.6, D7.3, D7.5.
- North Sea Grid study of the benefits of a meshed offshore grid in Northern seas region (NSOG), Directorate-General for Energy, 2014.

The starting point of the CBA methodology for offshore grids is the 2nd ENTSO-E Guideline for CBA of grid development projects. This methodology is applied to assess Ten-Year Network Development Plan (TYNDP) projects through a common CBA methodology and multi-criteria framework, to identify candidate *projects of common interest* (PCIs). PCIs often concern transmission interconnections between two countries. Although the evaluation of these projects can be complex, an offshore grid touches upon many more issues than a single transmission project. The current CBA methodologies are insufficient and limited in scope for the evaluation of complex systems, such as offshore grids.

The 2nd CBA methodology of ENTSO-E focuses on assessing the costs and benefits of projects in specific target years, rather than on assessing the costs and benefits during the development path over time of a system. The ENTSO-E CBA methodology focusses on relatively minor changes to the existing grid system and does not provide guidance for situations where a large and complex project is evaluated over time, nor guidance for the definition of offshore grid topologies.

In this deliverable, a CBA methodology will be developed to evaluate a complex system. The ENTSO-E CBA methodology will be used as the basis. First the limitations of this methodology for the evaluation of offshore grid systems are investigated. In addition, a gap analysis identifies the differences between the ENTSO-E methodology and the desired features of a CBA methodology for offshore grids.

[10] ENTSO-E, „2nd ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects“ (draft for review by European Commission), 6 September 2017.

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Within the PROMOTioN project, an initial gap analysis has already been performed in Deliverable D7.3.[11] This resulted in ten key guidelines for the implementation of a common methodology for a CBA. These guidelines are depicted in Table 4-1 below. The dimensions for which improvements should be made were highlighted in orange. Also, the dimensions that are of greater importance in the offshore context compared to onshore contexts, were marked. A remark has to be made here concerning the status of *calculation (6)*. For all three ENTSO-E methodologies (1st Guideline, 2nd Guideline, and market design) it was stated that an explicit model is available. Although general characteristics of the required models are given, details are not specific enough to consider the model as explicit, i.e. it does not provide the equations to use. In addition, a common discount rate is required to consistently evaluate projects within the European context. Finally, the ranking of projects within a societal CBA will not necessarily be based solely on monetisation (see also Section 5.7).

Table 4-1 Ten key guidelines for implementing a common method for cost benefit analysis as presented in the PROMOTioN Deliverable D7.3.

STATUS OF IMPLEMENTATION	ENTSO-E 1.0	ENTSO-E 2.0	ENTSO-E MARKET DESIGN (BALANCING)	SIGNIFICANTLY MORE IMPORTANT IN THE OFFSHORE CONTEXT?
INPUT(1) Project interaction must be taken into account in the project and baseline definition	One baseline (TOOT). Arbitrary clustering rules	One baseline (TOOT), ambiguous update of the clustering	Harder applicable but dealt with.	x
INPUT(2) Data consistency and quality should be ensured	TYNDP	TYNDP	TYDNP	
INPUT(3) Costs should be reported in disaggregated form	Not clear	Not clear	Not clear	x
CALCULATION(4) CBA should concentrate on a reduced list of effects	Reduced list	Reduced list	Reduced list	
CALCULATION(5) Distributional concerns should not be addressed in the calculation of net benefits	OK	OK	OK	
CALCULATION(6) The model used to monetize the production cost savings, and gross consumer surplus needs to be	Explicit model available	Explicit model available	Explicit model available	
CALCULATION(7) A common discount factor should be used for all projects	4 % for all	4 % for all	Uniform; aligned with TYNDP & PCI	
CALCULATION(8) A stochastic approach/scenario analysis should be used to address uncertainty	OK	The need is mentioned, but not specified how to apply the tools	OK	
OUTPUT(9) Benefits should be reported in disaggregated form	Not clear	Not clear	Regional and country effects should be reported	x
OUTPUT(10) Ranking should be based on monetization (opinion not shared by TenneT)	Multi-criteria analysis	Multi-criteria analysis, additional monetization of losses	Monetized ranking is suggested	x

[11] PROMOTioN D7.3: Intermediate Deliverable of WP7- Economic framework for offshore grid planning.

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4.3 GAP ANALYSIS

This section describes the gaps of the present CBA methodologies with respect to offshore grid systems. The gap analysis is performed for each dimension of the CBA methodology, as described in Chapter 3. These dimensions are once again shown in Figure 4-2.

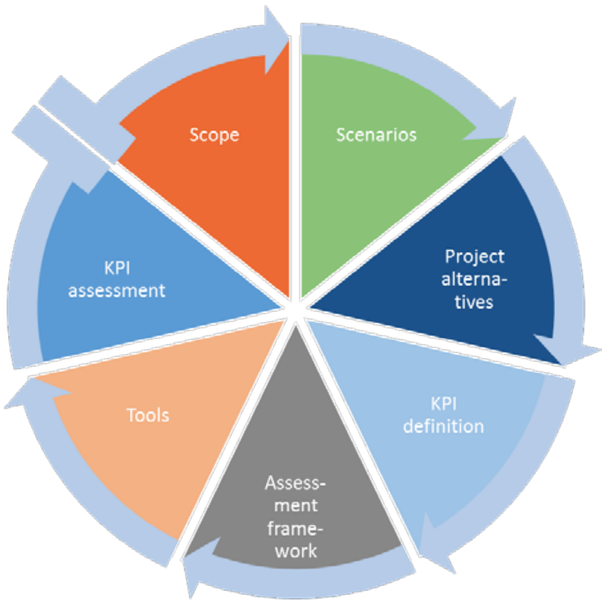

Figure 4-2: Dimensions of CBA methodology

I. Scope

The ENTSO-E methodology presents guidelines for a societal CBA to assess single projects. This is mainly focused on single transmission interconnections and storage projects of international relevance. For the PROMOTioN project the analysis covers a complex offshore multi-purpose system (see Figure 4-3). An offshore system is a cross-national complex project that connects generation and transmission assets, to enable the evacuation of offshore wind energy potential in the offshore area. The offshore grid system can also facilitate increased market integration between the countries connected to the meshed offshore grid. For offshore grids, this implies that the following items need to be incorporated in the CBA methodology:

- incorporate the complete offshore network in the form of project alternatives;
- consider, and where appropriate incorporate offshore wind farms in the scenarios and project alternatives;
- consider the two purposes that offshore systems fulfil: wind energy evacuation and market integration.

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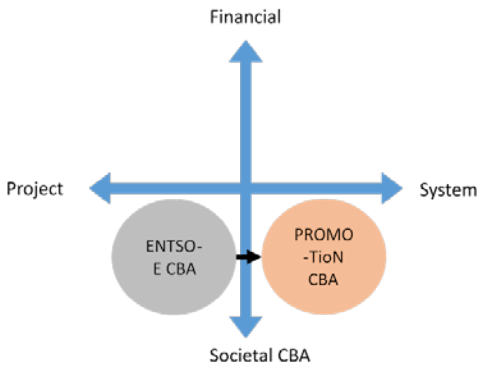

Figure 4-3: Scope of the CBA methodology used in PROMOTioN: single project vs. system.

II. Scenarios

The wider project scope (system rather than single project) requires a broader range of scenarios than currently foreseen in the ENTSO-E CBA. The ENTSO-E methodology provides guidelines for the development of scenarios for the European power systems, including the development of generation capacity (both on- and offshore) and demand. The ENTSO-E scenarios also include developments in the offshore area (e.g. offshore wind capacity) for each relevant country. However, within the scope of offshore grids, the development in the offshore area ("sea scenarios", see Section 5.3.1) will need to be redefined. Additional guidelines for specific "sea scenarios" are required to ensure a set of offshore scenarios that describes a credible but broad enough range of possible future developments in the offshore area. These *sea*-scenarios should be able to encompass the greater uncertainty that comes with offshore wind and offshore infrastructure developments, due to technical, economic and regulatory challenges. The main difference with the ENTSO-E CBA Guideline relates to the significant interdependency between the realisation of offshore wind capacity as assumed in these "sea scenarios", and the successful development of an offshore grid. The scenario assumptions with regard to installed generation capacities for wind energy for both on- and offshore are influenced by the transmission project. This is not necessarily reflected in the context of, e.g., ENTSO-E's TYNDP. The following needs to be incorporated:

- Guidelines for sea scenarios that describe the development of offshore wind capacity in the offshore area.

III. Project alternatives

Contrary to the projects treated in the ENTSO-E methodology, where single projects are the subject of assessment, the offshore grid concerns a conglomerate of single projects in a multi-purpose complex system that develop over time. Project alternatives of offshore grids are different complex topologies that each consist of multiple single projects. Clear boundaries (in space and time) need to be set to define the framework within which these complex project alternatives should be assessed. Additionally, the scope and range of technologies and sectors that have to be considered in the different project alternatives should be detailed (see Chapter 5.4). These include technologies and sectors that are not yet covered in the ENTSO-E methodology in the context of

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offshore grids, such as gas networks for evacuation of offshore wind energy or hybrid networks combining transmission infrastructure and large scale storage.

IV. KPI definition/identification

Comparing systems might require different KPIs and different valuation methods for KPIs than when comparing single projects. The following questions need to be addressed in the context of offshore grids:

- Are the KPIs presented in the ENTSO-E methodology relevant for offshore grids?
- What additional KPIs do we need?
- Do we need a different description/valuation of (some of) the KPIs of the ENTSO-E methodology?
- How does the system develop over time (potentially spanning multiple decades)?

In Chapter 6, the individual KPIs will be discussed in more detail. A definition of each KPI will be provided along with an explanation of its assessment and analysis. A decision needs to be taken for each KPI whether it can/should be quantified or not and, if quantified, whether it can/should also be monetised (see section 5.6 and Chapter 6).

V. Assessment framework

The assessment framework describes how to execute the CBA in terms of assessment and analysis. Clustering of investments and also the TOOT and PINT[12] approaches are less relevant when assessing the development of complex systems over time, in contrast with the ENTSO-E CBA Guideline. The assessment framework described in the ENTSO-E CBA methodology focuses on the contribution of a transmission or storage project in comparison to a reference network. This approach does not meet the needs when assessing complex offshore systems with regard to the aspect of development over time. Where a single project has a rather fixed point in time for commissioning, a complex system like an offshore grid will be under development over the course of time. This needs to be taken into account in the assessment. Also, the reference or *null-alternative* for the comparison of project alternatives cannot simply be the reference system with or without the project (cfr. TOOT or PINT), but should reflect a business-as-usual development in the offshore area.

As already highlighted in Table 4-1, none of the reviewed CBA methodologies provides clear guidelines on cross-border cost allocation (CBCA) of the infrastructure. A decision thus needs to be made whether or not it is necessary from a societal point of view to disaggregate costs and benefits between each/surrounding states and how to do this. Chapters 5 and 6 will investigate this where appropriate.

VI. Tools and use of tools

For the assessment of the KPIs (cost, benefits, etcetera), tools will be used. These tools may be (partly) the same tools as those proposed by the ENTSO-E CBA methodology and will be mainly geared towards market modelling and network modelling. In the CBA methodology, the kind of tools to be used will be described as well as how to use these tools. The gap lies more in the use of tools than in the tools itself, as described in Section 5.5. For the market modelling, an offshore area needs to be incorporated to capture the costs and benefits,

[12] The ENTSO-E methodology compares each project against one of two extreme baselines or reference grids. Projects can be included in the reference grid (and are subsequently assessed following the "take one out at a time", or TOOT principle), or excluded in the reference grid (and are assessed following the "put one in at a time", or PINT principle).

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including the arrangement of (virtual) bidding zones. For the network modelling, boundaries need to be set on the interaction with the onshore grid.

VII. KPI assessment

The KPI assessment is based on the assessment framework, the agreed tools and the use of tools. The gap analysis for the KPI assessment has in fact already been addressed in the gap analysis of the assessment framework. Table 4-2 summarises the gaps discussed.

Table 4-2: Summary of gaps in current CBA methodologies with respect to offshore grids, for each dimension of the CBA methodology.

Dimension	Main gaps
Scope (Section I)	- Incorporate the complete offshore network (complex system) in the form of project alternatives; - Consider, and where appropriate incorporate, offshore wind farms in the scenarios and project alternatives; - Consider the multiple purposes of wind energy evacuation and market integration.
Scenarios (Section II)	- Guidelines for specific sea scenarios that describe the development of offshore wind capacity in the offshore area.
Project alternatives definition (Section III)	- Clustering of long-term, complex projects (project vs system CBA). - Scope of boundaries, technologies, sectors to be used and evaluated in offshore grid projects. - Consider gas networks for evacuation. - Consider energy storage as part of the system.
KPI definition/identification (Section IV)	- What additional KPIs do we need? - Do we need a different description/valuation of (some of) the KPIs of the ENTSO-E methodology? - How does the system develop over time (potentially spanning multiple decades) - What is the degree of monetisation of KPIs?
Assessment framework (Section V)	- Project assessment framework inappropriate (timeline + baseline). - Reference/base vs. Null alternative.
Tools (Section VI)	- Market modelling of the offshore area to capture costs/benefits. - Boundaries of the network model (onshore grid).
KPI assessment (Section VII)	- See assessment framework.

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5 CBA METHODOLOGY AND ASSESSMENT FRAMEWORK FOR OFFSHORE GRIDS

5.1 INTRODUCTION

This Chapter defines the level of complexity, assumptions and choices that have to be made in order to facilitate the finalisation of a societal CBA methodology for offshore grids. Since the CBA methodology developed in this task will be executed in WP12, the discussion in this Chapter will focus on both an **ideal** as well as a **practical CBA methodology**. From *an ideal point of view*, the developed CBA methodology should be applicable for a broad range of projects and should have a great level of detail for each dimension to accurately capture all possible effects and developments of offshore grids. From a *practical point of v*iew, however, to ensure the practical feasibility of the execution of the CBA within the PROMOTioN project, assumptions and simplifications will need to be made compared to the ideal CBA methodology. The extent of these assumptions and simplifications will be extensively discussed in the following sections for the different dimensions of the CBA methodology.

The discussion will focus on the project of a meshed offshore grid in the North Seas, as will be assessed under the PROMOTioN project. Since this project regards cross-national multi-purpose energy infrastructure, a societal CBA methodology will be developed. However, the discussion and methodology could be applied on offshore energy networks more generally.

Decisions and choices, covering the different dimensions of the CBA methodology (see Figure 3-1), are made in the following six sections regarding:

I. the scope of the project and CBA methodology (section 5.2);
II. the scope and context of the scenarios (section 5.3);
III. the extend and definition of project alternatives (section 5.4);
IV. the use of tooling to determine KPIs (section 5.5);
V. the definition of the KPIs (section 5.6), and
VI. the characteristics of the assessment framework (section 5.7).

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5.2 SCOPE OF THE PROJECT AND CBA METHODOLOGY

Table 5-1 summarises the three options one must choose from when deciding on the scope of a CBA analysis and shows the increasing levels of complexity belonging to dimension I: scope of the project and CBA methodology. The different choices and options will be detailed in the following sections.

Table 5-1: Summary of options and choices within the scope of the project and methodology.

Activity	Choices	Options → *Complexity*			
CBA	1	Value to society	Value to each (surrounding/North Sea) state	Value to society **&** each (surrounding/North Sea) state	Value to all stakeholders
	2	Non-monetised CBA	Augmented CBA (hybrid)	Financial CBA (full monetisation)	
Purpose of project	3	Offshore grid for evacuation of wind	Offshore grid for evacuation of wind ***& market integration***	Offshore ***& onshore*** grid for evacuation of wind	Offshore ***& onshore*** grid for evacuation of wind ***& market integration***

5.2.1 CHOICE I: PURPOSE OF THE CBA METHODOLOGY

An **initial choice** to be made is "what" value the societal CBA should assess. This value could be the value to society (in case of the offshore grid in the North Seas: Europe), the value to the countries directly surrounding the offshore grid, both the value to society as a whole and the surrounding countries, or even the value of the project to all stakeholders that could be involved in the project (TSOs, governments, consumers, …).

