North Sea Energy

Value of a coordinated offshore power grid for offshore energy sectors

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Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken, Nationale regelingen EZ-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland.

Executive summary

In the current situation offshore power infrastructure is developed and deployed most dominantly for the offshore wind sector. A power grid in the future will also potentially serve other purposes than transporting wind energy to shore, but this is not yet studied in detail yet. This warrants an assessment of the value of joint-developments regarding platform electrification and offshore power grid developments. The objective of this study is to assess the value of developing a shared power grid for system integration. Within the research the value of an offshore power grid is determined as the difference between (A) the sum of value created when selected platforms are connected individually to IJmuiden Ver to (B) the sum of value created when stakeholders collaborate and the selected platforms are connected through an offshore power grid to IJmuiden Ver. As multiple stakeholders are involved in developing and utilizing an offshore power grid, the research assesses multiple types of values.

The value assessment consists of three steps. In the first step, the values which are part of the analysis are determined by means of the Value Creation Canvas method. This stakeholder value analysis results in criteria that represent the value of the power grid. In the second step, three scenarios are developed in detail to set the stage for individual or collaborative grid development. These scenarios are based on the system integration option which is applied at the platform: Electrification, CO_2-storage and Electrification + CO_2-storage. In the third and last step, the value of each scenario is assessed per value criteria including cable costs, emission reduction, business model lifetime and organizational complexity.

In all three scenarios considered in the analysis, the cable investment costs per platform are 54 - 66% lower for a power grid compared to an individual connection to the platform. This leads to an investment cost reduction of 21-26 million euro per platform. The power demand of CO_2-storage is significantly lower than the power demand for platform electrification. When a power grid is developed for electrification, it is also dimensioned for CO_2-storage activities on the platforms.

In the scenario Electrification, 480 kiloton CO_2 emission that is attributed to the 10 platforms combined could be realized annually. This local reduction directly relates to the elimination of fuel gas consumption and is based on the fuel gas consumption in 2017. This amount is calculated by limiting the scope of the system under consideration to the platform fuel gas emissions due to gas turbine operation only, this is an indication of locally reduced CO_2-emissions. When the platforms close to IJmuiden Ver offshore wind farm replace fuel gas-based electricity supply with green electricity supply, the total GHG and NOx emissions attributed to one m^3 NG produced on the Dutch North Sea may be reduced by approximately 16% of GHG and 25% of NOx. The impact of the power grid is dependent on the amount of additional electrification due to reduced investment costs.

In developing an offshore power grid, relations between platform operators, grid suppliers and renewable energy suppliers have to be maintained. With an increasing number of platform operators, the complexity of the cooperation will increase. Agreements have to be made on operating the grid, sharing the costs and responsibility for grid security. The complexity for a platform operator is lower in the case where an individual cable is developed compared to a power grid where all platform operators have to make agreements. Introduction of a central party that is responsible for the development, operation and maintenance of the power grid will decrease the organizational complexity. This central party could organize the platform operators and communicate on their behalf to the electricity supplier and engineering party.

These results lead to the following conclusion:

Developing an offshore power grid reduces the investment costs for connecting an offshore platform to the IJmuiden Ver substation. The investment reduction because of an offshore power grid increases the chance of a positive business case for system integration. In assessing the value of an offshore power grid both positive effects related to the investment reduction and negative effects due to increased complexity should be considered.

The researchers identified several additional considerations are valued in favor of an individual grid solution. These considerations were not analyzed in depth but should be considered. This are considerations based on the security of supply, a hub function for the platform closest to IJmuiden Ver and phasing of the grid development.

Developing an offshore power grid requires the acknowledgement of, and anticipation on, a wide range of interests amongst a diverse stakeholder network. The first step toward an offshore power grid is to create a consortium willing to realize an offshore power grid. In acquiring such a consortium it should be realized that several direct and indirect effects follow from an offshore power grid connecting offshore platforms.

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1. Introduction & Methodology

In the current situation the offshore power grid is developed and deployed most dominantly for the offshore wind sector. A power grid in the future will also potentially serve other purposes than transporting wind energy to shore, but this is not yet studied in detail yet. Offshore power transport cables are typically developed and deployed on a case-by-case basis; not with a future grid perspective. Also for offshore system integration, assessed in the former North Sea Energy program phases (I and II), platform electrification was mostly studied on a case-by-case basis. This results in that potential synergy between connecting multiple platforms or clusters to the offshore power grid or to the onshore grid has been neglected so far. High investments and economy of scale apply to installing power cables offshore. This warrants an assessment of the value of joint-developments regarding platform electrification and offshore power grid developments.

The objective of this study is to assess the value of developing a shared power grid that services both the offshore wind and offshore oil and gas sector in the IJmuiden Ver area

. By answering the following research questions scoped to the IJmuiden Ver area, this value is assessed:

- Which platforms are of highest interest for joined electrification development projects?
- How can offshore platforms be connected to the offshore and/or onshore power grid?
- Which scenarios are feasible for connecting these platforms in coordination with offshore wind developments?
- What is the value of a coordinated development of the offshore power grid in the Netherlands to serve both the offshore wind and oil & gas sector?

Within the study, the value of an offshore power grid is determined as the difference between (A) the sum of value created when all platforms are connected individually to IJmuiden Ver, compared to (B) the sum of value created when all stakeholders collaborate, and the platforms are connected through an offshore power grid. As multiple stakeholders are involved in developing and utilizing an offshore power grid, the research assesses multiple types of values are considered: business value and societal value. Furthermore, the research analyzed the organizational complexity of the proposed power grid.

The value assessment consists of three steps. Figure 1 illustrates these steps.

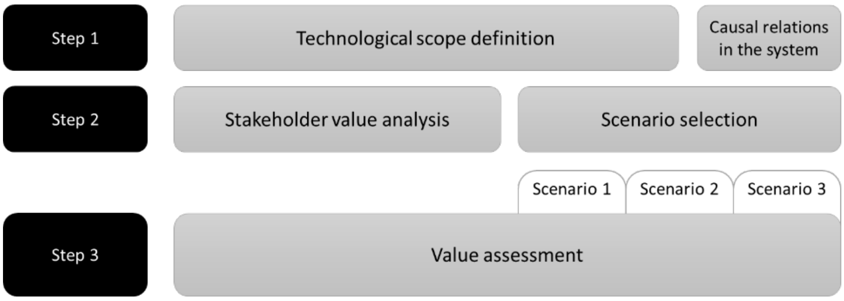

Figure 1 Stepwise project methodology

In the first step, the scope definition describes the technological interventions that are considered as well as the causal relations within the broader context to introduce non-monetary added values. Three technological interventions are considered at the platforms: Platform Electrification, offshore CO2-storage and an offshore power distribution grid. These interventions are described in the next paragraph. In the second step, three scenarios are developed based on the technological interventions and cable configurations. The second step also includes the formulation of the most important stakeholder values by performing a stakeholder analysis. This stakeholder value analysis results in criteria that represent the value of the power grid.
In the third and last step, the value of each scenario is assessed per value criteria.

In the following paragraphs we will discuss the steps more in depth.