From an ideal perspective, the CBA methodology should be able to assess the value of the project to society as a whole, since the CBA methodology developed in this task is a societal CBA. If the offshore grid project would add value to society, the decision should be to proceed with the project. Subsequently, financial CBAs on specific single projects within the offshore grid system and cross-border cost allocation analyses could be used to determine who will pay for the system and how the system will be financed. The latter two would come in a later stage, after the societal CBA proved to be positive to society. Incentives to build offshore grids (legislative measures, permitting, subsidies, etc.) should namely only be provided if the construction is desirable from a societal perspective.
From a *practical perspective*, the CBA should be able to assess both the value of the project to society, and possibly - in the light of practical implementation - some indication of the value to the main stakeholders involved (e.g. countries surrounding the offshore grid). This would enable the study to assess whether the

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project would be beneficial to society and how the costs and benefits could relate to the countries directly affected by the project (i.e. in which territory direct project-related assets will be built). In contrast, to assess the value to all involved stakeholders, would not add much benefit to the decision-making process in this stage of the project and would introduce too much complexity for the practical assessment. In the practical methodology, the focus relates to the total value to society first to then potentially propose an idea on how to disaggregate benefits, if relevant.

Decision

- **Ideal:** Value to society.
- **Practical:** Value to society and possibly an indication of the value to key member states surrounding the offshore grid, if relevant.

5.2.2 CHOICE II: TYPE OF CBA

A **second choice** to be made regards the type of CBA methodology to be used in the context of offshore grids. The type of CBA methodology could be a full financial CBA, where all KPIs are quantified and monetised and an NPV calculation will result in the identification of the "best" project alternative. However, since also societal indicators should be analysed to assess the total value to society of offshore grids, not all indicators can potentially readily be quantified or even monetised in an objective way. Additionally, monetisation could also not be relevant to certain KPIs. To enable transparent comparison between project alternatives, the different KPIs should be clear, simple and objective (see section 5.6).

Adding monetisation factors to certain quantified KPIs might be a very subjective process. For example, to assess security of supply, the expected energy not served [MWh] could be determined as KPI. To monetise the latter, a monetisation parameter has to be determined, e.g. Value of Lost Load [EUR/MWh]. Defining the value of lost load is in the absence of comprehensive, well-understood, and incontrovertible values, a rather subjective process, which might lead to biases towards certain project alternatives. To mitigate the issue of non-objective monetisation of KPIs, an augmented CBA could be used, which uses both monetised and non-monetised (quantitative and/or qualitative) indicators where appropriate and relevant. A full non-monetised CBA will only have various quantitative and qualitative non-monetised indicators. The identification of the "best" project alternative becomes here less straightforward and might be possible through some form of multi-criteria analysis or a comparison through a spider chart (see Section 5.7). The former would require assigning weighting factors to the different KPIs, which again is a subjective process. The latter would enable the project sponsor or involved stakeholders to perform a comparison between projects depending on the KPIs they value the most.

Monetisation leads to a straightforward comparison between project alternatives. However, the approach to monetise various indicators might not be objective or relevant as various assumptions and biases would be required in setting parameters for monetisation. In contrast, the identification of the "best" project alternative becomes less straightforward in augmented CBAs. Full monetisation is therefore the *ideal* to enable objective project comparison, on the condition that objective monetisation parameters can be established and that it is relevant to monetise all KPIs. However, monetisation is more complex and subjective in regards to identifying appropriate parameters. From a *practical* perspective, comparing indicators in their respective units (either monetised or non-monetised) enables a more objective valuation of projects.

Decision

- **Ideal:** Financial or augmented CBA depending on objective monetisation parameters and relevance.
- **Practical:** Augmented CBA.

5.2.3 CHOICE III: PURPOSE OF THE PROJECT

A **third choice** to be made is what the purpose of each project alternative is, i.e. the purpose to the overall energy system that needs to be fulfilled by each considered project alternative. This purpose needs to be defined in order to facilitate the remaining dimensions of the CBA methodology. Comparison between alternatives is eased by the definition of an unambiguous purpose for the offshore grid. However, an offshore grid will have per definition several purposes: the evacuation of the offshore wind energy in the area and market integration. This dual purpose should be captured in both the ideal CBA and the practical CBA. Note that the definition of project alternatives must then be based on a common methodology, to allow a fair comparison.

Decision

- **Ideal:** to evacuate the planned offshore wind energy in the offshore area *and* to increase market integration.
- **Practical:** to evacuate the planned offshore wind energy in the offshore area *and* to increase market integration.

5.3 SCOPE AND CONTEXT OF THE SCENARIOS

Table 5-2 summarises the options and level of complexity belonging to dimension II: scope and context of the scenarios for the CBA assessment. The different options will be detailed in the following section.

Table 5-2: Summary of options and choices within the scenarios used for project comparison.

Activity	Choices	Options	→ *Complexity*	
Offshore development (sea scenarios)	1	One scenario of capacity and location	One scenario of capacity ***with multiple locations***	***Multiple scenarios of capacity and locations***

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The CBA methodology should provide guidelines regarding the minimal number of scenarios under which to assess each project alternative to obtain a “no-regret” analysis under possible futures. Additionally, the type of scenarios and the parameters to be defined in each scenario should be detailed in the CBA methodology. The selection of scenarios should be appropriate to reflect the full range of possible future developments to ensure the projects are compared in an objective manner. It is important to ensure that the choice of scenarios does not bias towards a certain project alternative: for example, selecting a set of scenarios with a high set of growth scenarios for offshore wind capacity, in comparison to a central or moderate scenario, might favour the development of meshed offshore grids as compared to a business-as-usual or a delayed growth in offshore wind capacity.

To assess offshore energy infrastructure - that has as one of its main purposes to evacuate offshore wind energy, scenarios are needed to analyse different options for onshore market development, including the evolution of onshore generation mix and an assessment of demand in the different countries that are connected into the meshed offshore grid. Existing market scenarios might also describe the evolution in offshore wind energy capacity for the different researched countries. However, this scope of offshore development needs to be reassessed to ensure that the offshore scenarios cover an appropriate bandwidth of likely growth of offshore wind in the offshore area. Offshore scenarios are to an extent a “subset” of the onshore scenarios. Therefore, both onshore and offshore market scenarios will need to be defined to assess offshore energy infrastructure under an appropriate range of scenarios (see Table 5-3).

Table 5-3: Distinction between land and sea scenarios.

Scenario	Key parameters	Sources
Land	Installed capacities (RES, Conventional,…), demand, fuel prices, fuel mix, interconnections …	IEA, DNV GL ETO, ENTSO-E,…
Sea	Offshore wind *capacity*, offshore other technology capacity, *location* of offshore capacity	National/international plans

- **Onshore scenarios**, or “land scenarios”, describe, amongst others, the evolution of the capacity in generation mix, demand, fuel prices and interconnections for the researched countries. An example of land scenarios are the provisional ENTSO-E TYNP2018 scenarios that describe three alternative development paths. Typically, the range of possible land scenarios will be described along axes that reflect contrasting evolutions, for example, high – central/moderate – low growth in renewable energy, central – decentral, or combined policy – individual policy.
- **Offshore scenarios**, or “sea scenarios”, describe the evolution in *capacity* of offshore wind in the offshore area over *time* through, for example, high, moderate/central and low wind capacity scenarios. Additionally, the *technologies* used for offshore wind parks and the *location* of the offshore wind capacity should be defined. Care should be taken to ensure that the selected offshore scenarios are

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project-independent as to not create a bias towards a certain grid configuration. For example, offshore scenarios that have major offshore wind clusters close to shores might favour radial connections (see Figure 5-1, right). Offshore scenarios with a high concentration of wind clusters in the far-shore region might favour meshed and high-voltage direct current (HVDC) topologies (see Figure 5-1, left). A good range of offshore scenarios to assess the different project alternatives is therefore desirable.

Figure 5-1: Possible locations of wind parks in sea scenarios. Left: cluster of wind parks between countries; right: dispersed wind parks between three countries.

A decision will need to be made regarding how to represent the evolution in *onshore grid* infrastructure to ensure the necessary infrastructure upgrades are met that are required to accommodate the growth in offshore wind energy. This is required for the reference or business-as-usual onshore grid development for the range of onshore grid development scenarios and how to take into account the associated cost of reinforcement. The onshore grid development will be touched upon throughout the subsequent sections, where relevant.

5.3.1 CHOICE I: SCOPE OF OFFSHORE ("SEA") SCENARIOS

An **initial choice** to be made is what the scope and extent will be of the offshore scenarios under which the different project alternatives will be evaluated. Complexity will be added by varying each of the characteristics of an offshore scenario:

i. The development of foreseen *capacity* of offshore wind energy in the offshore area *over time*;
ii. The development of the *location* of the offshore wind capacity in the offshore area *over time*; and,
iii. The *technologies* used for each capacity and location combination of offshore wind.

In the *ideal CBA methodology*, sufficient variation is desired in the selection and the combination of each of the three above characteristics. This implies a set of evolutions of offshore wind capacity in the offshore area over time: for each evolution in capacity in time, a set of different locations in the offshore area, and for each combination of capacity and location evolution, multiple technology combinations of wind parks (floating, ….), see Figure 5-2.

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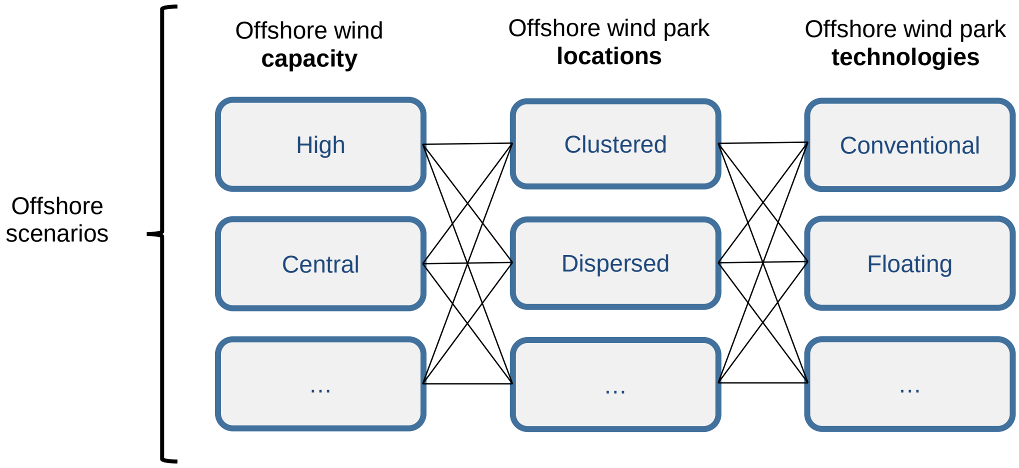

Figure 5-2: Combination of characteristics to build offshore/sea scenarios.

In the *practical CBA methodology*, a certain variation is desired in the selection and the combination of each of the above three characteristics. However, each additional variation will add to the complexity of the CBA execution. If three variations in each characteristic would be selected, this would result in 3*3*3 offshore scenarios that then still would need to be combined with variations in onshore/land scenarios. The predicted growth of wind capacity in the offshore area will need to be located in the researched area. This considered area will most likely be constrained due to a combination of, amongst others, shipping routes and Natura 2000 areas. The likelihood of finding different alternative locations for each capacity evolution will be a difficult exercise with high levels of offshore wind energy towards 2050. Moreover, in practice, certain wind turbine technologies might be more appropriate in the far-shore area, compared to the near-shore area. A variation in technologies of wind turbines might therefore not add much value to the assessment. To contain the complexity in the practical assessment process, the offshore scenarios could be limited to a selection of at least three scenarios of wind capacity (high – central – low) in the offshore area, with each scenario having a defined evolution in location and technologies. These evolutions could be set as the most logical and appropriate selection for each capacity evolution/development.

In order for transparent comparison between project alternatives, each compared project alternative should connect the same capacity of offshore wind energy over time as determined by the selected offshore scenarios. However, the location of the wind farms, and thus the yield, could depend on offshore grid topology; radial connections might only be feasible for near-shore wind farms where different wind profiles occur than in the far-shore region.

Decision

- **Ideal:** Multiple scenarios of offshore wind capacity over time, with different locations and technologies.
- **Practical:** Multiple scenarios of offshore wind capacity over time (at least three: high – central – low) with a common selection of most appropriate location and technologies.

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5.4 EXTENT AND DEFINITION OF PROJECT ALTERNATIVES

Table 5-4 summarises the options, choices and level of complexity belonging to dimension III: extent and definition of project alternatives that will be evaluated through the CBA assessment.

Table 5-4: Summary of options and choices within the definition of project alternatives.

Activity	**Choices**	**Options** →			*Complexity*
Scope of alternatives	1	Electricity network	Electricity network, ***including storage***	Electricity network, including storage ***and P2X options***	Electricity network ***and gas network,*** including storage and P2X options
Boundaries	2	Offshore grid, including onshore and wind park connection points	Offshore grid ***and wind parks***	Onshore grid ***and offshore grid***	Onshore grid, offshore grid and wind parks
Onshore infrastructure development	3	Assume onshore grid reinforcement is similar for all offshore grid alternatives.	Simplified onshore infrastructure cost	Full development and reinforcement needs onshore	
Project alternatives	4	Optimised radial AC	Optimised radial AC and DC	Optimised meshed DC	Hybrid radial/meshed
Null alternative	5	Base case	Null-alternative		

Chapter 2 provided a definition for “a project”. A project in the context of the offshore grid is defined as a complex system used for the evacuation of offshore wind energy and market integration. With the CBA methodology, different (technical or conceptual alternatives) alternatives of this project will be evaluated to decide on the “best” solution to fulfil the defined purpose(s). Project alternatives are thus choices of different topologies and technologies for offshore infrastructure.

To determine the different project alternatives, a set of guidelines is required that details the scope of technologies and sectors that can/should be considered in setting up a wide enough range of project alternatives to ultimately obtain the “best” overall solution for society. The geographical boundaries common to all project alternatives need to be defined. Finally, the base-line needs to be defined that will serve as a reference for project comparison. These different decisions/choices regarding project alternatives are detailed in the following sections.

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5.4.1 CHOICE I: SCOPE OF SECTORS COVERED BY PROJECT ALTERNATIVES

The **initial choice** to be made is what the scope and extent will be of the different sectors and technologies that can be covered by the selected project alternatives.

From an *ideal perspective*, a range of project alternatives should be considered that covers a complete and broad spectrum of plausible sectors and technologies that can be considered in offshore infrastructure to evacuate offshore wind energy. This can range from only focussing on electricity grids with technological variations (AC, HVDC, meshed, radial, hybrid) to also considering offshore electrical storage alternatives, to not only looking at electrical solutions but also the power-to-gas infrastructure alternatives. The latter could be an alternative that converts wind energy offshore to gas, which could then be evacuated through the use of pipelines or shipping alternatives. For each topology, various technology combinations should then be evaluated as project alternatives to assess not only the “best” topology (e.g. radial, meshed, hybrid, …), but also the “best” implementation in terms of technologies (e.g. AC, HVDC,…) of each topology.

From a *practical perspective*, the scope of the above sectors would lead to a very complex CBA execution. Additionally, PROMOTioN’s main objective is to research the different topology options of meshed HVDC grids in the offshore area. Hence, the scope of alternatives will be limited in the practical CBA methodology to possible alternatives of offshore electricity infrastructure topologies. Additionally, each topology alternative will not be evaluated under various technology implementations due to the complexity in analysis. For each topology, a suggestion will be made of the most appropriate (combination of) technologies for its implementation and assessment.

Decision

- **Ideal:** Project alternatives of possible electricity networks, gas network, including storage and P2X options.
- **Practical:** Project alternatives of possible topology options of electricity networks with each the most appropriate implementation of (combination of) technologies.

5.4.2 CHOICE II: GEOGRAPHICAL BOUNDARIES OF THE PROJECT

The **second choice** to be made relates to the geographical boundaries of the project, i.e. where does the offshore infrastructure begin and end? The geographical boundaries of the project will determine the complexity of the CBA execution and KPI assessment. Developing infrastructure in the offshore area to evacuate a high amount of wind energy will result in costs for society, not only in building the offshore infrastructure, but also the costs related to the development and installation of wind parks *and* the reinforcement of the onshore grid to ensure that the wind energy will reach load centres.

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From an *ideal perspective*, all the above should be taken into account in setting the different project alternatives. However, the full reinforcement needed for the onshore grid is beyond the scope of PROMOTioN. Furthermore, SCBAs in the energy sector have been focussing on transmission infrastructure (regulated asset base is paid for directly by consumers) rather than generation. Therefore, wind parks will not be considered part of the practical project alternatives. From a *practical perspective*, a geographical project scope comprising the whole onshore grid reinforcement is not feasible due to complexity. Electricity infrastructure and generation assets are typically driven by different investment patterns (regulated assets vs. privatised). Therefore, the practical CBA methodology will have as boundaries for each project alternative the connection point with offshore wind parks and the closest, most appropriate, connections in the near-shore area with the onshore grid.

Decision

- **Ideal:** The project alternatives encompass the offshore infrastructure, including wind parks, and the whole onshore grid.
- **Practical:** The project alternatives encompass the offshore grid infrastructure, including connection points with wind parks and the near-shore onshore grid.

5.4.3 CHOICE III: EXTENT OF CONSIDERATION OF ONSHORE GRID REINFORCEMENT

Apart from onshore and offshore scenarios that describe the evolutions in the market, also a decision will need to be made regarding how to represent the evolution in onshore grid infrastructure to ensure the necessary infrastructure upgrades/reinforcements required to accommodate for the growth in offshore wind energy (see Figure 5-3). A **third choice** relates to the second choice, namely the extent to which the onshore grid will be considered.

From the *ideal perspective*, the full development and reinforcement needs of the onshore grid to take on all offshore wind energy and transport it to load centres, should be considered to provide a clear and complete picture of the costs and benefits that will be raised by the offshore grid project. This would involve a full planning exercise of the European transmission network to assess the value of an offshore grid to Europe.

However, from a *practical* point of view this is not achievable with the currently available modelling tools. Given the large need of offshore infrastructure and the high level of wind energy that needs to be evacuated to the onshore load centres in each project alternative, the reinforcement need of the onshore grid is expected to be significant regardless of project alternative.[13] Also, the onshore grid is assumed to be very similar for all project alternatives. Differences may be aligned by specific measures or investments. A practical assumption could therefore be that the costs for onshore grid reinforcement will likely be in a similar order of magnitude across all project alternatives. This is a reasonable assumption if the landing points of the offshore grid are similar across the topologies. The difference in onshore grid reinforcement costs between project alternatives could thus be

[13] This Deliverable looks at the value to society as a whole. When one would look at how costs would compare for individual countries, different project alternatives might favour more development (and thus costs) of the onshore grid in a particular market. However, this is beyond the scope of the societal CBA methodology

neglected for the practical assessment (see also section 5.6). The onshore grid reinforcement needs will be considered to the nearest onshore substation that has an appropriate hosting capacity.

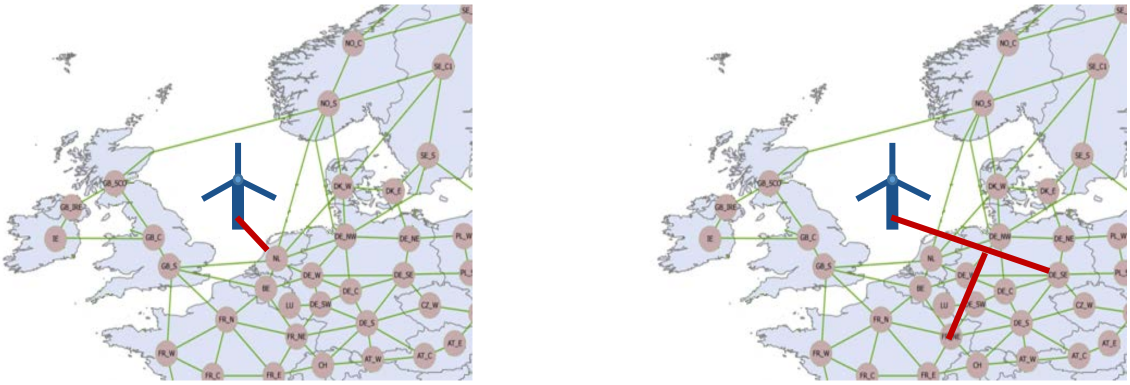

Figure 5-3: Simplified representation of possible boundaries of the offshore grid: untill the first substation onshore (left), further reinforcement of the onshore grid (right).

Decision

- **Ideal:** Full development and reinforcement needs onshore grid.
- **Practical:** Assume onshore grid reinforcement is similar for all offshore grid alternatives if connections are made with appropriate substations (with hosting capacity). The difference in costs for grid reinforcement between project alternatives can thus be neglected.

5.4.4 CHOICE IV: SCOPE OF TECHNOLOGIES

The **fourth choice** relates to the types of technologies that should be evaluated within project alternatives. In the *ideal* case, a set of different network topologies (meshed, radial, hybrid) should be evaluated, each under multiple considered technology implementations of grid technologies (AC, HVDC, hybrid, …). This will lead to a large number of project alternatives (topology x technologies) to ensure a full comparison of possible project alternatives is made with the CBA.

In *practice*, however, certain combinations between network topologies and technologies are less likely than others. Therefore, to reduce complexity in the practical analysis, a set of project alternatives (topologies) with each a single technology implementation will be assessed from a practical perspective. Each project topology will then consist of the most appropriate (combination of) grid technology(ies).

For each combination of topology and technologies for the *ideal perspective* different protection schemes should be considered to determine the most cost-effective operation of the network. The protection schemes are analysed within WP4 of PROMOTioN. Given that the extent of the analysis of different protection schemes on the full offshore infrastructure of each project alternative is a very complex exercise, the protection schemes will

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only be included from a cost-perspective in the *practical* CBA (see Chapter 6). It will be assumed that each project alternative will adopt the most appropriate protection scheme for its topology and grid technologies. The protection scheme and related costs are seen as part of each project alternative. The most appropriate protection scheme for each offshore grid concept is expected to be obtained from WP4.5.

Decision

- **Ideal:** Each project alternative has a different topology with multiple variations in grid technologies.
- **Practical:** Each project alternative has a different topology with a single most appropriate selection of grid technologies.

5.4.5 CHOICE V: REFERENCE BASE BETWEEN PROJECT ALTERNATIVES

The **final choice** to be made in relation to the reference of comparison between project alternatives. As will be detailed in section 5.7.1, the PINT and TOOT approaches of project comparison with respect to a base-case are not appropriate in the context of system CBAs, which deals with the long-term development of offshore transmission capacities over time rather than the marginal benefit of individual projects at a given moment of time. Therefore, each (system) project alternative will be compared to a business-as-usual (BAU) development of the offshore area.

The BAU development of the offshore area will be the "null-alternative" of development, using only existing established technologies, i.e. radial connections of wind farms with AC interconnectors (see for example, Figure 5-4). Given that the purpose of the offshore network is to both evacuate offshore wind energy and increase market integration, interconnectors could be part of the null-alternative. The null-alternative project assessment will be adopted in both the ideal and practical CBA methodology.

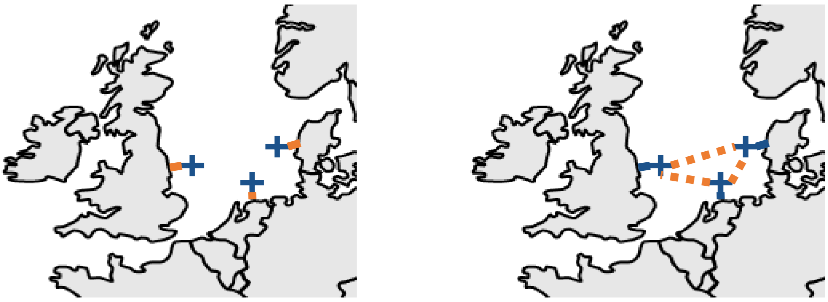

Figure 5-4: Schematic example of a null-alternative (left) and one project alternative (right) between countries for a certain sea scenario.

Decision

- **Ideal:** Null-alternative
- **Practical:** Null-alternative

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5.5 USE OF TOOLING TO DETERMINE KPIS

Several tools are required to enable the valuation of the different KPIs (see Chapter 6) for each project alternative. These tools include market and grid models of the area under research. These models use scenarios and other assumptions to model a certain geographical area. Depending on the implementation aspects and assumptions, the results of simulations, and hence the KPIs, might differ. It is therefore important to provide guidelines on how to set up these models. Additionally, choices also will affect the ability to disaggregate costs and benefits that will be determined with the models.

Market models will evaluate the exchanges, generation dispatch, unit commitment, and local price formation processes whilst minimising variable generation costs. Network models will evaluate the behaviour of physical network flows. The main focus of the choices in this section is the market model. Network models focus on common criteria to evaluate the network, including the effect of contingencies through load flow analysis, short circuit analysis and stability analysis. For these studies, several criteria need to be identified to assess the consequences of events. The use of network models to determine KPIs is detailed further in Chapter 6. Table 5-4 summarises the choices and level of complexity belonging to dimension IV: tools to determine the KPIs.

Table 5-5: Summary of choices and options within the tools to determine the KPIs.

Activity	Choices	Options			*→ Complexity*
Scope onshore market model	1	Zonal (per bidding zone)	Zonal market (per BZ) with nodal redispatch.	Nodal	
Scope offshore market model	2	Zonal in current national bidding zones	One appropriate market design per project alternative	Multiple market designs per project alternatives	Nodal
Region	3	States surrounding the North Sea network	Europe	European countries + borders	

5.5.1 CHOICE I: GEOGRAPHICAL SCOPE OF ANALYSIS (REGION)

An offshore grid is not a single cross-border project but a combination of internal and cross-border projects with significant multiple cross-border impacts. An **initial choice** needs to be made related to the scope of the region that is analysed for the assessment of KPIs. The region could be limited to countries that border the offshore area and have a direct connection with the offshore grid. However, the effects of the offshore grid could have an impact on the countries that have a connection with a country that has a connection to the offshore grid but that do not have a direct connection themselves. Additionally, in the context of the societal CBA the value to society

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needs to be determined. For an offshore grid in the North Seas the costs and benefits should be evaluated to the European energy system (see section 5.2). In practice, the energy system of the Europe has a large number of connections with surrounding countries beyond European borders. Therefore, as a minimum in both the ideal and practical CBA methodology, society should be defined at the start of the CBA methodology potentially with the consideration of any surrounding connections.

Decision

- **Ideal:** Society as a whole plus any further connections if relevant (Europe (+))
- **Practical:** Society as a whole plus any further connections if relevant (Europe (+))

5.5.2 CHOICE II: SCOPE OF ONSHORE MARKET MODEL

A **second choice** to be made regards the scope and level of detail of the onshore market model. Indeed, the way the power dispatch is simulated in the CBA must be in line with what will actually happen, in order to obtain meaningful results. Power markets are currently organized in Europe on a zonal basis. For that reason, market models used to estimate the benefits brought by transmission projects of international importance in Europe (e.g. projects gathered in the TYNDP) are typically based on a zonal representation of the power system, consisting of different bidding zones, where each zone is seen as a "copper plate" without internal congestions. Each bidding zone is connected to other bidding zones with net transfer capacity (NTC) exchange possibilities. Note that exchange possibilities between different bidding zones can also be considered through a flow-based approach when relevant. In a zonal market model, each bidding zone in the onshore area could thus be represented by a single node. A major limitation of such a zonal market model is its inability to value the impact of a transmission project on congestions within a bidding zone, i.e. its impact on internal redispatch needs. This is not an issue when a transmission project impacts mainly transfer capacities between different bidding zones, but it could be irrelevant to adopt a zonal market model to estimate the benefits of internal grid reinforcements. Consequently, the zonal market model can be complemented by a nodal implementation of the transmission system where appropriate and enable the simulation of redispatch within bidding zones.

From an *ideal perspective*, implementing a zonal market model complemented by a representation of the internal redispatch at a nodal level could be beneficial to assess the full impact of offshore transmission projects. However, given that bidding zones are already set to reflect the main congestions and that the amount of offshore wind energy to evacuate in the different project alternatives is the same, internal congestions are not expected to be a discriminant factor for the project alternatives. Consequently, from a *practical perspective*, a zonal onshore model will provide enough detail.

Decision

- **Ideal:** Zonal market (per BZ) with nodal redispatch.
- **Practical:** Zonal (per BZ).

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5.5.3 CHOICE III: SCOPE OF OFFSHORE MARKET MODEL

A **third choice** involves the scope of the offshore market model. The governing market design and bidding zone configuration is important to the results of the CBA, as the governing market design impacts certain KPIs. The governing market design and in particular bidding zone configuration will impact the development of the grid and operational strategies. The latter two impact in their turn the development, topology and operational strategy of offshore grid alternatives and the value of their KPIs. The choice of bidding zone configuration influences the KPIs and the disaggregation of benefits. Note that any political considerations regarding market design are beyond the scope of this task.

Bidding zones within the current European power system are largely defined along national borders. Offshore wind parks can bid in to the market of the country in which territory they are located in. However, in some offshore grid topologies it might make more sense from an economic and societal point of view to change this configuration model either virtually or in practice. The market design might require changes depending on the considered offshore grid topology. However, the offshore grid topology that will be realized will most likely depend on the governing market design. There is a “chicken-or-egg” problem (see Figure 5-5) in that they are interdependent on each other.

Ideally, each project alternative should be assessed under different (virtual) bidding zone configurations to assess the impact on KPIs. Bidding zones configurations could also be part of offshore scenarios. To capture the full offshore behavior, a full nodal model could be used to implement the offshore area. However, there are no demand centres in the offshore area and unrealistic offshore price dynamics could occur in this way.

From a *practical* perspective, this will lead to a very large number of potential configurations, which are not all relevant or likely to materialise for certain project alternatives. Therefore, a practical assumption has been made to select project alternatives based on the location of wind farms and hosting capacities of the onshore grid. For each project alternative can then be decided what an appropriate (virtual) bidding zone configuration could be to return most benefit from the offshore grid and to reflect internal bottlenecks. In order to capture the right KPIs and potential disaggregation of indicators, multiple (virtual) bidding zones might be required. These (virtual) bidding zones do not necessarily need to correspond with national territories and do not have to be a recommendation for offshore market design. For example, the choice of (virtual) bidding zones could, follow from flow-based analysis in the offshore area to capture the restrictions in the offshore grids and clusters of wind capacity. The virtual bidding zones could therefore be different for each project alternative.

Decision

- **Ideal:** Each project alternative valued under various market designs.
- **Practical:** For each project alternative, one appropriate market design.