1.1 Scope definition and causal relations in the system

In the first step of the study, the technological scope of the power grid is defined and the causal relations on which a power grid will have a direct or indirect effect are described. The scope the study is described as:

- Platforms connected to the IJmuiden Ver high voltage substation. The transmission system from IJmuiden Ver to shore is not considered. The Ijmuiden Ver wind farm scope is chosen based on the “Kamerbrief voortgang routekaart windenergie op zee 2030”, where a research question is posed for a more efficient use of the infrastructure in IJmuiden Ver.
- 66 kV voltage offshore electricity cables connecting platforms to the offshore wind farm transformer. In this study we will refer to this voltage level as high voltage. The TenneT transmission grid and DC high voltage infrastructure is out of scope.
- Operational offshore gas production platforms either:
    - Produce natural gas consuming electricity from diesel or fuel gas consumption;
    - Produce natural gas consuming electricity from an external source;
    - Storing CO_2 in empty gas fields.
- Other activities on platforms, such as possible hydrogen production, are out of scope for this study.
- Timing of grid and platform development is out of scope, as the goal is to value the offshore power grid and not the design of the grid.
- For CO_2-storage 2030 is used for determining injection rates to dimension the grid on representative power demand.
- For platform electrification, 2023 is considered as aim for electrified gas production, based on scenarios constructed in NSE 2.
- Pipelines and refurbishment of existing platforms are not within scope of this study, business case information related to platform electrification and CO2-storage is used from NSE 2 analysis.

To determine the impact of an offshore power grid, three technological interventions are considered in the study. Two interventions are system integration options considered within the North Sea Energy program, the third is the offshore power grid as investigated in this work package.

- *Platform Electrification:* this includes connection to the IJmuiden Ver high voltage substation, platform refurbishment is out of scope.
- *Offshore CO_2-storage:* this includes CO_2-distribution from a landing point near IJmuiden Ver. Electricity demand of CO_2 storage and transport is included, pipeline development for transport of CO_2 is excluded from the study.
- *Offshore power distribution grid*

These interventions have an impact on key factors that, together, describe the context in which the technological interventions are placed. Figure 2 depicts the key factors that represent the context as well as the relationships amongst factors and interventions.

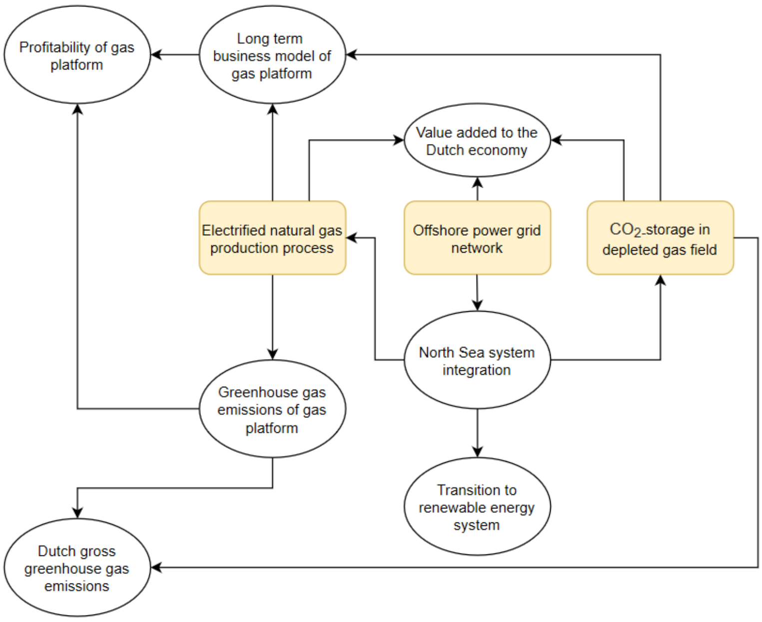

Figure 2 Context diagram of the offshore power grid network

1.2 Cost and value analysis

There is a wide range of interests and influence amongst the stakeholders involved in developing an offshore power grid. To analyze the value of an offshore power grid a structured approach is followed to determine the different types of values. First, an overview of possible stakeholders for development of the offshore power grid was composed. This overview is possibly non-exhaustive. From this overview, five stakeholders were selected for an in-depth value analysis. The five stakeholders were chosen by having a direct impact in the creation of an offshore power grid. When developing the power grid, all identified stakeholders should be involved.

The value analysis was conducted by means of the *Value creation canvas* **[1]**. The canvas, developed by TNO, aims to identify the changes in value proposition of individual actors by focusing on the current and future activities and required (im-)material resources to create that value. The project team aggregated the wide range of individual value propositions, into a set of five criteria was selected. An example of the Value creation canvas is included in Appendix D. Table 1 lists the actors considered as well as the actors analyzed with the value creation canvas. In Table 2 the five resulting criteria are described.

Table 1 Overview of possible stakeholders involved in an offshore power grid

Actors identified	Analyzed with *Value Creation Canvas.*
Gas platform operator	Yes
Offshore renewable energy producer (e.g. wind farm operator)	Yes
Transmission System Operator	Yes
Dutch government	Yes
Dutch Industry	Yes
Gas infrastructure operator	No
Asset management / operation & maintenance parties offshore assets	No
Offshore contractors (platforms, cable, pipeline)	No
Offshore asset supply chain stakeholders	No
Onshore residents impacted by North Sea development	No
CCS value chain	No
Foreign governments of North Sea countries (e.g. UK, DK, Ger)	No
NGO’s	No
Exploitants of the Dutch North Sea ‘’ruimtelijke (concurrenten) medegebruik zoals visserij/scheeptsvaart/militair/zandafgraving/…”	No

The set of five criteria aim to represent a significant part of the business and societal value of the offshore power grid. The criteria are aggregated to a generic level to incorporate as much of the viewpoints from different stakeholders. The researchers note that this value analysis is non-exhaustive. The value of the power grid is assessed using the criteria in
Table **2** for each scenario under consideration, as is described in the next paragraph.

Table 2 Description of the criteria selected for value assessment.

Criteria	Description
Cable costs	Investment costs for purchasing and laying cables. The costs are calculated for scenarios specified in Chapter 2 and through the scope specified in Chapter 3.
Added value for the Dutch economy	Qualitative assessment of the impact of investment reduction towards the added value in the Dutch economy.
Emission reduction	Reduction for the direct platform CO_2 emission due to reducing fuel gas and percentual impact on Dutch emissions related to natural gas production. The impact on Dutch emissions is calculated based on the NSE 1 LCA analysis.
Business model lifetime	Qualitative assessment of the impact of platform electrification and CO_2-storage on the economic lifetime offshore platforms. The extend of the lifetime extension is based on NSE 2 scenario analysis for system integration options on platforms.
Organizational complexity	The amount of relations that need to be maintained because of the development of an offshore power grid. The analysis considers relations between platform operators, O&M companies and grid operators.

1.3 Report Outline

In Chapter 2 the scenarios for platform electrification and CO_2-storage are described. Chapter 3 discusses the resulting cable costs for a power grid and in Chapter 4 the macro-economic value and emission reduction related to an offshore power grid is discussed. The impact on the business model of offshore gas operator is the subject of Chapter 5. In Chapter 6 we will discuss the organizational complexity of developing an offshore power grid and in Chapter 7 the conclusions of the study will be presented.

2. Scenarios

In this chapter, three scenarios are described that were used to analyze the offshore power grid connected to the offshore windfarm IJmuiden Ver. Each scenario consists of two designs (individual connection per platform to IJmuiden Ver and power grid connecting all platforms to IJmuiden Ver), which will be discussed in detail in this section. Two main activities are considered regarding the utilization of the electricity grid, namely (i) electrification of gas platforms in order to eliminate the use of fuel gas, and (ii) carbon storage in depleted gas fields.

Based on these two main activities three scenarios were defined:

1. **Electrification**: gas turbines used as direct mechanical drive for compression or local power generation, gas fired gensets, gas fired heaters or diesel engines may all be replaced by electrical drivers or electric heaters sourced by a power connection.
2. **CO_2-storage**: storing CO_2 in gas fields. To transport and inject CO_2 a power source is necessary, and this could be sourced by a power connection.
3. **Electrification and CO_2-storage**: Combination of both previous scenarios

The TenneT platform IJmuiden Ver beta[1] that will connect the wind farms in the IJmuiden Ver area is chosen as the main connection to provide the power to the connected offshore gas platforms. Therefore, only platforms that are in proximity to this TenneT platform are considered.