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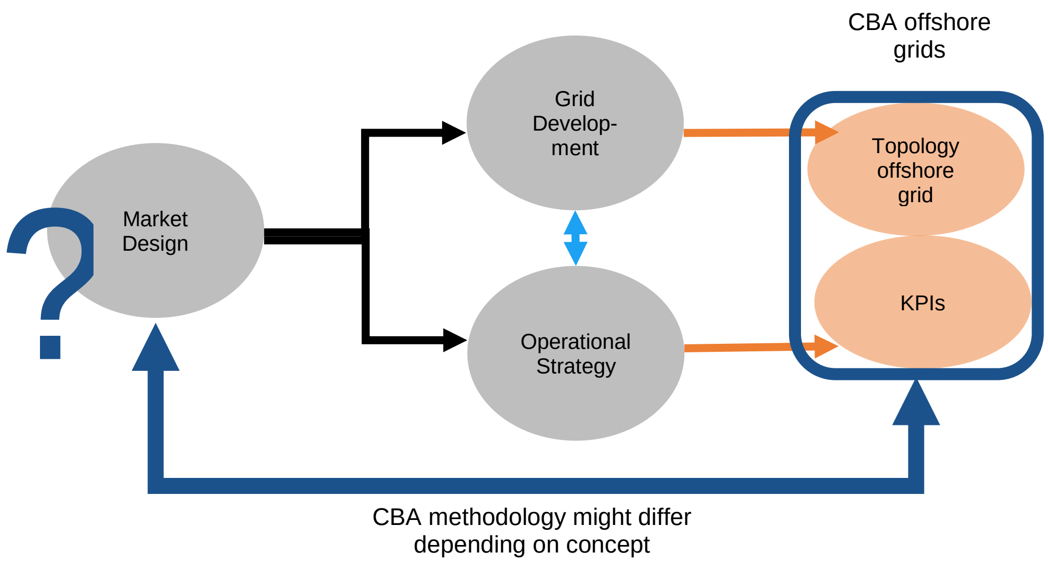

Figure 5-5: Impact of market design on offshore grids.

5.6 DEFINITION OF THE KPIS

The value to society of each project alternative will be determined through valuing a defined set of indicators (KPIs) for each project alternative. The values for the different KPIs will be combined for each project alternative and compared as defined in the assessment framework (see section 5.7). The selection of the KPIs for the valuation of offshore grids and the guidelines to determine them, are detailed in Chapter 6. This section focusses on overarching decisions in order to facilitate the definition of the KPIs. Table 5-4 summarises the choices and level of complexity belonging to dimension V: the definition of the KPIs.

Table 5-6: Summary of choices within the definition of the KPIs.

Activity	Choices	Options			*Complexity* →
KPI definition	1	Qualitative	Quantitative	Hybrid (monetised, quantitative, qualitative)	Monetised if relevant

5.6.1 CHOICE I: TYPE OF KPIS

The major decision that needs to be made is to what extent KPIs will be expressed in monetary terms. KPIs might namely be expressed in either qualitative, quantitative or monetised units or a combination of either (hybrid). In terms of KPIs, not only the costs and revenues of offshore grid alternatives could be mapped, but also the impact and benefits to society and KPIs for which there is no market or representation (such as, the environment and ecology). Hence, each KPI has its inherent units, either euros or other.

The effects that occur should *ideally* be expressed as much as possible in monetary terms (monetised) if relevant to do so and if objective monetisation parameters can be obtained. By expressing all effects in the same unit (euros), project alternatives can readily be compared with each other. However, in *practice*, objective monetisation of certain KPIs is not straightforward or relevant. For example, monetising a security of supply KPI, valued in the form of expected energy not served [MWh/yr] could be monetised through a monetisation factor associated with the value of lost load [EUR/MWh]. However, currently there is no single objective and transparent guideline to determine this monetisation factor. Therefore, maintaining the original units of MWh/yr will lead to the most objective and relevant results. Further discussion on how to value the different KPIs is provided in Chapter 6.

Decision

- **Ideal:** Hybrid: monetise as much as objectively possible and relevant.
- **Practical:** Hybrid: monetise as much as objectively possible and relevant.

5.7 CHARACTERISTICS OF THE ASSESSMENT FRAMEWORK

Once the project alternatives have been determined and the tools have been set up, the value of each project alternative over time (the value of KPIs) needs to be assessed. Additionally, guidelines for the comparison between project alternatives need to be formulated. Table 5-4 summarises the choices and level of complexity belonging to dimension VI: the definition of the KPIs.

Table 5-7: Summary of choices and options within the assessment framework.

Activity	Choices	Options		Complexity →
Assessment projects	1	With and without the project (PINT/TOOT)	Projects vs null alternative	
Project comparison	2	Spider diagram	Multi-criteria analysis	NPV-calculation with full monetization
Evaluation period	3	End-situation, as build in one go & 30 years operational life (2050-2080)	Complete development and operation (2020-2050) discounted	Complete development & operation (2020-2080)
Time steps for evaluation	4	Build “in one go”	Each X years	1 year
Taking into account uncertainty	5	Scenario analysis	Minmax regret	Real options

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5.7.1 CHOICE I: TYPE OF ASSESSMENT

The **initial choice** regards the type of assessment of the project alternatives. As highlighted in section 5.4.5, the reference for comparison of project alternatives will be a business-as-usual development of the offshore area, connecting the same capacity of wind parks from the sea scenarios but with current technologies. The reason not to employ the PINT or TOOT approaches for project assessment as described in the ENTSO-E CBA methodology, is that the offshore grid is a system, which cannot readily be declustered into single projects that can be incorporated into the system and subsequently removed. The offshore grid is also representative of a development over time that is likely to be in continuous development and can thus be seen as one project that will continuously interact with the rest of the system. Therefore, the terms of reference, for both the ideal and practical CBA methodology is a business-as-usual offshore grid development, or null-alternative.

Decision

- **Ideal:** project assessment with respect to a null-alternative.
- **Practical:** project assessment with respect to a null-alternative.

5.7.2 CHOICE II: PROJECT COMPARISON

The **second choice** to be made relates to the guidelines to compare project alternatives. The approach to compare projects depends on the type of CBA (financial vs social) and the extent of monetisation of the KPIs. From an *ideal perspective*, each KPI should be expressed as much as possible in monetary terms on the condition that objective monetisation parameters can be obtained and that monetisation is relevant for the KPIs. For each project alternative, the overall value to society can then be expressed in monetary terms (through a net present value (NPV) calculation). Project alternatives can in this way easily be compared to identify the “best” project alternative from the set of alternatives (highest positive NPV). However, *in practice* objective monetisation parameters are not always attainable or relevant for all KPIs. Therefore, some KPIs might be expressed in monetary terms, whereas others in quantitative units (e.g. MWh) or even qualitatively. The aim in the practical CBA is to quantify and monetise the KPIs as much as possible. With hybrid KPIs (combination of monetary, quantitative and qualitative), project comparison becomes less straightforward. One approach includes assigning weighting factors to different KPIs to create one value per project alternative. Alternatively, the importance of the different KPIs will be ranked rather than combined into a single value, and therefore the “best” project alternative will be at the discretion of the project promotor (multi-criteria analysis). In the former case, determining weighting factors is again a subjective exercise. From a practical perspective, the latter approach will be followed where each KPI will be reported in its own units – possibly through a spider chart – and the “best” project will be sought through the importance that the involved stakeholders and project promotor will put on the different KPIs. In practice, this decision process will involve political complexity as agreement from all North Seas countries should be obtained.

The SCBA serves as a decision support tool. The most cost-effective project alternative is not necessarily the “best” decision from a societal perspective. Not all interests can be expressed in cash and can be weighed in a

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comparable way. The analysis does highlight the consequences of different offshore grid alternatives on broader society. The final decision in the decision-making process will probably be taken by a range of stakeholders, for whom, with the help of the information from the SCBA, the discussion can be structured, rigorous and transparent. The goal of the PROMOTioN project is to gain understanding of the behaviour and impact on the European power system of an offshore grid system. The results are not aimed to predict what will to happen in the future but to show contrasting developments to increase understanding of the value of offshore grids to society. The outcomes from the CBA within PROMOTioN as obtained within WP12.2 are intended for use by various stakeholders, including the European Commission and national governments that will consider the results to gain an understanding of the importance of offshore grids for potential further analysis.

Decision

- **Ideal:** Full monetisation if objective parameters are available and if monetisation is relevant and project comparison based on NPV calculation and spider diagram.
- **Practical:** Monetisation as much as objectively possible and relevant, project comparison based on spider diagram.

5.7.3 CHOICE III: EVALUATION PERIOD AND TIME STEPS

A **third choice** relates to the evaluation period of the offshore grid, the time steps for development, the time steps of KPI evaluation and related parameters.

From an *ideal perspective*, KPIs of each project alternative should be assessed on a yearly basis over its lifetime. However, the various components for each project alternative will be commissioned continuously (i.e. a project alternative is not fully commissioned at once at a specific point in time), this is not feasible from a practical point of view. Indeed, the start of development of each offshore grid alternative could be around 2020 with continuous development up to at least 2050. After 2050, the latest commissioned elements of the offshore grid could be operational for at least another 30 years. During that time period, new assets could still be commissioned, while already commissioned assets could be replaced or decommissioned. This lifetime is illustrated in Figure 5-6. For each project alternative, an estimation of the investment plan up to a point in the far future (e.g. 2080) would need to be set up, in order to estimate the benefits brought by investments commissioned up to 2050. A more pragmatic approach could be to limit the analysis up to 2050, with an implicit assumption that the last year of the time period considered (i.e. 2050) is repeated afterwards an infinite number of times. This approach is the preferred one in the *practical CBA*. Furthermore, instead of analysing every single year, in the practical CBA larger time steps for the evaluation of benefits between 2020 and 2050 could be used with a linear interpolation of the values of the KPIs between these time steps.

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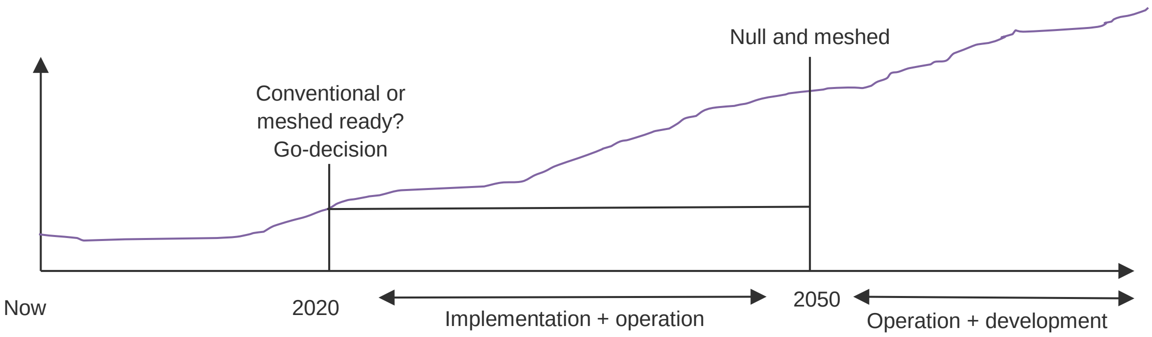

Figure 5-6: Schematic timeline of offshore grid development.

Decision
• **Ideal:** Complete development & operation with yearly evaluation of benefits. • **Practical:** Complete development (2020-2050) with evaluation of benefits in certain time steps with linear interpolation & operation after with 2050 repeated an infinite number of times.

5.7.4 CHOICE IV: EVALUATION PARAMETERS

A **fourth choice** to be made relates to the parameters that are required to perform the assessment of each project alternative, including the economic lifetime of components, the interest rate employed and the residual value of the offshore grid. The ENTSO-E Guideline will be followed as much as possible. These parameters will be used for both the ideal and practical CBA.

Economic lifetime

A lifetime of 25 years with a residual value of zero for different assets has been recommended by ACER[14] and adopted in the ENTSO-E Guideline. Although a lifetime of 30 years seems more appropriate in the context of offshore grid infrastructure, the recommended 25-year lifetime has been selected as the economic life for all assets with a residual value equal to zero and no decommissioning cost. Note that the last years in the economic lifetime of components have a limited contribution to economic indicators such as NPV when a discount rate of at least several percent is used. Therefore, the difference between an economic lifetime of 25 years and an economic lifetime of 30 years is marginal. Note that it is assumed that in the practical methodology, decreasing performance of components over their lifecycle is not explicitly considered. In the ideal methodology, however, this should be considered for each component separately.

Interest rate

Underlying variations exist in the monetary value of future investments, a discount rate is applied to include this risk in the calculation. This means that income that is received in the future will be valued lower than income received today. A Euro today is worth more than a Euro in ten years’ time, and a Euro that is put in the bank now will become more than a Euro received in ten years' time. Uncertainty plays here a role (can you spend the

[14] ACER Opinion on ENTSO-E CBA Methodology - Jan 2014.

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Euro as well in 10 years as it you can now? What is the certainty that you will actually receive or have to pay the Euro in ten years?). It is important to ensure that future effects are valued lower. By discounting, all future effects are expressed in values of today and can be added together.

Another important topic (assuming a net present value approach) is the interest rate. The choice of interest rate used generally requires a number of decisions. It can be based on a risk-free interest rate (governmental bonds) and a risk premium depending on the project. For transmission grid owners, most of the time a regulated WACC (Weighted Average Cost of Capital) is available. However, commercial companies may require a higher expected return on investment (higher interest rate). So, it might be necessary to discount loss of wind energy due to grid faults with an alternative interest rate used for grid investments.

This is a CBA in the form of a societal CBA therefore a societal interest rate[15] should be adopted. This is likely to be lower than the interest rate private investors would receive. The appropriate societal discount rate has been agreed at 4% (real values) in line with the ENTSO-E guidelines that follow the recommended interest rate from ACER. Investors might receive a higher interest rate, but they might be able to offset this rate through subsidies. The ENTSO-E guidelines (advised interest rate of 4% by ACER and 25-year lifetime) will be followed in the CBA methodology for offshore grids.

Residual value

The residual value could be set at zero when working with annuitized investment (cfr. ENTSO-E Guideline).

5.7.5 CHOICE V: TAKING INTO ACCOUNT UNCERTAINTY

The offshore grid will be developed over several decades and projects are considered to have an economic lifetime of 25 years. There is uncertainty about the way the power system, in particular the load and the generation, will evolve over that period of time. This uncertainty is partly addressed through the scenario approach described in section 5.3, and could have a significant impact on the development of the offshore grid. For example, an offshore hub and meshed assets have high upfront investment costs that will only become fully operational and show benefits to society in a later stage. This could pose a risk to the financial viability of the project. Additionally, unforeseen developments in cost trajectories of onshore technologies might decrease the need large-scale offshore infrastructure. It is therefore important to consider risks linked to uncertainties in the CBA of project alternatives. There are a couple of methods to account for uncertainties.[16]

One option consists simply in performing distinct CBAs for the various scenarios, without deducing a single indicator. The ranking of alternatives is however difficult. In order to rank alternatives, expected values of indicators such as the expected NPV can be obtained by affecting probabilities of occurrence to scenarios.

[15] J. Zhuang, Z. Liang, T. Lin, and F. De Guzman, „Theory and Practice in the Choice of Social Discount Rate for Cost-Benefit Analysis: A Survey“, ERD Working Paper, Series No. 94, Asian Development Bank, May 2007. Available online: https://www.adb.org/sites/default/files/publication/28360/wp094.pdf.

[16] Konstantelos, Ioannis & Moreno, Rodrigo & Strbac, G. (2017). Coordination and uncertainty in strategic network investment: Case on the North Seas Grid. Energy Economics. 64. 131–148. 10.1016/j.eneco.2017.03.022.

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However, the conclusions rely then strongly on the specific choice made for probabilities, which are difficult to estimate. Another possibility is the use of the minimax regret approach. It consists of selecting the project alternative leading to the least maximum regret compared to all other alternatives. The regret can be defined as the economic loss (e.g. decrease of NPV) through having made a suboptimal decision for a specific scenario. The minimax regret approach does not need probabilities but can be sensitive towards the set of scenarios selected, in particular if extreme scenarios are used.

In addition to uncertainty in the scenarios risks exist in the timing and development of offshore grid. For example, the availability and training of a skilled work force, and the risk of not being able to manufacture the assets in the required multitude due to process or resource constraints. A full risk assessment is beyond the scope of the practical CBA assessment. In the ideal CBA methodology, a risk assessment should be part of the investigation. An example of a flow chart for risk assessment is provided in Figure 5-7, taken from the North Sea Grid Final Report.[17]

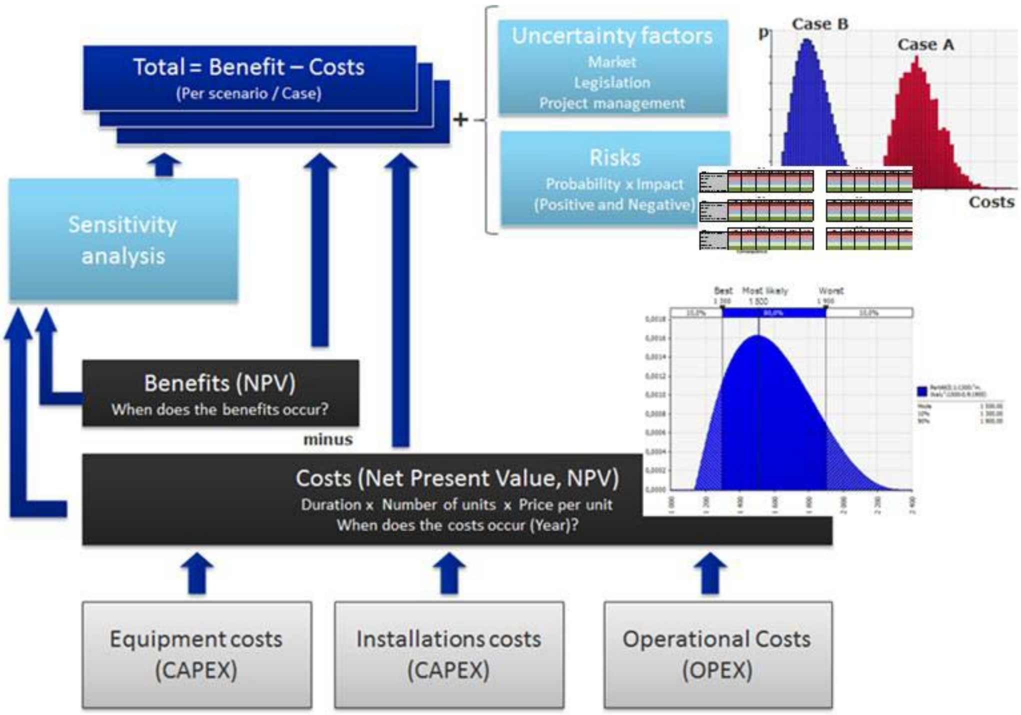

Figure 5-7: An example of a flow chart of risk assessment (NorthSeaGrid – Offshore Electricity Grid Implementation in the North Sea – Annexes to the Final Report, 24/03/2014).

5.8 SUMMARY OF DECISIONS

Table 5-8 summarises the different choices and decisions for the ideal and practical CBA methodology.

[17] NorthSeaGrid – Offshore Electricity Grid Implementation in the North Sea – Annexes to the Final Report, 24/03/2014.

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Table 5-8: Summary of choices within the ideal and practical CBA methodologies. Green indicates the decisions of the ideal methodology and yellow for the practical.

Dimension	**Activity**	**Choices** →			*Complexity*
Scope	**CBA**	Value to society	Value to each (surrounding/North Sea) state	Value to society **&** each (surrounding/North Sea) state	Value to all stakeholders
		Non-monetised CBA	Augmented CBA (hybrid)	Financial CBA (full monetisation)	
	Purpose of project	Offshore grid for evacuation of wind	Offshore grid for evacuation of wind ***& market integration***	Offshore **&** ***onshore*** grid for evacuation of wind	Offshore **&** ***onshore*** grid for evacuation of wind **&** ***market integration***
Scenarios	**Offshore development (sea scenarios)**	One scenario of capacity and location	One scenario of capacity ***with multiple locations***	***Multiple scenarios of capacity and locations***	
Project alternatives	**Scope of alternatives**	Electricity network	Electricity network, ***including storage***	Electricity network, including storage ***and P2X options***	Electricity network ***and gas network,*** including storage and P2X options
	Boundaries	Offshore grid, including onshore and wind park connection points	Offshore grid ***and wind parks***	Onshore grid ***and offshore grid***	Onshore grid, offshore grid and wind parks
	Onshore infrastructure development	Assume onshore grid reinforcement is similar for all offshore grid alternatives.	Simplified onshore infrastructure cost	Full development and reinforcement needs onshore	
	Project alternatives	Optimised radial AC	Optimised radial AC and DC	Optimised meshed DC	Hybrid radial/meshed
	Null alternative	Base case	Null-alternative		
Tooling	**Scope onshore market model**	Zonal (per BZ)	Zonal market (per BZ) with nodal redispatch.	Nodal	

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	Scope offshore market model	Zonal in current national bidding zones	One appropriate market design per project alternative	Multiple market designs per project alternatives	Nodal
	Region	States surrounding the North Sea network	Society as a whole plus any further connections if relevant (Europe (+))	Society as a whole plus any further connections	
KPI definition	**KPI definition**	Qualitative	Quantitative	Hybrid (monetised, quantitative, qualitative)	Monetised (if relevant)
Assessment framework	**Assessment projects**	With and without the project (PINT/TOOT)	Projects vs null alternative		
	Project comparison	Spider diagram	Multi-criteria analysis	NPV-calculation	
	Evaluation period	End-situation, as build in one go & 30 years operational life (2050-2080)	Complete development and operation (2020-2050) discounted	Complete development & operation (2020-2080)	
	Time steps for evaluation	Build "in one go"	Each X years	1 year	
	Taking into account uncertainty	Scenario analysis	Minmax regret	Real options	

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6 KEY PERFORMANCE INDICATORS

This Chapter discusses the relevant KPIs to be used in the CBA for offshore grids. The starting point is again the ENTSO-E CBA methodology. For the assessment framework as well as for the determination and definition of the KPIs, the main question is to what extent an offshore grid assessment framework differs from the ENTSO-E framework. Comparing different systems instead of different single projects may lead to different KPIs and/or to a different assessment of the same KPI. The assessment framework needs to provide guidelines and methods on how to calculate this.

For all involved KPIs, a definition will be given and its relevance for the CBA for offshore grids. The calculation method of the KPIs and their interaction with other KPIs will also be presented. For the calculation, a distinction is again made between the ideal situation and the practical execution.

6.1 INTRODUCTION

As mentioned above, the starting point for the KPIs is the ENTSO-E CBA methodology[18]. The KPIs mentioned in this methodology are shown in Figure 6-1 below.

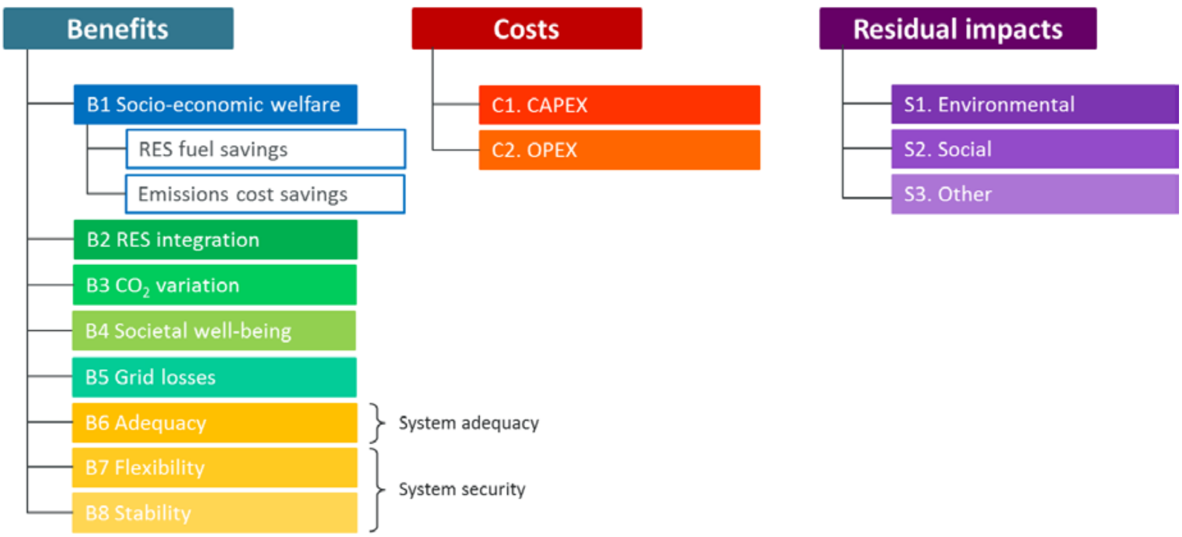

Figure 6-1: KPIs of the project assessment methodology from the 2nd ENTSO-E Guideline on Cost Benefit Analysis of grid development projects (September 2017).

[18] ENTSO-E, „2nd ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects“ (draft for review by European Commission), 6 September 2017.

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The KPIs according to the ENTSO-E Guideline are organised in three categories: Benefits, Costs and Residual impacts. The effects have been categorised as below:

- **Direct effects**: the "intended" effects of the project (investments and revenues, also connection of offshore wind farms);
- **Indirect effects**: effects on other markets (in the case of offshore grids, for example, on shipping and sand extraction);
- **External effects**: unpriced effects associated with the project, such as effects on nature and environment.

Appendix I: List of indirect and residual effects of offshore infrastructure, shows several examples of indirect and external effects of offshore wind from an SCBA perspective[19]. These effects could partly apply to offshore grids and in the case that wind farm locations would be considered in the CBA, most of these effects could apply.

There are two different ways of comparing project alternatives using KPIs. The common way is to quantify (or qualify) KPIs based on the defined project alternatives. The other way is to fix some KPIs across project alternatives if relevant. Although there may be advantages to fixing KPIs across project alternatives, this will not be considered within the proposed practical methodology in order to be consistent with the ENTSO-E methodology. For the ideal methodology, there seem to be considerable advantages in using this method (see for instance 6.2.6.1).

In the following sections, all three categories of effects and the involved KPIs will be discussed, along with the definition of the KPI according to the ENTSO-E Guideline.

6.2 BENEFITS

In the ENTSO-E Guideline the following eight benefits are mentioned:

B1. Socio-economic welfare
B2. RES integration
B3. CO_2 variation
B4. Societal well-being
B5. Losses / efficiency
B6. Adequacy
B7. Flexibility
B8. System stability

In the discussion within the scope of this study, benefits are seen as total benefits for society which is consistent with the ENTSO-E methodology. Disaggregation of benefits towards stakeholders and/or countries is not further worked out in this report. In principle, disaggregation could be applied for the following benefits: consumer and

[19] Maatschappelijke Kosteneffectiviteit van ruimtelijke opties voor offshore Windenergie MKEA Windenergie Noordzee, eindrapport, Decision, 27 oktober 2010 (only in Dutch).

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producer surplus, congestion rent, social welfare, CO_2 emissions and RES curtailment. However, this is not relevant within the scope of the SCBA. To enable the disaggregation of benefits, for example, the generation costs (without load shedding) per country/bidding zone would be needed for the Socio-economic welfare (SEW) indicator. To obtain these values, market design influences and also issues like correct determination of Norwegian market prices would need to be investigated. The latter is not straightforward due to the high levels of hydro generation in Norway. The chosen market design / bidding zone configuration thus impacts indicators, such as SEW. Additionally, the use of tools can strongly influence results, different ways of modelling approaches and dispatch can affect prices. Not only marginal costs will need to be considered for transparent price formation modelling, but also opportunity costs of hydro. Storage could become a further price setter/maker.

To finance an offshore grid, the benefits to all involved players should be understood. There would be considerable value in being able to determine accurately the value that each stakeholder will receive in a North Sea meshed offshore grid. However, there is no standard and well recognised methodology yet to assess these factors. Disaggregation cannot yet be done in very meaningful way within the scope of this study. Moreover, the objective of the PROMOTioN project is to find out whether meshed HVDC offshore grids would have positive economic and social impacts in the North Sea area. For this first assessment, disaggregation is not required.

6.2.1 B1 SOCIO ECONOMIC WELFARE

Definition

The socio-economic welfare (or social welfare) can be defined as follows for electricity markets:

> *The Socio-Economic Welfare (SEW) is the sum of the consumer surplus, the producer surplus and the congestion rent. The consumer surplus is the difference between the overall willingness to pay electricity of consumers and the amount of money they will effectively pay. The producer surplus is the difference between the amount of money producers will receive and the actual generation cost. The congestion rent is the sum on all interconnectors of the product of the difference between electricity prices on both ends of the interconnector by the flow in the interconnector.*

The change in socio-economic welfare (SEW), or the benefits obtained from market integration, is characterised by the ability for a project to reduce congestion. It provides an increase in transmission capacity that makes it possible to increase commercial exchanges, so that electricity markets can trade more power and fulfil demand in a more economically efficient manner.

Relevance for offshore grids

Offshore grids are primarily meant for the evacuation of offshore wind energy and the increase of market integration between countries (market coupling). The question is whether the ENTSO-E definition of social welfare is suitable for offshore grid development. Does this definition reflect the socio-economic welfare of both wind evacuation and market integration, and does this definition show the influence of both aspects in a clear

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way in order to be able to judge the obtained results properly? It may very well be that one offshore grid solution scores better on wind evacuation and another on market integration. On the one hand, this may not be a problem when both are monetised. On the other hand, the effect on both items will not be visible when using this definition. If both benefits are combined into one KPI and wind evacuation is considered more important, this KPI definition does not see adequate.

How to calculate socio economic welfare?

A common definition of the socio-economic welfare KPI is:

> *The socio-economic welfare KPI is defined as consumer surplus + supplier surplus + congestion rent; while respecting all the given grid constraints[20].*

The consumer and producer surpluses are shown in Figure 6-2 below, with the following definitions:

- Consumer surplus = difference between the demand offer price and market price;
- Producer surplus = difference between the supply offer price and market price;
- Congestion rent = price difference between two markets multiplied with the traded volume between the two markets.

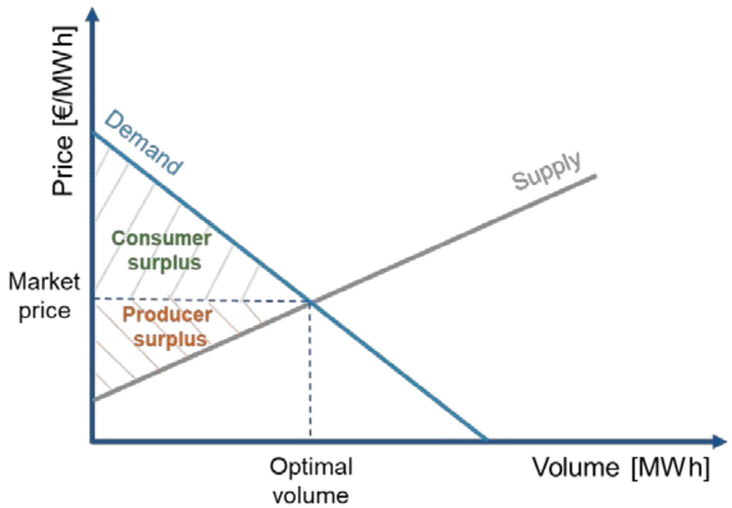

Figure 6-2: Graphical depiction of consumer and producer surplus.

[20] See for instance: Nord Pool, Power market Integration and challenges in Europe, Strommarkttreffen Berlin, 2 June 2017. Available online: https://www.strommarkttreffen.org/2017-06-02_Rabassi-Power_market_integration.pdf and P. Kaderják, SEERMAP training, Introduction to transmission network assessment methodology: the ENTSO-E CBA methodology and the PCI selection process,7 March 217. Available online: https://rekk.hu/downloads/events/2017_SEERMAP_ENTSOE_CBA_Kaderjak.pdf.