In the next paragraphs, the platform selection criteria will be explained more extensively. The selection criteria are based on the potential for electrification or CO_2 storage For each scenario two power grid designs were developed; (i) each selected platform is electrified individually, and (ii) an integrated offshore power grid is constructed that connects all selected platforms.

2.1 Electrification

The top 25 platforms with the highest consumption of fuel gas have been selected. Source of this information is from NLOG and if possible improved with information required in the MIDDEN project and previous North Sea Energy work. From these 25 platforms, the platforms with an expected decommissioning date - according to the fast scenario of NexStep - between 2018-2022 are disregarded. Further, platforms with a distance further than 150 km from IJmuiden Ver are disregarded and platforms that lie closer to other wind farms - which can be a source of energy - are disregarded because these are not in line with the scope of the IJmuiden Ver Area. Ten platforms remained after applying these criteria and these are selected for the electrification scenario.

The electricity demand on a platform consists mainly of power for the compressors. This electricity demand is calculated by multiplying the fuel consumption of the platforms by the thermal efficiency of the gas turbine, the thermal efficiency. An average thermal efficiency of 33% is assumed based on data from equipment vendors. In appendix C, the conversion table is shown. The fuel consumption of the platforms is drawn from the MIDDEN project [2] or the NLOG database[2] for the year 2017. For simplicity the electricity demand is assumed to be constant over the year. This leads to the electric consumption shown in Table 3. It is possible that gas is treated on these platforms for other operators the fuel gas consumption of this gas treatment is not in scope of the research. Therefore the electrification potential can be underestimated.

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[1] www.netopzee.eu/IJmuidenverbeta/waar-ligt-net-op-zee-IJmuiden-ver-beta

[2] www.nlog.nl/data/

Platform ID	Fuel gas consumption [million nm3]	Electric Consumption [MWe]
J6-A-Markham	33.1	14.7
K1-PA	8.3	*2.4*
K4-PA	11.9	4.2
K5-PA[3]	16	6.2
K5-PB[4]	*9.3*	*2.9*
K14-FA-1	58.4	27.2
L05-FA-1	8.9	2.7
L10-AD[5]	30.1	13.2
L9-FF-1W	27.9	12.1
L15-FA-1	9.7	3.1

Table 3: Electricity consumption per selected platform

The power grid designs for this scenario can be found in Figure 3. The power grid has been designed on the shortest distance between platforms. Other criteria for routing are not considered, this underestimates the true costs. In the cable cost calculation a margin of 10% is calculated to adjust for this underestimation.

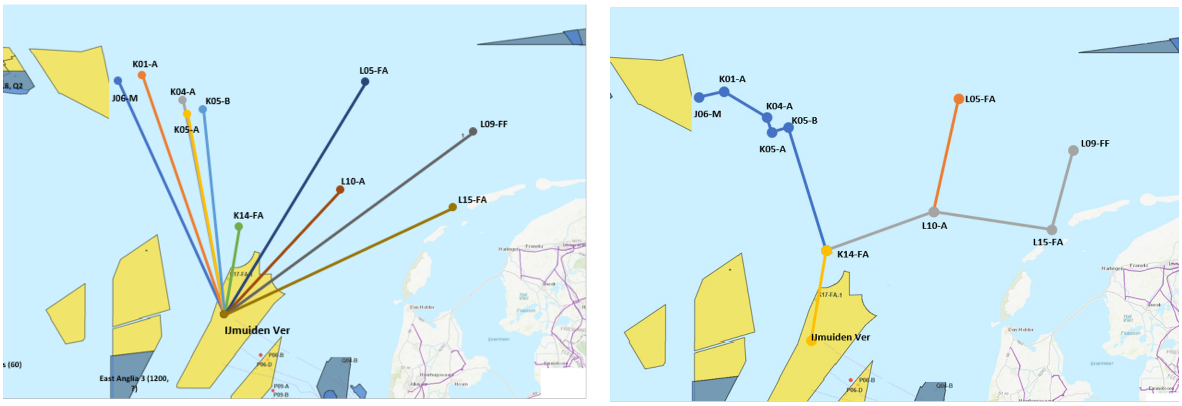

Figure 3: Each selected platform is electrified individually (left) and an integrated offshore power grid (right) in the electrification scenario. The design is based on the shortest distance between platforms and not on other routing parameters.

2.2 CO_2-storage

The top 15 platforms with the highest expected storage capacity potential have been selected based on data from EBN and Gasunie. Further, platforms with a distance further than 150km from IJmuiden Ver are disregarded and platforms that lie closer to other wind farms or are very close to shore - which can be a source of energy - are disregarded because these are not in line with the scope of the IJmuiden Ver Area. Thirteen platforms remained after applying these criteria and these are selected for the CO_2-storage scenario. In line with the CCUS roadmap, the assumption was made that in 2030, 30Mt/yr CO_2 will be stored among the selected platforms.

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[3] NLOG 2017 data was used, which might differ from the ‘MIDDEN’ and NSE 2 data, which is about the whole K5 complex aggregated. No subdivision per platform was available

[4] NLOG 2017 data was used, which might differ from the ‘MIDDEN’ data and NSE 2 data, which is about the whole K5 complex aggregated. No subdivision per platform was available

[5] The ‘MIDDEN’ data differed from the NLOG 2017 data. Since the ‘MIDDEN’ data was checked with the platform operators this was used.

Not every platform will start the injection of CO_2 at the same time and with the same rate. In order to incorporate the impact of different injection rates, two analysis are made.

- An analysis in which 2.3Mt/yr is injected, when the injection is divided over all platforms equally. This covers the extreme scenario when all platforms are phased at the same time.
- An analysis wherein each platform injects 5Mt/yr, which is considered a maximum regarding technical-economic considerations. This covers the extreme scenario where the platforms are phased sequentially.

The electricity demand to store CO_2 in de gas fields consists of:

1. **Compression on land:** This will be done using the electricity grid onshore and therefore not part of this analysis.
2. **Compression at sea:** In order to transport the CO_2 to the platforms it is necessary to keep the CO_2 at a certain pressure. The specific compression configuration depends on an economic optimization[6]. In this analysis we assume that every 50 km compression on sea is necessary to keep the CO_2 between 80 and 100 bar. The electricity need is assumed to be 1MW per 5Mt CO_2. This is an overestimation of the calculated electricity demand[7] to account for fluctuations in the CO_2 flow.
3. **Injection at the platforms:** the CO_2 needs to be injected in the gas fields. Since the CO_2 is already pressurized, electricity is only needed to operate the pipeline valves. A power supply of 100kW is enough to do this, including safety margins.
4. **Heating:** Heating of the CO_2 on the platform can improve the injection rate for empty gas fields. This means that on the platform additional heating equipment needs to be installed. This will increase the energy demand of the platform and also needs additional investment in heating equipment. Furthermore sufficient deck size is needed for heating. An offshore power grid can facilitate heating for larger platforms. The energy demand for heating is out of scope in this study as there is additional research needed on the technical and economical application of heating.

The CO_2 has to be transported from land where the CO_2 is captured. CO_2 can be transported either via ship or via pipelines. EBN and Gasunie assumed in their explorative study that the CO_2 will be transported via pipelines. A few possibilities have been mentioned in Porthos, Aramis and Athos project; 1) The CO_2 can be transported from Den Helder via the WGT pipeline to platform K14FA or the LOCAL pipeline to platform K15 – maybe even coming from Rotterdam by ship 2) Another possibility is transport via the NGT from Uithuizen. Yet this is a less realistic option for the near future as there are quite a lot of platforms that are expected to be decommissioned after 2027 dependent on NGT for their gas transport. 3) A last possibility mentioned is a new pipeline that will transport CO_2 from a more southern part of the North Sea. It is expected that the first storage of CO_2 will be in the more southern part of the north Sea as these reservoirs (such as P15 and P18) are closer to Rotterdam, are closer to shore and are sooner available because of their expected decommissioning date. In all these options, the CO_2 to be transported to the reservoirs in the IJmuiden Ver area will come through from the K14. This is why this study assumes the CO_2 will be transported into the selection platforms from K14.

Every 50 km compression on sea is necessary to keep to CO_2 within an acceptable pressure level. Platforms are identified which can function as a hub for this electricity demand. The electricity demand of these platforms depends on the amount of CO_2 that will need to be transported further along. This results in the power demand shown in Table 4.

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[6] Design process that includes injection pressure, flow, diameter distance and pipeline material.

[7] Calculated electricity demand for 5 Mt CO_2 is between 0.46 and 0.67 MW (dependent on temperature). For calculation see Appendix D

Platform ID	Activity	Electrical power demand at 2.3Mt/yr	Electrical power demand at 5Mt/yr
L13-FC	Injection	100 kW	100 kW
L02-FA	Injection	100 kW	100 kW
K04-A	Injection	100 kW	100 kW
K12-B	Injection	100 kW	100 kW
K14-FA	Injection and compression	5.7MW	12.1MW
K05-A	Injection and compression	1.1 MW	2.1 MW
L04-A	Injection	100 kW	100 kW
J06-Markham	Injection	100 kW	100 kW
K15-FA	Injection	100 kW	100 kW
K15-FB	Injection	100 kW	100 kW
L09-FF-1	Injection	100 kW	100 kW
K08-FA-1	Injection	100 kW	100 kW
L10-A	Injection and compression	1.5MW	3.1MW

Table 4: Electrical power demand of platforms for CO2-storage

In Appendix A, a visualization of the power grid configurations is shown. The power grid has been designed on the shortest distance between platforms. Other criteria for routing are not considered, this underestimates the true costs. In the cable cost calculation a margin of 10% is used to adjust for this underestimation.

2.3 Electrification and CCS

In this scenario the platforms and adjoining fields are selected when they occur in both the electrification scenario as in the CO_2-storage scenario. The scenario therefore captures platforms with a potential for electrification and CO_2-storage Platform operators may decide to start with CO_2-storage while production of gas is still running. Whether this is possible and wise is very reservoir specific. In this study we assume that CO_2-storage while start after the gas production seizes. The grid is designed on the maximum energy demand, therefore timing of the transition to CO_2-storage does not impact the grid design. The assumption is made that a maximum of 30Mt/yr of CO_2 is injected in the whole system, with a maximum of 5Mt/yr per platform. The electricity need per platform consists of the electricity for the mechanical drive for compression, the need for injection of CO_2 in the adjoining fields, and - on selected platforms - the need to keep the CO_2 on the right pressure. This results in the electricity demand stated in Table 5. This table shows that the demand for CO_2-storage is structurally lower as the demand for electrification. The calculations for the electrification and CO_2-storage power demand are specified in paragraph 2.1 and 2.2. Therefore, the grid will be designed based on the demand for electrification.

Platform ID	Electrical power demand for electrification	Electrical power demand for CO_2-storage
J6-A-Markham	14.7 MW	100 kW
K4-PA	4.2 MW	100 kW
K5-PA[8]	6.2 MW	2.1 MW
K14-FA-1	27.2 MW	5.1MW
L10-AD	13.2 MW	1.1MW
L9-FF-1W	12.1 MW	100 kW

Table 5: Platform selection for scenario electrification and CCS and the electrical power demand for both

In Appendix A, a visualization of the power grid configurations is shown. The power grid has been designed on the shortest distance between platforms. Other criteria for routing are not considered, this underestimates the true costs. In the cable cost calculation a margin of 10% is calculated to adjust for this underestimation.

The total power needed for CO_2-storage is significantly lower than the power demand for electrification. On the platform itself, only 100kW is necessary to operate the valves and on only a selected number of platforms extra power is needed to keep CO_2 at the right pressure. The total power demand for scenarios that include electrification of gas fired turbines is a lot higher, as can be seen in Figure 4. This result shows that the decision of storing CO_2 in depleted fields can be made after the power grid for electrification is already constructed.

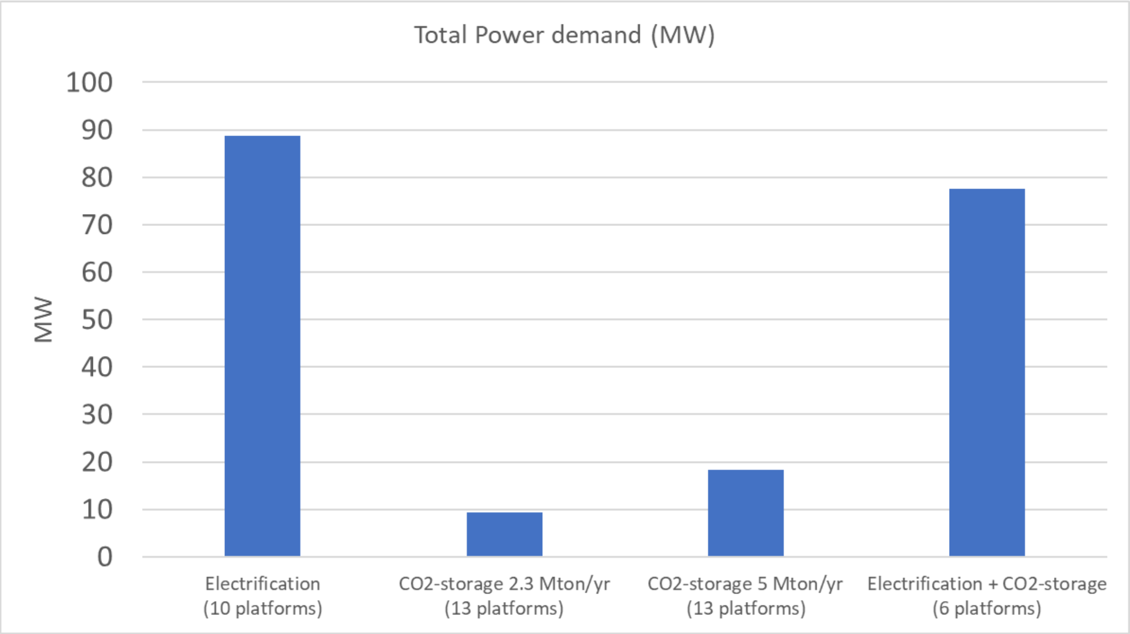

Figure 4 Total power demand per scenario in MW

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[8] For the electrification power demand NLOG 2017 data was used, which might differ from the ‘MIDDEN’ data, which is about the whole K5 complex aggregated. No subdivision per platform was available

3. Cable Costs

In this chapter the cable cost calculation of the different power grid designs will be discussed. These costs were calculated by TNO based on general assumptions and by North Sea Energy partner Boskalis Subsea Cables based on tender criteria. In paragraph 3.1, the TNO and Boskalis calculations are compared based on the Electrification scenario. In paragraph 3.2 the results for all three scenarios on the cable costs are calculated using the TNO calculation, following the grid designs as presented in Chapter 2. In Paragraph 3.3 the impact of the cable costs calculations on the business cases for platform electrification and CO_2-storage is discussed.