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This method covers the benefit of market integration and some indirect benefits of wind evacuation. The latter refers to cheaper production of electricity (already taken into account in the values of the Consumer Surplus and Producer Surplus), to RES integration and to a reduction of CO_2 emissions.
In general, two different approaches can be used to calculate the socioeconomic welfare, as defined in the ENTSO-E CBA methodology:

- The **generation cost approach**, which compares the generation costs of different solutions for offshore grids for all involved and affected bidding areas.
- The **total surplus approach**, which compares the producer and consumer surpluses of different solutions for offshore grids for all involved and affected bidding areas, as well as the congestion rent between them, for different offshore grid solutions.

In the *ideal CBA methodology*, the second approach is preferred as demand is not in practise fully inelastic. Hence, consumption will be somewhat higher if electricity can be supplied at a lower price, and vice versa. For the *practical execution*, a price inelastic demand is assumed and the change in socio-economic welfare is calculated from the reduction in total generation costs.

The reduction of generation cost for an offshore grid can be attributed to enabling more renewable energy capacity (at zero marginal cost) and cheaper units that are made available to more expensive price regions through additional interconnection of bidding zones. Part of the reduced generation cost may be attributed to avoided CO_2 emissions, which come at a price under a scheme such as the ETS or a carbon tax.

Interaction with other KPIs

The KPI socio-economic welfare interacts with the KPIs B2 RES integration, B3 CO_2 variation and B4 Social wellbeing. There is a danger of duplication for the benefits if all would be expressed in monetary terms for B2 RES integration and B3 CO_2 variation.

6.2.2 B2 RES INTEGRATION

Definition

The benefit of the contribution to RES integration is defined in the ENTSO-E Guideline as:

> *the ability of the system to allow the connection of new RES generation, unlock existing and future "renewable" generation, and to minimise curtailment of electricity produced from RES.*

The aim to increase RES integration is included as one of the EU 20-20-20 targets and is therefore displayed as a separate indicator.

Relevance for the CBA for offshore grids

Wind evacuation is a major goal of the offshore grid. The KPI that values the contribution of RES integration of offshore grids is of significant importance for the CBA methodology. Forecasts indicate a very large amount of

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wind energy capacity in the offshore area, the influence on the surrounding power systems and bidding zones is expected to be substantial. Each project alternative is assumed to connect the same offshore wind capacity per each scenario, but different project alternatives might result in different wind yields and also different curtailment, due to different locations of wind farms and different network topologies in each project alternative.

An effective method to value this KPI is of major importance. This KPI indicates the amount of wind evacuated from the Northern Seas area. Onshore effects with regard to RES integration are expected to be negligible in the comparison between offshore project alternatives (see also Section 5.3).

How to calculate the KPI? - ideal vs practical execution

In principle, the calculations are the same for the ideal methodology and the practical methodology but the ideal methodology will take into account more sea scenario combinations (capacity, location, technology), as detailed in Section 5.3. In the ENTSO-E CBA methodology, RES integration can be valued through either the connected RES or avoided RES spillage, respectively determined as:

- Interconnection of RES to the main power system [MW];
- Avoided RES spillage (curtailment) [MWh/yr].

Given that all project alternatives are assumed to connect the same offshore wind capacity [MW] per scenario, avoided RES spillage (curtailment) is the chosen valuation method for the KPI B2 RES integration for both the ideal and practical CBA.

Interaction with other KPIs

Like already mentioned in the previous section, the KPI RES integration interacts with socio-economic welfare and there may be double counting when monetised. RES integration will be monetised (partly) for socio-economic welfare. Therefore, the RES integration KPI will be used for reporting purposes and to be able to see the explicit difference between project alternatives based on this KPI. Avoided spillage can be extracted from the studies for indicators B1 and B4.

6.2.3 B3 CO_2 VARIATION

Definition

The variation in CO_2 emissions represents the change in CO_2 emissions in the power system attributed to the project. This is a consequence of changes in generation dispatch and unlocking renewable potential. The aim to reduce CO_2 emissions is one of the EU 20-20-20 key targets and is therefore displayed as a separate indicator.

Relevance for the CBA for offshore grids

Offshore wind generation can reduce carbon emissions if replacing fossil fuel generation. This KPI is therefore very relevant for offshore grids. Different project alternatives of the offshore grid may evacuate different volumes of wind energy to load centres, resulting in different CO_2 emissions of European and the connected national electricity supply systems. In addition, offshore grids might significantly increase interconnection between

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countries, the capacity of which can also be used if the grid is not used for the evacuation of offshore wind. Hence, local renewable energy fluctuations could be smoothed out through increased interconnection and local excesses of renewable energy could be better shared between countries, potentially reducing local curtailment needs and contributing to a regional reduction in CO_2 emissions. A fully connected meshed offshore grid system could facilitate greater renewable energy capacity. For example, during outbreaks of high pressure and hot weather, solar energy is likely to create more energy and there is likely to be less wind and therefore less wind energy generation. Conversely, during a low-pressure period you may expect the opposite. For example, a meshed offshore grid could enable the United Kingdom to sell its excess capacity from offshore wind during a windy period to central Europe, and conversely when there are stable conditions – continental Europe could sell backs its solar energy.

How to calculate the KPI? - ideal vs practical execution

The variation of CO_2 emissions can be measured through performing market simulations of the European power market with each project alternative to determine the CO_2 emissions for each case. The variation in CO_2 emissions realised by a certain project alternative will be measured with respect to the emissions in the null-alternative. Monetisation may be done with an assumed value for CO_2. However, monetisation is already indirectly included in the social-economic welfare indicator, if the desired societal value of CO_2 is the same as the value set for CO_2 emissions when calculating production costs of conventional power plants in the market model. However, in practice the price of CO_2 emission rights under the ETS is (according to many stakeholders) presently well below the actual cost of CO_2 emissions in terms of 'damage done' to society.

An alternative way to determine variations in CO_2 emissions could be to calculate the (avoided) costs of mitigating harmful effects of CO_2 emissions: the societal cost of CO_2 emissions. This is difficult and not straightforward to do. Additionally, life cycle emissions could be evaluated. Life cycle impact is expected to be less important when comparing alternatives, since the set of infrastructure assets will be similar across project alternatives. Hence, fossil fuel use from the dispatch of generators is expected to be the dominant factor that will result in differences in CO_2 emissions between project alternatives. Therefore, in the practical CBA the considered emissions of the electricity generation will be solely based on fuel use. In the ideal CBA, we suggest to calculate the life cycle CO_2 emissions.

Interaction with other KPIs

Like already mentioned in section 7.2.1, the KPI CO_2 emissions interacts with socio-economic welfare and there may be double counting when quantified. CO_2 emissions will be monetised (partly) for socio-economic welfare. This KPI (B3) is for reporting purpose.

6.2.4 B4 SOCIETAL WELL-BEING

Definition

The ENTSO-E CBA methodology defines societal well-being as:

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The variation in societal well-being as a result of RES integration and variation in CO_2 emissions is the increase in societal well-being, beyond the economic effects, that are captured in the computation of SEW (indicator B1).

Relevance for the CBA for offshore grids

The ENTSO-E CBA methodology provides the following relation between the variations in societal well-being of project alternatives:

- The integration of RES and evolution of CO_2 emissions in the power system attributed to the project are partially accounted for in the calculation of socio-economic welfare.
- The integration of RES and a variation of the CO_2 emissions result in a change in variable generation and emission costs due to the variation in energy produced by non-zero variable cost conventional generators and the cost of emissions (e.g. carbon tax or rights under ETS) respectively, and therefore impact the system costs.

However, this may not reflect the full societal benefits of having more renewables in the energy system or the full societal cost of CO_2 emissions (i.e. the damage done by emitting one tonne of CO_2 is not necessarily reflected by the cost of emission certificates that producers must pay). Any further effects can therefore be reported under this indicator. An example of an additional benefit includes the project contribution to sustainability.

How to calculate the KPI? - ideal vs practical execution

Due to the uncertain form of this KPI, the choice in adopting this KPI in the SCBA execution would be at the discretion of the project promotor to reflect any societal impacts that might arise through the project. This approach is proposed for both the ideal and practical CBA methodology.

Interaction with other KPIs

Social well-being may interact with socio-economic welfare. There may be a risk of double counting with the residual impacts discussed in section 6.4.

6.2.5 B5 GRID LOSSES

Definition

Variation in grid losses [GWh] in the transmission grid encompasses the cost of compensating for thermal losses in the power system attributed to the project. It is an indicator of energy efficiency and expressed as a cost in Euros per year.

Relevance for the CBA for offshore grids

Different offshore grid configuration may result in different grid losses in both the offshore and the onshore grid. The cost of these grid losses typically account for a small percentage of the total operational expenditure (OPEX) of the project. This can be assumed due to the large share of network infrastructure, regardless of

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project alternative. Therefore, we advise to neglect the difference in grid losses in the practical CBAFor the ideal CBA, grid losses should however be taken into account and quantified.

How to calculate the KPI? - ideal vs practical execution

Grid losses depend on the load flows in the onshore and offshore electricity network. Quantification of grid losses can be done based on (hourly) simulation of the market operation (dispatch) and simulation of the load flow, based on this dispatch using an adequate grid model. The methodology presented in the ENTSO-E Guideline[21] can be followed (*italic*), with the exception that the simulations that have to be performed are for each project alternative and the null-alternative, rather than the system with and without the project:

In order to calculate the difference in losses (in units of energy [GWh]) and the related monetisation attributable to each project, the losses have to be computed in two different simulations with the help of network studies: **one for each project alternative, and one of the null-alternative***. The calculated losses are sufficiently representative if at least the following requirements are met:*

- *Losses are representative for the relevant geographical area;* (AC calculation approach should be used where possible)

In the ideal CBA methodology, the relevant geographical area should encompass a European network model. Due to complexity of the simulations, the practical CBA methodology could focus on a regional network model of the Northern seas and surrounding areas. The regional model should include the relevant bidding zones to the project and losses should be report at the level of market nodes at a minimum.

- *Losses are representative for the relevant period of time;*

The simulations should be performed over a complete year with sufficiently small time steps of around one hour to reflect reality. This should be adopted in both the ideal and practical CBA methodology.

- *Market results (generation dispatch pattern) used for each simulation are in accordance with the grid model, especially regarding cross-border capacities.*

The change in generation pattern can impact the losses of the system. The generation change could be considered through Net Transfer Capacity changes in the market modelling, or re-dispatch methodologies.

The obtained grid losses (expressed in MWh) could be monetised based on market prices obtained through the market simulation.

Interaction with other KPIs

The costs of grid losses are separate to the costs included in the Socio-economic welfare indicator and operational expenditure (OPEX).

[21] ENTSO-E, „2nd ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects“ (draft for review by European Commission), 6 September 2017.

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6.2.6 SECURITY OF SUPPLY

Transmission projects can improve security of supply.[22] The security of supply provided by a power system is related to its reliability. The term reliability has different meanings according to this context. For a power system, reliability has a general meaning of "a measure of its ability to deliver electricity to all points of utilization within accepted standards and in the amount desired"[23].

Traditionally, the reliability of a power system is attributed to two fundamental aspects: adequacy and security. Adequacy relates to the existence of sufficient facilities (e.g. generation, transmission, distribution facilities) within the system to supply the consumer demand while satisfying operational limits, taking into account scheduled and unscheduled outages of system facilities. Adequacy is therefore associated with static conditions which do not include system disturbances. Security, in contrast, can be defined as the ability of the system to withstand disturbances arising from faults and unscheduled removal of equipment without further loss of facilities or cascading failures. Security is therefore associated with the response of the system to these disturbances.

These two aspects were defined when the penetration level of variable renewable energy sources (e.g. wind, solar photovoltaic) in power systems was low. The increasing share of intermittent energy sources poses another reliability concern: even if sufficient facilities exist to supply the load (i.e. the system is adequate) and the system is able to withstand sudden disturbances (i.e. the system is secure), the system might be unable to accommodate unexpected and/or rapid changes of the load and of variable RES output. This consideration might lead to an additional and third aspect of reliability: flexibility. Although the 2nd ENTSO-E CBA guideline considers flexibility as a part of security, the authors would advise otherwise: they believe security should be associated with disturbances initiated by events developing on a short time scale (e.g. up to several seconds) while flexibility should be associated to changes developing on a longer time scale (e.g. between several minutes and several hours).

Furthermore, the 2nd ENTSO-E CBA guideline does not define a specific security indicator but considers stability as a second part of security. Power system stability can be defined as the "ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact"[24]. To be secure, a power system must obviously be stable, but this criterion alone is not sufficient: electrical variables must also stay within specific limits after the disturbance (e.g. no equipment overload, no voltage violation). The definition of security encompasses the definition of stability, but it is more general. Because

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[22] Cigré Technical Brochure 026, "Power system reliability analysis – Application guide," 1984.; P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem and V. Vittal, "Definition and Classification of Power System Stability," IEEE Transactions on Power Systems, vol. 19, no. 4, pp. 1387-1400, 2004.; S. Espinoza, M. Panteli, P. Mancarella, H. Rudnick, "Multi-phase assessment and adaptation of power systems resilience to natural hazards," Electric Power Systems Research, vol. 136, pp. 352-361, 2016.

[23] Cigré Technical Brochure 026, "Power system reliability analysis – Application guide," 1984.

[24] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem and V. Vittal, "Definition and Classification of Power System Stability," IEEE Transactions on Power Systems, vol. 19, no. 4, pp. 1387-1400, 2004

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stability and security issues are strongly interrelated (e.g. a transient stability problem can lead to the disconnection of one or several generators and could then entail voltage issues), for offshore grids it is proposed not to limit an indicator only to a stability index, but rather to include all security aspects into a security index.

Finally, the interest rose recently in the power engineering community for the concept of “resilience”. This concept is cited explicitly in criteria 2d of Annex IV and in criteria 6d of Annex V of the EU Regulation 347/2013. Resilience of a power system can be defined as its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event. Resilience encompasses adequacy and security aspects, but specifically for disruptive events (e.g. earthquake, hurricane), and includes considerations beyond traditional reliability analyses.[25]

As a conclusion for offshore grids, four security of supply indices can be defined: adequacy, flexibility, security and resilience.

Interaction with other KPIs

Lack of adequacy and shedding of load will impact socio-economic welfare. The reduction in SEW due to lost load is excluded from the primary SEW figure to prevent double counting. The same applies for flexibility. This will also depend on how market simulation is performed. Loss of load might also be captured due to a lack of flexibility.

6.2.6.1 B6 SECURITY OF SUPPLY – ADEQUACY

Definition

Adequacy of a power system can be defined as its ability to satisfy the consumer demand and system's operational constraints at any time, in the presence of scheduled and unscheduled outages of generation and transmission components or facilities.

Relevance for the CBA of offshore grids

Offshore grids may influence the adequacy of the electricity supply in different ways:

- Interconnection may improve the adequacy due to more available generation capacity after the interconnection of systems. A new equilibrium will develop in the course of time with probably the same adequacy as before, considering the objective of many countries is to monitor the adequacy inclusive of interconnection.
- Facilitating the evacuation of wind energy contributes to the available generating capacity and to the adequacy of the supply in first instance. Here also a new equilibrium will evolve.

[25] S. Espinoza, M. Panteli, P. Mancarella, H. Rudnick, “Multi-phase assessment and adaptation of power systems resilience to natural hazards,” Electric Power Systems Research, vol. 136, pp. 352-361, 2016.

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How to calculate the KPI? – ideal vs practical execution

There are two main paradigms about the impact of a transmission project, such as an interconnector or an offshore grid on power system adequacy.

The first paradigm implicitly assumes that the generation system is not impacted by the presence of the transmission project. In that case, the adequacy benefits are computed as the difference in adequacy levels with and without the project; or in the case of offshore grids, the difference in adequacy levels of two different projects/systems. Generation adequacy levels are usually expressed with two metrics: the LOLE[26] and the EENS[27].