3.1 Comparison of cable costs of scenarios

The assumptions for the TNO and Boskalis calculation are compared in Appendix B. The results of the two studies are compared to create a benchmark for the cost calculations performed by the TNO method for all scenarios. The total costs as calculated by Boskalis are € 15 million (9%) lower than the costs calculated by TNO, as shown in Figure 5. This difference can be traced back to assumptions in the analysis:

1. In the TNO analysis an increase of 10% in distance is assumed to account for uncertainties in the cable laying route. This accounts for an additional 33 km of cable, and € 14 million higher costs.
2. The TNO and Boskalis analysis have made different design choices regarding cable material and diameter. TNO chose copper cables, whereas Boskalis opted for aluminum cables with a larger diameter. Overall, the cable costs of TNO are € 4 million more expensive (6% of the total investment costs).
3. TNO assumed a dual cable from Ijmuiden Ver to K14 to account for the large capacity on this line. Boskalis assumed a single cable with a larger diameter. This results in the TNO calculation in € 12,3 million higher costs, of which €1.2 million in cable costs and € 11.1 million in installation costs.
4. Boskalis made additional assumptions on accessories and cable joints. Overall this assumption accounts for additional costs of € 10 million. In Figure 6 it is shown that the purchasing cost per kilometer is higher in the calculation of Boskalis.
5. In Figure 6 it is shown that the installation cost per kilometer is higher in the calculation of Boskalis. This accounts for a € 5.8 million higher cost.

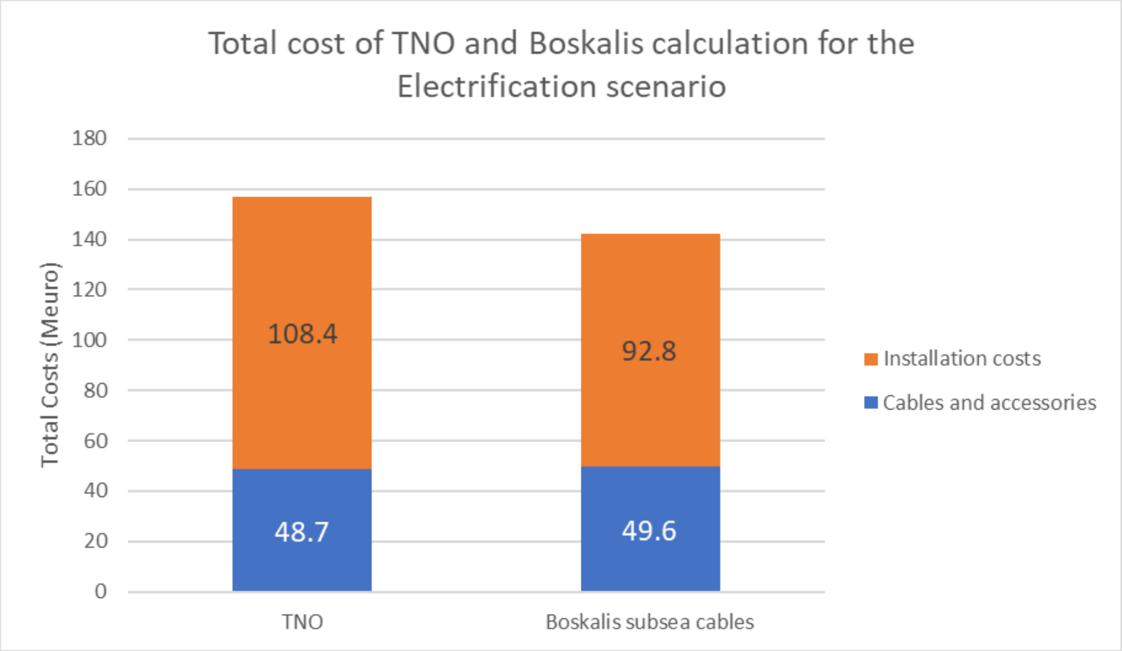

Figure 5 Total cost of TNO and Boskalis Subsea Cables calculation for the electrification scenario. The total cost is split into installation cost and purchasing cost for cables and accessories. The TNO calculation analyses a higher cable length.

From Figure 6 it can be seen that in the electrification scenario there is no difference between the assumed installation costs in the TNO analysis and the detailed analysis of installation costs performed by Boskalis. All differences are caused by design choices. For each specific case where the validity of an offshore power grid is evaluated, a specific design choice will be needed to calculate the actual costs. The in-depth analysis can be found in Appendix B.

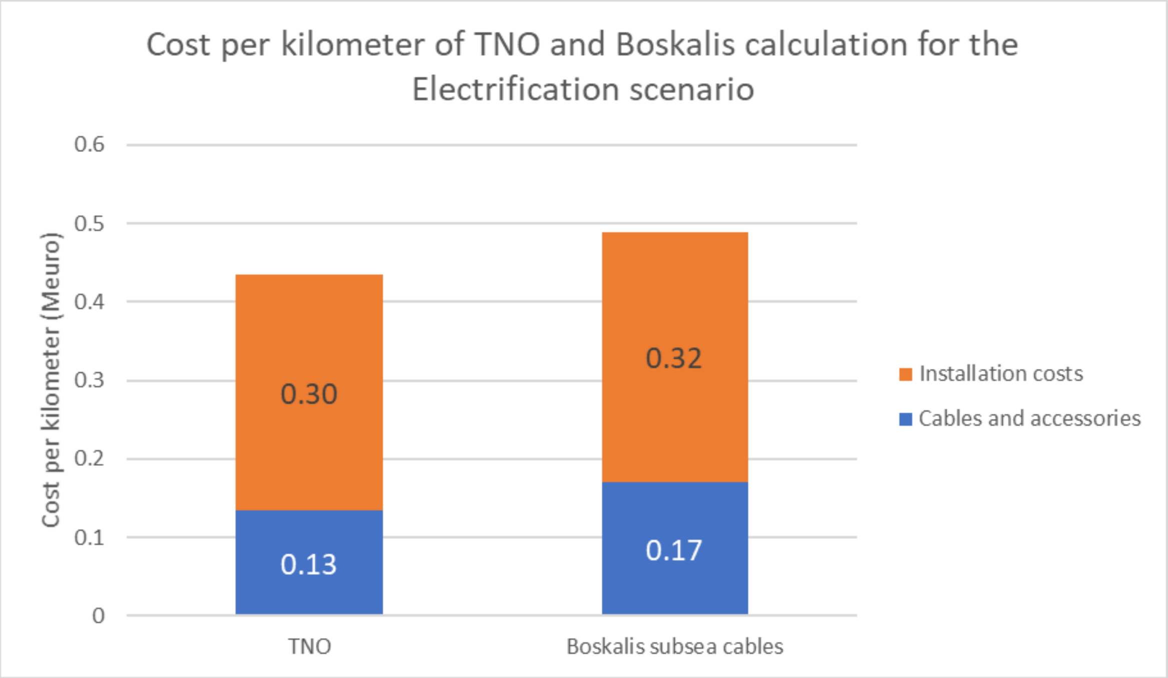

Figure 6 Cost per kilometer of TNO and Boskalis calculation for the electrification scenario. The costs is split into installation cost and purchasing costs for cables and accessories.

The comparison with the in-depth analysis of Boskalis shows that the TNO calculations of power grid costs will be an underestimation of the actual costs for the designed power grid. Design choices influence the cable and accessories purchasing costs and can increase the total costs, which is why the total cost in the TNO calculation is higher. This design choices have an impact on the reliability of the grid. The cost underestimation partly follows from the assumption that the costs are driven by the distance that has to be installed. Cases with a larger distance will have a larger underestimation. The installation costs are equal under the assumptions of the analysis, however the analysis of Boskalis took several costs out of scope as depicted in Table 8. In order to specify the underestimation, information about the seabed, platform conditions and timing needs to be collected and analyzed.