Monetisation of the benefits in this first paradigm can then be done by valuing the expected electricity not supply (EENS) with the value of this electricity through the Value of Lost Load (VoLL), expressed typically in Europe in EUR/MWh. There have been several studies in and outside Europe to determine the value of lost load. The results show a bandwidth of values and it seems not straightforward to distil reliable values from these studies to monetise the difference in generation adequacy.

In contrast, the second paradigm argues that transmission projects can impact the generation system and lead to a reduction of the generating capacity because the economic viability of peaking units is decreased. It argues that the generating capacity will be decreased in such a way that the adequacy level remains the same because it corresponds to the economic optimum. In that case, the benefits are estimated by setting the adequacy criterion (LOLE and maybe also EENS) to a certain value, and then by quantifying and monetising the difference in the required generation capacity to meet this criterion. This difference could be investment in peaking units.

When a system has an adequacy level close to the economic optimum, and when the impact of a considered transmission project on adequacy is small, the two paradigms are expected to lead to similar monetary values. However, when the adequacy level is far from the economic optimum, the paradigms can lead to very different results (if the level of adequacy is poor, the first paradigm will lead to much larger benefits than the second, and, if the level of adequacy is excellent, it will be the opposite). In long-term planning, it is of paramount importance to base the analysis on generation scenarios that are close to the economic optimum. In principle, legal adequacy criteria existing in some European countries (e.g. LOLE of 3 hours/year in Belgium) should lead to adequacy levels close to the optimum.

Although an ideal analysis should estimate the adequacy benefits using the two different paradigms, a practical analysis could then be limited to the first paradigm which is the easiest one to apply. The accuracy of the outcome would however depend on the quality of the used values for VoLL. It is expected that the first paradigm requires more effort but would in principle lead to more accurate answers.

[26] LOLE=Loss of Load Expectation, expressed in hours per year, represents the expectation that the available generating capacity cannot meet the load.

[27] EENS=Expected Energy Not Supplied, expressed in GWh per year, represents the expected amount of electricity that cannot be delivered per year.

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6.2.6.2 B7 SECURITY OF SUPPLY – FLEXIBILITY

Definition

System flexibility characterizes the impact of the project on the capacity of an electric system to accommodate fast and rigorous changes in the net demand in the context of high penetration levels of non-dispatchable electricity generation.

Relevance for the CBA of offshore grids

The supply of offshore wind energy is highly variable; therefore the development of offshore wind energy requires a flexible energy system. Offshore transmission projects can improve the system flexibility by connecting multiple offshore wind farms and thus by smoothening the fluctuation of offshore wind power through the geographical spread. Further, the meshed offshore grid connects different countries (interconnection function) by increasing the reserve sharing between countries to deal with these fluctuations. Note that the lack of flexibility can threaten the security of supply when changes in the net demand cannot be adequately forecasted.

How to calculate the KPI? – ideal vs practical execution

Ideally, the difficulty to supply the load due to a lack of flexibility should be emphasized through a market simulation considering restrictions on units (ramping rates, minimum stable power, etc.) and the stochasticity of load and of generation. However, the ideal execution is hampered by two main barriers: the lack of standardized tools to consider forecast errors in the market simulation, and the high computation time required to reach a satisfying statistical accuracy. For practical execution, a qualitative estimation of the impact on flexibility is proposed for offshore grid projects.

6.2.6.3 SECURITY OF SUPPLY – SECURITY

Definition

Security of a power system can be defined as its ability to withstand disturbances arising from faults and unscheduled removal of equipment without further loss of facilities or cascading failures.

Relevance for the CBA of offshore grids

Transmission systems are usually planned and operated according to the deterministic N-1 security rule: the system must be able to withstand any single failure without stability problem or violation of operational limits. Note that the interpretation and the application of this general rule is system-specific and that, for offshore grids, a dedicated N-1 security rule must be defined.

The N-1 security rule is already considered to some extent in the assessment of the socio-economic welfare. In an alternating current (AC) grid transfer capacities between areas are computed such that transmission elements are not overloaded in normal conditions and after any single contingency. For direct current (DC) grids, transfer capacities must be computed such that voltages at the DC nodes are within acceptable ranges in

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normal conditions and after any single contingency. However, some aspects such as voltage issues in the AC grid are not considered, specific measures (e.g. installation of reactive power compensation devices) might have to be taken to allow the simulated dispatch to take place while maintaining a N-1 secure grid. A transmission project linked to an offshore grid might avoid such measures by contributing to security beyond aspects already considered in the socio-economic welfare impact assessment. For example, a VSC-based HVDC converter can contribute to reactive power compensation and voltage stability and could thus avoid the investment in capacitor/reactor banks (or other devices). A first category of benefits related to the security aspect of reliability is thus constituted by avoided investments.

However, even if the N-1 security rule is a standard to assess and manage a grid, the level of security of a grid goes beyond the behaviour towards single contingencies. Indeed, contingencies not covered by the N-1 rule (e.g. busbar fault, tower failure) happen as well and can lead to demand loss. A project can improve the ability of the grid to withstand disturbances beyond single contingencies: this is a second category of benefits related to the security aspect of reliability.

Finally, transmission projects linking different synchronous areas can improve the restoration capabilities. This is a third category of benefits that offshore grid's projects could bring.

How to calculate the KPI? – ideal vs practical execution

<u>Avoided investments</u>

Because thermal aspects in both the AC and the DC grid and steady-state voltage aspects in the DC grid of the N-1 security rule are already considered in the evaluation of the socio-economic welfare. The evaluation of avoided investments to respect the N-1 security rule must go beyond these aspects. Ideally, the benefits related to avoided investments for a specific transmission project (or in this case a specific offshore grid solution) should be estimated through the determination of investments needed with and without the project (or in the case of offshore grids the difference in investments of different alternative grids) based on standard security analyses (static and dynamic). It must be noted that a pure power flow study will analyse quasi-steady-state voltage issues in the AC grid (i.e. violation of voltage limits and voltage stability) and will thus reveal only the needs of capacitor/reactor banks that have a minor cost compared to the typical costs of offshore transmission projects. In contrast, the estimation of avoided costly investments (e.g. STATCOM, SVC) must rely on a dynamic study, requiring detailed data and a significant amount of computations. Quantification is therefore only advised in the ideal CBA methodology and for the practical CBA methodology a qualitative assessment identifying the possible avoided investments is advised.

<u>Improvement of security beyond N-1 events</u>

The improvement of the system's security beyond N-1 events can be assessed in two ways: either through a deterministic approach, or through a probabilistic approach. In the first way, a pass/fail criterion can be used to assess the security of the system towards more extreme contingencies: either the system fulfils the security criteria, or it does not, similarly to N-1 assessment. Such a deterministic analysis is easy to perform but is difficult to interpret and no monetization is possible. In contrast, a probabilistic approach aims to estimate the

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average consequences of the lack of security in terms of meaningful metrics that can be converted into a monetary value (e.g. Expected Energy Not Supplied, similarly to adequacy assessments). The main idea behind probabilistic security analyses is the following: if the system is not secure towards a specific set of contingencies, unacceptable conditions will occur (e.g. overloads, voltage problems, instabilities, etc.). These problems can end up in the loss of additional elements (cascading effect), and the eventual loss of load can happen (e.g. localized loss of load at one or a couple of isolated buses, partial blackout, total blackout). The main aim of a probabilistic security assessment is to estimate the risk of loss of load. Ideally, an estimation of the benefits linked to the improvement of security beyond N-1 events should be based on a probabilistic simulation of cascading outages following unsecure contingencies, in a dynamic fashion and considering potential maloperation of protection systems. However, there is currently no standard methodology for AC grids, and the problem of cascading outages in DC grids has not yet been thoroughly analysed. Further R&D work is needed to define a methodology for the computation of the associated KPI. Quantification is therefore only advised in the ideal CBA methodology and for the practical CBA methodology a qualitative assessment estimating if the project can improve the security beyond N-1 events is advised.

Impact on restoration (black-start services)

After the occurrence of a blackout (partial or total) in an area, the power system must be re-booted such that power plants can be restarted, and consumers resupplied. This is the restoration process. To initiate the restoration process, black-start services must be provided by generation units, storage units or HVDC links. A meshed offshore grid could improve the restoration process by either reducing the time needed to resupply the customers or it could reduce the costs related to the procurement of black-start services for a specific restoration. However, it should be noted that black-start services management in Europe is changing (from a centralised management inherited from the vertically integrated electricity sector to a market based management), and there is no uniformity between the different countries. A qualitative analysis of the impact on restoration is thus proposed for offshore grid projects.

6.2.6.4 SECURITY OF SUPPLY – RESILIENCE

Definition

Resilience of a power system can be defined as its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event.

Relevance for the CBA of offshore grids

The North Seas could provide a significant share of European energy capacity. In that case, European load supply will be highly reliant on offshore wind energy and on offshore grids. The resilience of offshore grids to storms and earthquakes will be critical to ensure the security of supply of Europe.

How to calculate the KPI? – ideal vs practical execution

Ideally, the contribution of a project to power system resilience should be estimated through a quantitative

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assessment. Recent works on the topic divided such an assessment in four phases.[28] The first phase consists in modelling the magnitude, the probability of occurrence and the profile in space and time of the hazards considered (e.g. earthquakes, floods, windstorms, hurricanes). The second phase consists in modelling the response of each vulnerable component to the hazard using fragility functions (or fragility curves). The third phase consists in an evaluation of the capacity of the power system to keep supplying the load after the loss of several (potentially numerous) elements due to the hazard occurrence ("survivability"), or in an equivalent way, in evaluating the loss of supplied power. Finally, the fourth phase consists of modelling the restoration process, based on an estimation of the time needed to repair each damaged component. In the context of offshore grids, the lack of data hampers the application of the second phase. There is a lack of existing offshore HVDC systems and therefore there is a lack of operational feedback to characterize their response to extreme events. Note that the response depends on the type of platform used (or the artificial island, if applicable). Furthermore, there is a lack of data to allow for the estimation of the time needed to repair damage components. When multiple components are damaged, it could be difficult to mobilize simultaneously different repair teams. Note that a full repair of the offshore grid component will be at liberty to environmental factors such as weather and environmental conditions. Therefore, a detailed quantitative assessment is currently difficult. A qualitative estimation of the impact on resilience is thus proposed for the practical CBA of offshore grid projects, based on an estimation of the consequences (e.g. loss of power infeed to the onshore grids) of the loss of critical assets (e.g. loss of a platform). For that purpose, a preliminary analysis of the hazards that could threaten the offshore grid is needed. For the ideal CBA methodology quantification is advised. Probably a similar method described as the second paradigm in section 6.2.6.1 (Security of supply – Adequacy) would be suitable. In this case this would mean to aim for similar resilience for all alternatives and quantify the cost of the implications to realise this resilience.

6.3 COST

Two types of indicators are defined to capture the costs of all project alternatives: capital (CAPEX) and operational (OPEX) costs. Other cost indicators might be considered as well within the context of offshore grids, as highlighted throughout the following paragraphs.

6.3.1 C1 CAPEX

Definition

The capital expenditure (CAPEX) indicator reports the capital expenditure of a project, which includes elements such as the cost of obtaining permits, conducting feasibility studies, obtaining rights-of-way, land, preparatory work, designing, dismantling, equipment purchase and installation. CAPEX is established by analogous estimation (based on information from prior projects that are similar to the current project) and by parametric estimation (based on public information about cost of similar projects). CAPEX is expressed in Euros.

[28] S. Espinoza, M. Panteli, P. Mancarella, H. Rudnick, "Multi-phase assessment and adaptation of power systems resilience to natural hazards," Electric Power Systems Research, vol. 136, pp. 352-361, 2016.

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Relevance for the CBA for offshore grids

Costs need to be determined, quantified and monetised to be able to compare solutions for offshore grids. These costs comprise both the costs for offshore grid alternatives and the costs of reinforcements and extensions of onshore grids. For the offshore grids, differences in costs may arise from differences in wind capacity, wind locations, offshore grid solutions, onshore grid solutions, connection point locations between the onshore and offshore grids, time of investment and different ways of including storage (including power-to-gas (P2G) and gas transport).

How to calculate the KPI? - ideal vs practical execution

Quantification and monetisation should be used both in the practical and ideal CBA methodology. A net present value calculation can be adopted with the below assumptions (see also section 5.7.3). Full quantification of the onshore grid reinforcement is considered beyond the scope of the practical CBA since this would require optimisation of the full European grid (see also section 5.4.3). Quantification will be done in a simplified way. The use of storage will not be taken into account in the practical CBA. In the ideal CBA methodology, however both onshore grid and storage are part of the assessment.

Assumptions for the practical CBA are, in line with the recommendations from ACER:[29]

- ***Depreciation / lifetime***: in the ENTSO-E CBA guideline, a value of 25 years of economic lifetime of assets with a residual value of zero is advised based on the recommendation of ACER.[30] 30 years seems more appropriate but in case of decommissioning there is a negative residual lifetime. Therefore, it is advised to use 25 years of economic lifetime with a residual value equal to zero and no decommissioning cost.
- ***Discount rate***: a societal discount rate of 4% (2012).
- ***Cost of temporary construction***: This is considered to be included in the CAPEX cost.
- ***Workforce training cost***: These costs are highly uncertain and could be considered part of the installation cost (should be covered in the cost of components). Therefore, there is a risk of double counting. These costs are more important for a financial CBA rather than a societal CBA.
- ***Decommissioning costs*** will not be taken into account with a 25-year economic life (see economic life). It is assumed that once the offshore grid has been developed, assets will be replaced with new assets, rather than just being removed completely at the end of their life.
- ***Onshore grid reinforcement costs*** will be considered only close to the shore (in the European approach maybe connect Dutch wind to Germany) but not within countries (e.g. reinforcement needs within Germany). The included costs could be in the form of a longer cable to connect the offshore grid to a more robust substation.

For the ideal methodology, more effort needs to be put into the cost of temporary constructions and workforce training. Also, the residual value should be determined and decommissioning and replacement cost need to be

[29] ACER Opinion on ENTSO-E CBA Methodology - Jan 2014.
[30] ACER Opinion on ENTSO-E CBA Methodology - Jan 2014.

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included. The residual value could be set at zero when working with annuitized investment (conform ENTSO-E CBA Guideline). Additionally, the investment cost of grid components will in reality not necessarily stay constant, but learning effects could change costs over time. This introduces uncertainty in the investment costs of components. The ideal CBA methodology should thus account for this uncertainty through, for example, various cost learning curves.

In the practical CBA methodology, onshore grid reinforcement could be taken into account in a limited manner as it is beyond the scope of WP12.2, and not practically feasible, to evaluate the reinforcement needs of the whole European grid. Onshore grid reinforcement could be taken into account as follows:

- Determine the unique hosting capacity of the countries surrounding the meshed grid for each project alternative,
- If the first substation is saturated, measures should be taken to reinforce in a simplified way by connecting to the next appropriate substation further inland. Effects close to shore should be modelled (shallow connection).

In another approach, it could be considered that the costs for onshore grid reinforcement are equal for each project alternative under a certain scenario, given the high volume of wind energy capacity that will need to be evacuated (see also section 5.4.3). Hence, onshore grid costs can be assumed to not count towards project evaluation. In the ideal CBA methodology, a more extensive evaluation and quantification/monetisation is required to show possible differences in cost based on multiple onshore grid scenario.

Interaction with other KPIs

The capital expenditure represents costs and needs to be strictly separated from the benefits (which may be avoided costs) to prevent double counting. CAPEX interacts with OPEX where OPEX is expressed in percentage of CAPEX.

6.3.2 C2 OPEX

Definition

The operating expenditure (OPEX) is based on the project operational and maintenance costs. OPEX of all projects must be given on the actual basis of the cost level with regard to the respective study year (e.g. for TYNDP the costs should be given related to 2018) and expressed in Euro per year.

Relevance for the CBA for offshore grids

The same considerations apply as for CAPEX.

How to calculate the KPI? - ideal vs practical execution

OPEX needs to account for the cost of operating the electricity system. This concerns losses in the network and costs of redispatch. Losses are already covered in B5. Redispatch costs arise through bottlenecks in the network and through bidding zones that are not well-chosen. They occur through changes in forecast. It is not

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yet possible to calculate N-1 redispatch cost. It is therefore not realistic to perform this analysis fully within PROMOTioN as no meaningful result would be obtained from this analysis on a European scale. The probability of forecast errors, is assumed similar for all project alternatives and it could be assumed that the offshore grid concepts will not have significant differences in redispatch costs. Moreover, redispatch mechanisms are different for the different market areas and are very complex to capture in a practical CBA. Therefore, in the practical CBA, redispatch costs will not be taken into account.

For the ideal CBA methodology, until models are available to capture the possible redispatch cost, it is advised to build a simplified model to understand the impact of redispatch on a limited scale. This might allow the CBA to get a better understanding of the redispatch costs of the offshore grid. For example, a parallel path along the coast of the United Kingdom could be created as this will show a significant impact on redispatch. Germany has a relatively small coast line with the North Sea, which will probably show a small impact on redispatch within Germany. Redispatch costs are thus complementary to the CBA but not part of the main CBA.

The following items will not be part of the OPEX:

- ***Curtailment of RES*** will be evaluated in MWh not in costs. This effect is partly included in a monetised manner under KPI B1 socio-economic welfare. The MWh curtailed are captured under KPI B2 RES integration.
- ***Opportunity cost: dealing with uncertainty*** (see also section 5.7.5).[31] Valuing the offshore grid under uncertainty through, for example, multiple scenarios can get very complex if using a real options approach. Within the practical CBA, potentially a small case study could be executed to determine the value of real options using the same probability for different options/scenarios. Alternatively, a minimax regret framework[32] could be used within WP12. In this framework, the maximum regret will be minimised without the need to attach probabilities.

Interaction with other KPIs

Like CAPEX, OPEX represents costs and needs to be strictly separated from the benefits (which may be avoided costs) to prevent double counting. OPEX interacts with CAPEX where OPEX is expressed in percentage of CAPEX. The monetisation of the grid losses is already accounted for in B5.

6.4 RESIDUAL IMPACTS

The three indicators for the residual impact - Social, Environmental and Other impact - refer to the impacts that remain after impact mitigation measures have been taken. That means that impacts that will be mitigated by additional measures are not relevant here. Possible residual impacts of offshore grids have not been identified yet, but residual impacts are estimated to have a small influence. In the practical CBA, residual impacts are not quantified but only assessed through a qualitative discussion. For the ideal CBA methodology, further effort

[31] Konstantelos, Ioannis & Moreno, Rodrigo & Strbac, G. (2017). Coordination and uncertainty in strategic network investment: Case on the North Seas Grid. Energy Economics. 64. 131–148. 10.1016/j.eneco.2017.03.022.

[32] https://www.youtube.com/watch?v=NQ-mYn9fPag

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needs to be made when practical alternatives are defined based on the importance of residual impacts determined by the project promotor. Possible residual impacts to be evaluated in the offshore area are at the discretion of the project sponsor. Examples of residual impacts in the offshore area are provided in Appendix I: List of indirect and residual effects of offshore infrastructure. Depending on the project, certain impacts might be relevant.

6.4.1 S1 ENVIRONMENTAL

Definition

Residual environmental impact characterises the (residual) project impact as assessed through preliminary studies and aims at giving a measure of the environmental sensitivity associated with the project.

Relevance for the CBA for offshore grids

An overhead line or underground/submarine cable may run through environmentally 'sensitive' areas. This could lead to an irreversible impact on the seabed and marine life, even with implemented mitigation measures. Additional activity at sea may have a detrimental or positive impact on the environment. The necessary strengthening of the onshore grid may influence the environment as new overhead lines are developed. Besides CO_2 emissions, other emissions like NOx, SOx and particles could differ depending on project alternative. Ecological impacts are seen as part of the residual environmental impacts.

How to calculate the KPIs? - ideal vs practical execution

In the practical CBA, the possible impacts are briefly discussed without quantification. In the ideal methodology, effort will be taken to quantify possible impacts. This may include cost of protection, as well as cost of DeNOx, DeSOx and dust removal. Also, the full life cycle effect of all relevant emissions may be relevant here although this is expected to be less important when comparing alternatives.

Interaction with other KPIs

Interaction with B1 socio-economic welfare.

6.4.2 S2 SOCIAL

Definition

Residual social impact characterises the (residual) project impact on the (local) population affected by the project assessed through preliminary studies. Local population includes all humans and animals that might be affected. The aim is to quantify the social sensitivity associated with the project.

Relevance for the CBA for offshore grids

Strictly speaking there is hardly a local human population offshore, except people who are there professionally like fishermen and crews on other ships. However, new societies may emerge with the development of offshore hubs like the proposed energy islands that will house a permanent population. When we also involve the onshore grid, overhead lines or underground cables may influence (local) population. Further, the offshore wind parks might be visible from coastal communities and might alter the physical appearance of the landscape.

How to calculate the KPIs? - ideal vs practical execution

Residual social impact should be assessed using a qualitative method. In the practical CBA, these may be neglected based on the assumption that each project alternative will lead to comparable social residual impacts

Interaction with other KPIs

Interaction seems relevant with KPIs B1 socio-economic welfare and B4 societal well-being. For the local population, the balance between these KPIs and the residual social impact may be different than for those not based locally. For instance, the negative residual social impact from new overhead line close by may outweigh the positive social impact from less CO_2 emission. A concept known as 'not in my backyard' is likely to apply, this is where a population supports the project as long as they are not being directly influenced by it.

6.4.3 S3 OTHER

Definition

Other impacts provide an indicator to capture all other impacts of a project.

Relevance for the CBA for offshore grids

Offshore grids are very large systems that may impact the society in ways we haven't thought of (yet).

How to calculate the KPIs? - ideal vs practical execution

This depends on the impacts that may come forward from further experience and research into the offshore grid. Since no other impacts have been identified (yet), the practical CBA will not account for these items but only mention other impacts that may exist. For the ideal CBA methodology, we advise the project promotor to carefully think of other impacts and try to qualify and quantify them.

Interaction with other KPIs

Depending on the impacts that are discovered interaction will be investigated.

6.5 SUMMARY OF KPIS

This Chapter discussed the relevant KPIs to be used in the CBA for offshore grids. The starting point is again the ENTSO-E CBA methodology. For the assessment framework as well as for the determination and definition of the KPIs, the main question is to what extent an offshore grid assessment framework differs from the ENTSO-E framework. For all involved KPIs, a definition was given and its relevance for the CBA for offshore grids. The calculation method of the KPIs and their interaction with other KPIs was also presented. For the calculation, a distinction was again between the ideal situation and the practical execution.

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The following KPIs have been identified as relevant to offshore grids.

Benefits:

- B1 Socio-economic welfare
- B2 RES integration
- B3 CO_2 variations
- B4 Societal well-being
- B5 Grid losses
- Security of supply
    - B6 Security of supply: adequacy
    - B7 Security of supply: flexibility
    - Security of supply: security
    - Security of supply: resilience

Costs:

- C1: CAPEX
- C2: OPEX

Residual impacts:

- S1 Environmental
- S2 Social
- S3 Other

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7 SUMMARY

To understand the economic and social consequences of undertaking an offshore grid development in a particular region, it is necessary to perform a cost benefit analysis to assess the value and costs of the meshed offshore grid to society. In order to perform this cost-benefit analysis, a CBA methodology should be employed that sets out a clear set of guidelines to ensure the transparent assessment and comparison of alternative offshore grid solutions.

Existing methodologies are generally insufficient when assessing complex systems such as offshore grids. Therefore, there is a need to develop a CBA methodology within the scope of PROMOTioN, which is well-suited to assess the value of offshore grid alternatives to society. This deliverable provides a set of guidelines to follow when performing a societal CBA analysis for offshore grids.

The presented methodology aims to enable the comparison of alternative offshore grid configurations in a certain geographical area, given developments of offshore wind capacity in the researched area. The CBA methodology set out the criteria and guidelines for the assessment of the costs and benefits of a complex project, i.e. an offshore energy system. A common set of indicators (KPIs) was defined to compare all project alternatives in a transparent manner. An offshore grid was defined in the context of the CBA methodology as a configuration of offshore infrastructure assets that enables:

(i) the connection and evacuation of foreseen offshore wind energy in a defined offshore area to surrounding onshore grids, and

(ii) the increase of market integration through offshore cross-border interconnections.[33]

The “best” offshore grid topology from a set of defined alternatives will be identified through the developed societal CBA methodology. The “best” configuration of an offshore grid is defined as the “project alternative” that will have the greatest value to society as a whole, this will be determined by the KPIs.

The societal CBA methodology developed in this deliverable, provided guidelines on the choices and options when comparing offshore grid solutions, the KPIs to value alternative configurations and the assessment framework. Throughout this deliverable both an ideal and a practical CBA methodology were detailed. The ideal methodology encompassed more complexity and levels of detail. To fit within the scope of the PROMOTioN project, a more practical CBA methodology was described to enable the assessment within the scope and time constraints. This practical CBA methodology will be used within WP 12.2 for the CBA assessment.

[33] Within the PROMOTioN project, the researched area will be the Northern Seas and evacuation of offshore wind to the surrounding countries.

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APPENDIX I: LIST OF INDIRECT AND RESIDUAL EFFECTS OF OFFSHORE INFRASTRUCTURE

The following list of indirect and external effects in the offshore area is taken from: "Maatschappelijke Kosteneffectiviteit van ruimtelijke opties voor offshore Windenergie MKEA Windenergie Noordzee", eindrapport, Decision, 27 oktober 2010 (only in Dutch), translated from Dutch, and "North Sea Grid – Offshore Electricity grid implementation in the North Sea. Final report", 2015.

"Maatschappelijke Kosteneffectiviteit van ruimtelijke opties voor offshore Windenergie MKEA Windenergie Noordzee, eindrapport, Decision, 27 oktober 2010 (only in Dutch)", translated from Dutch:

INDIRECT EFFECTS

Possible effects to oil and gas:

- Accessibility of existing platforms decreases
- Recently explored fields could become inaccessible
- Additional costs to exploit new fields

Effects for shipping:

- Changes to shipping routes requiring diversion routes
- Changes in safety (collision risk with turbines and other ships or obstacles)

For harbours, the following effects are expected:

- Shipping detours lead to higher costs and make it harder to compete with other harbors
- Without enough anchor possibilities in desirable locations, the efficiency of the harbors decreases
- The green image of the harbor can improve

Expected effects for sand mining:

- Sand mining locations become inaccessible. Dredgers need to make detours.

Possible effect for the fishing sector:

- Abundant fishing areas become inaccessible
- Shipping detours are required to access areas with abundant fish
- In the remaining fishing areas, the number of fisheries increases

DESCRIPTION OF EFFECTS

The effect on the fishing sector depends on certain factors:

- Are the wind farms being located in fishing areas?
- Are the wind farms being placed on shipping routes to fishing areas?

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- Is co-use of the area of wind parks possible?

North of the Wadden Islands there is military training zone for the Ministry of Defense where wind parks could be located. Possible effects are:

- The Ministry of Defence has to change training grounds to other areas that could be better or worse accessible
- Within existing training grounds, radar disturbances could occur
- The safety within and next to training grounds changes

Possible effects on radar systems:

- Radar operation can be disturbed

For the recreational sector three relevant effects could occur:

- Possibilities for recreational shipping could be reduced, or expanded if co-use of the wind farm areas is possible
- Beach recreational users could be impacted by the visual change to the landscape caused by the offshore infrastructure. The beach users could be less inclined to visit the beach in future and it could lead to a reduction in income for the local area. However, it could have the opposite effect if the beach users find the offshore infrastructure to be an interesting sight.
- Prices of (holiday) real estate in the coastal area could decrease due to the visual impact of the offshore infrastructure.

Possible effects on the job market:

- Creation of jobs in the offshore industry
- Creation of a shift in employment on the national job market

EXTERNAL EFFECTS

In this chapter, external effects will be discussed that could occur when developing win farms in the offshore area. External effects apply to the environment and ecology.

Emissions

Emissions with energy generation

CO_2-emissions: an important goal of renewable energy supply is a reduction in CO_2 emissions

Other emissions: The generation of *grey* electricity does not only lead to CO_2 emissions but also the emission of NO_X, SO_X or small particles (PM10)

Emissions when circumnavigating and developing wind parks

Emissions as external effect consists of the following components:

- Due to detours of ships, additional fuel will be used, leading to increased harmful emissions in the shipping sector
- The building of wind turbines requires energy, resulting in increased CO_2 emissions

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Ecology

Developing wind parks offshore leads to the following potential ecological effects:

- The occurrence of collisions between birds and wind turbines
- Disturbances to migratory birds and marine animal routes
- Changes in the living and feeding grounds of birds
- Implications on the breading season of birds
- Implications on the migration of fish larvae
- Changes of water flows
- Noise pollution or disturbances and hearing damage with sea mammals
- Changes in sea bed vegetation
- Vibrations

Clear horizon view

Restrictions in the free viewing of the sea depends on two factors: how close the wind farms are located to shore and the extent of the shore from which they are visible.

North Sea Grid – Offshore Electricity grid implementation in the North Sea. "Final report", 2015.

Other environmental impacts

This section presents a general qualitative evaluation of environmental impacts in terms of kilometres of line. For all environmental effects, other than RES integration and CO_2 emissions, it is assumed that they are proportional to line length and that they do not depend on any other parameter. These are for example audible noise, visual pollution, etc.

Strategic benefits

Security of Supply

The security of supply benefits are not directly evaluated. However, they are considered in the calculation of the generation investment cost savings: the investment cost savings are evaluated in SCANNER at constant reliability level.

A large, meshed offshore grid in the North Sea would be a critical infrastructure for the security of supply in Europe. While such a grid could support the onshore grid by providing alternative transmission paths, it has to be assured that a failure in the offshore grid does not lead to stability problems or even black outs in the onshore grid. This concern has been taken into account in the study. The offshore hubs are limited to 2 GW based on technology limitations. Submarine cables are limited to 2700 MW. A loss of a single element in the offshore grid will therefore not lead to a loss, greater than the current largest single outage in Europe, which is 3 GW.

Competition Benefits

The analysis of the competition benefits is based on qualitative estimations on the different impact that is expected to derive from each of the considered scenarios. As a matter of fact, it would not be possible to

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quantify the effect of this benefit, nor in terms of prices, nor in terms of market composition. Nevertheless, as the analysis relies on a qualitative analysis of the presence of barriers preventing competition to provide evidence of the different effect of each option, scenarios are hierarchized.

Competition benefits arise when market conditions allow for an increase in the number and or rivalry between players to grasp profits or favorable conditions. As generally regarded, in the case of free market, competitors overall increase benefits resulting from consumer price drop (i.e. price competition) and/or better products or services (i.e. quality competition).

Apart from market failures, competition therefore provides either better prices, better services or both. This positive impact is hereby assumed valid as there is no evidence to consider differently.

In the considered case, competition is currently limited by the presence of entry barriers, which hinder the opportunities for potential entering firms to gain profits at reasonable risks.

Thee major barriers have been identified and are hereby assessed for each considered scenario:

- limited connectivity;
- congestion of the infrastructure;
- technological limits.

Additional Benefits

The following additional benefits were not investigated in the scope of this study but can be added to the previous results:

- Investment savings in onshore grid. For certain scenarios, less investment in the onshore grid may be required thanks to the development of the offshore grid. Such combined optimization of onshore and offshore grid was out of the scope in the present study.
- Speed of construction. Instead of connecting each wind farm to the closest onshore substation as in the radial case, the HVDC cables connecting the hubs to shore in the meshed case could be connected directly at a load centre farther inland. It is expected that it is easier to obtain permits for an HVDC underground cable connection than for an overhead line that would be needed to reinforce the grid between the coast and the load centre in the radial case.

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