3.2 Detailed scenario analysis

For all three scenarios both an individual grid as well as an integrated power grid are analyzed by means of the TNO cable costs calculation. In the CO_2-storage scenario injection rates of 2.3 MT/year and 5 MT/year were considered. The scenarios are described in more detail in Chapter 3.

The total costs for each scenario are shown in Figure 7. In the analyzed grid designs, the cable costs per platform are higher individual designs than for an integrated offshore power grid. This analysis depicts the cable purchasing costs and the installation costs. The additional electrical components needed for the offshore power grid are not considered in this cost analysis. There are other ways to reduce the power connection costs besides a power grid, for instance installing a central hub to connect the platforms. These options are not analyzed in this study.

As covered in paragraph 3.1, the presented costs underestimate the actual power grid costs. In the assumptions, electric equipment, project development, financing, licenses and OPEX are taken out of scope. To cover part of these costs, 0.3 M€/km is assumed as Installation costs.

The costs for the scenarios with a higher amount of platforms yield a lower cost per platform. This is because in these scenarios, the average cable length per platform is lower, because the selected platforms are in closer proximity to each other. The cable length per platform is shown in Figure 8. The cable length and proximity of platforms is also the reason why the Electrification + CO_2-storage scenario has a higher cost per platform compared to the Electrification scenario. The platforms in the Electrification + CO_2 scenario are selected on potential for both functions, the grid developed in the Electrification scenario can also be used for facilitating CO_2-storage.

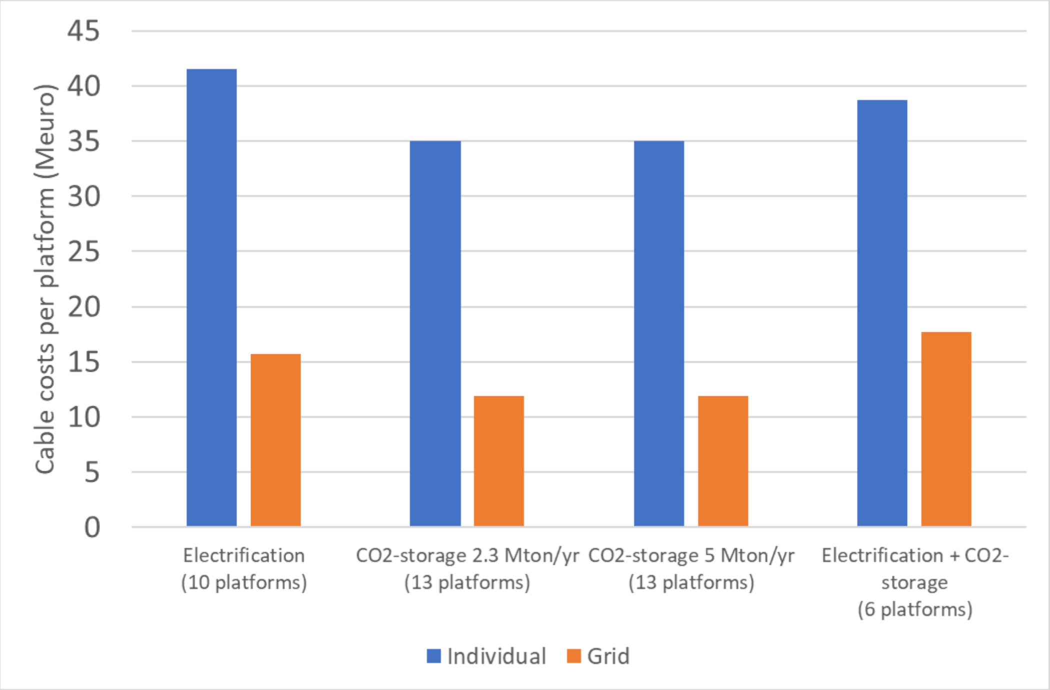

Figure 7 Cable costs per platform for each of the three scenarios with an individual grid design and a shared power grid design. The scenario CO_2-storage is calculated with two different injection rates. The presented costs underestimate the actual costs of a power grid.

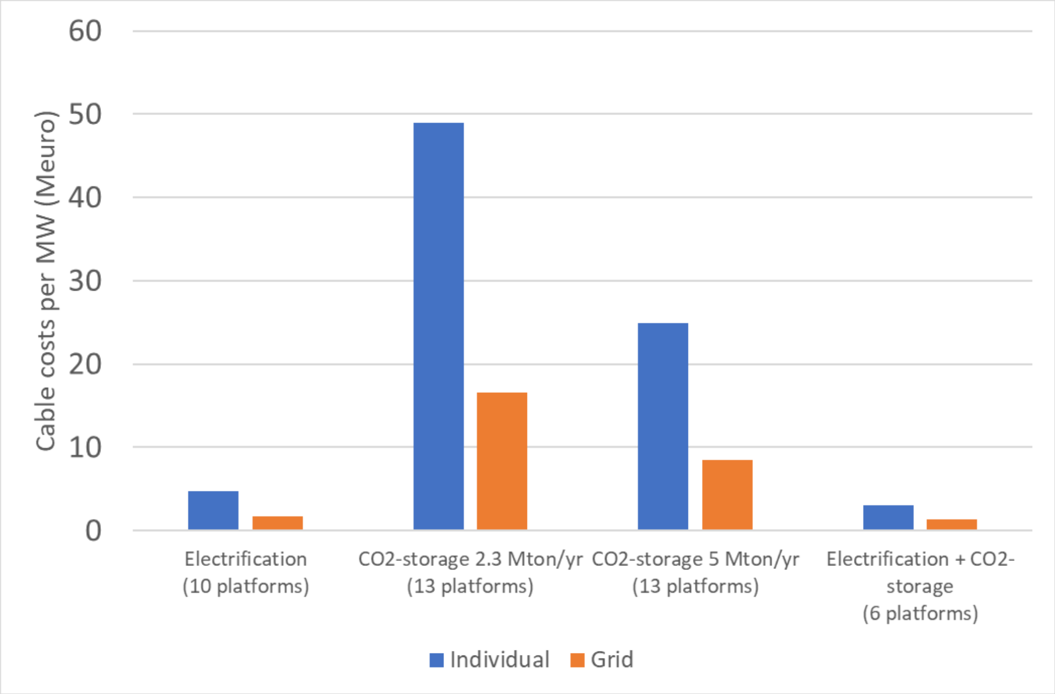

Figure 8 Cable length per platform for each of the three scenarios with an individual grid design and a shared power grid design. The scenario CO_2-storage is calculated with two different injection rates.

In Figure 9 the costs are shown per MW electricity demand. This graph shows that the CO_2 storage scenarios have a higher cost per MW. This is because the power demand of the CO_2-storage scenarios is significantly lower, as shown previously in Figure 4. Furthermore, the Electrification + CO_2-storage scenario has the lowest cost per MW. This is caused because in the scenario Electrification + CO_2-storage platforms with a high amount of electrification are selected. One should note that in the Electrification + CO_2-storage additional electrification is realized by combining both system integration options. This combination is not yet shown in the installed peak capacity of MW.

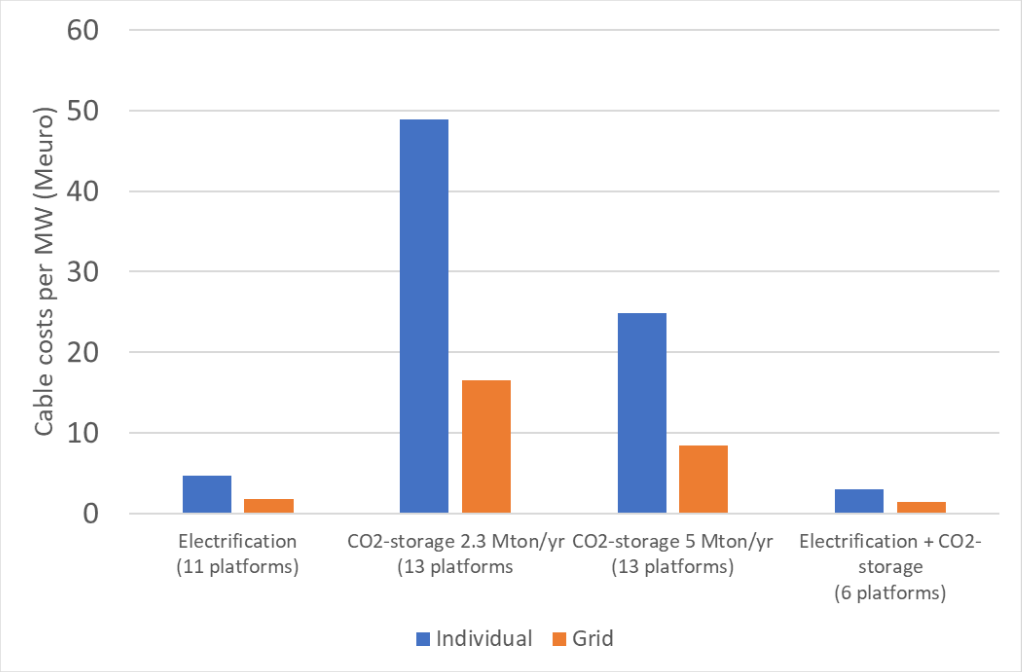

Figure 9 Cable costs per MW for each of the three scenarios with an individual grid design and a shared power grid design. The scenario CO_2-storage is calculated with two different injection rates.

3.3 Impact on the business case of system integration

In all three scenarios considered in the analysis, the cable investment costs per platform are 54 - 66 % lower for a power grid compared to an individual connection to the platform. This leads to a reduction of € 21-26 million per platform. Based on business case analysis conducted for several platforms in NSE2 [3], this can result in an average CAPEX reduction of approximately 20% for the electrification business case or the CO_2-storage business case. The business case of the combined CO_2 + Electrification scenario has a higher investment in equipment, therefore the improvement resulting by a power grid is lower at approximately 10%, however more functions are unlocked in this scenario. The business case depends on several more factors, such as CO_2 and energy prices, incentive and possible margins. The investment reduction because of an offshore power grid therefore increases the chance of a positive business case for system integration.

4. Environmental and macro-economic added value

4.1 Expected macro-economic effects of the offshore power grid

The offshore power grid has a facilitating function regarding the primary business activities of connected platforms. Added value related to the design and construction phase of the power distribution grid and platform electrification activities should however not be overlooked as the grid will require significant effort of contractors and technology suppliers.

Both the individual construction of cable connections and a collectively developed offshore power grid in the Dutch North Sea can offer direct and indirect economic benefit stakeholders involved. These direct and indirect economic benefits combined could be described as the total value added to the Dutch economy. This paragraph presents a line of reasoning based on macro-economic logic to determine the macro-economic added value of platform electrification and the power grid network under consideration in this project.

The following four effects can be expected regarding the macro-economic added value when considering the network configuration, compared to the individual cable configuration:

1. The total cable-related CAPEX investment reduces per platform and thereby a saving on total CAPEX investment is achieved, leading to a smaller shock and smaller value added (direct effect).
2. Sharing costs of the electricity infrastructure amongst multiple platform operators within the network leads to a lower CAPEX per platform. This increases the likelihood of a positive business case for platform electrification and/or CO_2-storage. It is therefore expected that more platforms will want to participate in collective development of the power grid. This phenomenon introduces a positive feedback loop that can reduce CAPEX investments per platform, while increasing the total CAPEX investment needed to connect all platforms and therefore increasing the value added (indirect effect).
3. As the operation and maintenance costs of the network grid can be shared amongst all platforms utilizing the network, OPEX cash flow will be lower compared to individual cables. Lower total OPEX leads to smaller macro-economic benefits for the network configuration (direct effect).
4. The availability of an offshore power distribution network can stimulate a variety of future business activities that require electrical power (e.g. additional CO2-storage, hydrogen production). Thereby, both the operational lifetime of the network can be maximized and the financial feasibility of future offshore business activities increases, possibly leading to additional economic shocks due to additional investments in the future (indirect effect).

Specific quantitative insights regarding the macro-economic benefits of the individually or collectively developed offshore power distribution grid will require an in-depth macro-economic analysis.

4.2 Power grid as an enabler of emission reduction potential via platform electrification

An individual high voltage cable or an offshore power grid can both provide platforms with electricity to electrify the natural gas extraction processes. Connecting the platform to an external power source makes the combustion of natural gas with the local gas turbine to generate electricity obsolete. If the electricity supplied has a large renewable energy share, the amount of greenhouse gas and nitrogen oxide emissions directly related to the production process decreases. Thus, the infrastructure to supply the green electricity can enable a reduction of the environmental impact of these platforms.

The emission reduction potential of electrifying the selected platforms, enabled by the offshore power grid, can be seen as an indirect environmental added value of the power grid. To better understand the order of magnitude of this environmental added value, previously conducted research on platform electrification in the NSE1 program is analyzed and translated to the NSE3 strategic offshore power grid scenarios.

An environmental life cycle assessment (LCA) on the environmental benefits of platform electrification was performed in the North Sea Energy 1 program [4]. In this LCA, all Dutch natural gas producing platforms on the North Sea were included in the scope of the assessment. From these platforms, the top 10 platforms with the highest fuel gas consumption were assumed to be electrified. The result of this LCA showed that, for each m^3 gas produced at all the platforms combined, greenhouse gas emissions and NOx emissions were significantly reduced due to selective platform electrification. The major driver of the reduced emissions was the elimination of fuel gas combustion.

The potential emission reduction achieved by electrification of the platforms within the scope of NSE3 only focusses on the replacement of fuel gas with green electricity. To assess the consequences of platform electrification, emission reduction is based on a comparison between de existing situation, with the use of fuel gas, and a future situation, where green electricity is supplied when available. In line with the approach of the NSE1 LCA, the existing emission per m^3 of the total gas production in the Dutch North Sea is based on all active platforms in the Dutch North Sea. Electrification of a selection of these platforms will thereby also reduce the emissions per m^3 of natural gas produced by all platforms. This percentage corresponds with the percentage of fuel gas consumption replaced at the selected platforms. By extrapolating the fuel gas consumption within scope of the NSE1 to the fuel gas consumption within scope of NSE3, indicative conclusions are drawn regarding the emission reduction potential.

Three assumptions are made in the extrapolation analysis:

- All assumptions and parameters of the system under consideration in NSE3 are identical to NSE1.
- Natural gas production and fuel gas consumption rates remain constant during the operational life of the platforms. The only parameter that is extrapolated and analyzed is the fuel gas consumption of the platforms.
- The emission reduction is assumed to scale linearly with the fuel gas consumption and fuel gas consumption is the only emission contributor that is manipulated in this study.

The contribution of the following systems may differ significantly within the NSE3 study and should therefore be studied in more detail:

- The platforms consume electricity from the Dutch distribution grid, not directly from the wind park itself. The renewable electricity share thus drives the emission reduction.
- Platform lifetime (may vary significantly based on prolonged natural gas extraction and CO2-storage activities)
- Variety of electrical platform equipment (out of scope in NSE1)
- Development of IJmuiden Ver wind park should not be attributed to platform electrification as to prevent double counting. The wind park will be constructed anyhow.
- The assumptions made to define the system boundaries of the NSE1 study cannot be extrapolated entirely to this NSE3 study. Additional assumptions regarding the electricity mix, operational lifetime of platforms and attributed impact of the wind park required to estimate the absolute CO_2e emission reduction.
- To emphasize the need for additional research due to a change of scope under consideration, the reduction potential per 1 m3 of natural gas produced is only given in percentages to present an indication of the order of magnitude of environmental value of the power grid.

Electrification of the platforms within the scope of NSE3 yields the results summarized in Table 6.

Selected platforms to be electrified	Replaced annual fuel gas consumption (nm3) [2]	GHG emission reduction per m3 NG produced in the Netherlands	NOx emission reduction per m3 NG produced in the Netherlands
NSE1: Top 10 platforms	348M (2014)	up to 25%	up to 40%
Scenario 0: 0 platforms	0	0%	0%
Scenario 1: 10 platforms	217M (2017)	up to 16%	up to 25%
Scenario 3: 6 platforms	181M (2017)	up to 13%	up to 21%

Table 6 Potential emission reduction per nm3 NG produced in the Netherlands through platform electrification

To conclude: When the 10 platforms in scope for the electrification scenario replace fuel gas-based electricity supply with offshore wind electricity supply, the total GHG and NOx emissions attributed to one m^3 NG produced on the Dutch North Sea may potentially be reduced by approximately 16% of GHG and 25% of NOx. The actual emission reduction will however strongly depend on the renewable share within the electricity mix throughout the year. A reliable power supply is crucial for the operation of platforms. When renewable power is not available, the power will need to be supplied from shore. As the electricity mix on the onshore power grid consists mainly of non-renewable energy sources, electricity supply from land leads to higher emissions and thereby a reduced actual indirect environmental value of the offshore power grid. The emissions attributed to the medium voltage cables are small. The difference in emission reduction by minimizing the length of cables through an integrated power grid network does not change the environmental added value significantly.

Important notification: The actual potential reduction of GHG and NOx emissions that could be achieved by developing an offshore power grid, electrification of the platforms connected to the grid and supplying the platforms with renewable wind energy will require a thorough and custom made LCA for the specific scope of systems and processes under consideration.

4.3 Direct local CO_2-emission reduction potential through fuel gas elimination

Electrification of platforms eliminates the consumption of fuel gas and thereby the direct CO2-emissions that are allocated to the platform. Quantifying the amount of CO_2-emissions reduced is an extensive exercise. The scope of the system under consideration is of importance as this determines the factors contributing to the total amount of emissions. By limiting the scope of the system under consideration to the platform fuel gas emissions due to gas turbine operation at the 10 selected platforms only, an indication of locally reduced CO2-emissions is found. On a system level, the emission reduction is expected to be lower, as discussed in the previous paragraph.

The CO_2-emission that can locally be reduced through platform electrification based on 2017 platform data is up to 478 kiloton CO_2 annually. The CO_2 emission values of the 10 platforms that are within the scope of this research are taken from the MIDDEN report by PBL and TNO [2]. The emissions of the platforms not included in the MIDDEN are estimated. For this estimation, the average ratio between the *gas consumed* and *CO2-emissions emitted* of the 15 platforms in the MIDDEN report is multiplied with the fuel gas listed in Table 3. The fuel gas-to-CO_2 ratio in this study is 2,2: Each 1000 nm^3 of fuel gas consumed results in 2,2 tons of CO_2 emission. The order of magnitude of the estimated values in is validated by comparison of a selection of individual platform values with the registered emissions as presented by the Dutch Emission Authority[9].

As discussed in the previous paragraph, the CO_2-emissions allocated to the electricity consumed by the platform are not eliminated but merely replaced outside the system scope of the platform. The local emission reduction potentials listed in Table 6 should therefore be interpreted appropriately.

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[9] Nederlandse Emissieauthoriteit (NEA). (2019). *Emissiecijfers 2013-2018-plaats inrichtingen.ods*.

5. Business model lifetime

As discussed in Chapter 3, development of a power grid improves the chance on a positive business case of platform electrification as well as CO_2-storage. The decision to electrify the platform and/or store CO_2 can increase the lifetime of the platform. This is a positive benefit for platform operators as the standing asset can be kept in operation and the business can remain viable.

Platform electrification can expand the operational lifetime of the natural gas production

Among others, the decision of continuing hydrocarbon production at a platform is based on the economic viability of the business model [5]. NSE 2 business case analysis of several platform electrification studies [3] indicate that electrification has several economic benefits leading to an increased economic lifetime. The scenario analysis in the study showed an average duration of electrified gas production was estimated to be 12 years for the three platforms under consideration. The actual lifetime expansion depends on several factors, such as the economic feasibility of electrified gas consumption, the operational strategy and energy prices.

Adding CO_2-storage business model expands operational lifetime after natural gas production.

When the operator adopts storing CO_2 in a depleted gas field, the business model of the platform is expanded after the decommissioning date based on natural gas production. Based on scenarios developed in NSE 2 [3], CO_2-storage has the possibility to expand the business model with an average of 20 years. This expansion depends on several factors, such as the injection rate number of wells, storage capacity and strategy. Specific lifetime expansion has to be analyzed for platforms separately. Furthermore, the possibility exists to adopt CO_2-storage before the gas production is seized. In a scenario where the grid is deployed for CO_2-storage, and the business case becomes feasible, the operational lifetime of the platform will increase. Alternatives to realize an electricity supply include the operation of a local turbine which requires continuous supply of natural gas against high OPEX. Another solution is to create a cable connection to an operational natural gas platforms gas turbine. Both alternatives are expected to reduce the business case for CO_2-storage significantly compared to an offshore power grid [2]. Furthermore, the risk of CO_2 injection interruptions is greatly reduced by having a connection to the power grid.

Offshore platform electrification can be a stepping stone for CO_2-storage (scenario 3)

Clear synergies exist between electrification and CO_2-storage in depleted gas fields. CO_2-storage has an electricity demand for injecting the CO_2 into the gas field and for transporting the CO_2 from shore to the platforms. As shown in Chapter 2, the electricity demand of CO2-storage is lower than the demand for electrification. Therefore, an existing power grid will increase the feasibility of changing the functionality of the platform towards CO2-storage. By doing both electrification and CO2-storage, if possible, the business model lifetime of natural gas production will increase, and additional economic lifetime will be added due to CO2-storage. Based on scenarios developed in NSE 2 [3] CO_2-storage has the possibility to expand the business model with an average of 20 years. However, this can create either flexibility or lock-in scenarios and if it is possible depends on a lot of factors such as technical feasibility, a match in the timing of decommissioning and CCS match and the state in which platforms will be mothballed.

The interaction when both CO_2-storage and Electrification are considered at the platform has an impact on the actual lifetime expansion. Prolonging gas production through electrification can postpone the availability for CO_2-storage. Furthermore the possibility exists to operate both gas production and CO_2-storage on the same platform.

Opportunities in developing a power grid for electrification should be seized within due time

Decommissioning dates of analyzed platforms in the power grid study show that expected decommissioning can already take place from the period 2023 onward. The number of platforms that have positive electrification business cases will decrease as time passes. This will thereby decrease the collective benefits of a power grid significantly. Therefore, opportunities in developing a power grid for electrification should be seized within due time.

6. Organizational Complexity

System integration on the North Sea requires intensive collaboration between stakeholders. Evaluating the impact of collaborative power grid development provides insights on the importance of this aspect and the extent to which stakeholders are mutually dependent on each other. The techno-economical evaluation of NSE2 concluded that the "*value of system integration lies in financial and economic benefits for multiple stakeholders and collaboration is key to capture all value*" [3]. In this analysis, organizational complexity is defined as the amount of stakeholder relations that have to be developed or maintained in the scenario under consideration. It is assumed that each relation between two stakeholders is a potential threat towards the successful collaboration of the stakeholder network. Fewer relations is expected to increase the rate of success for the entire scenario to develop platform electrification and/or CO_2-storage.

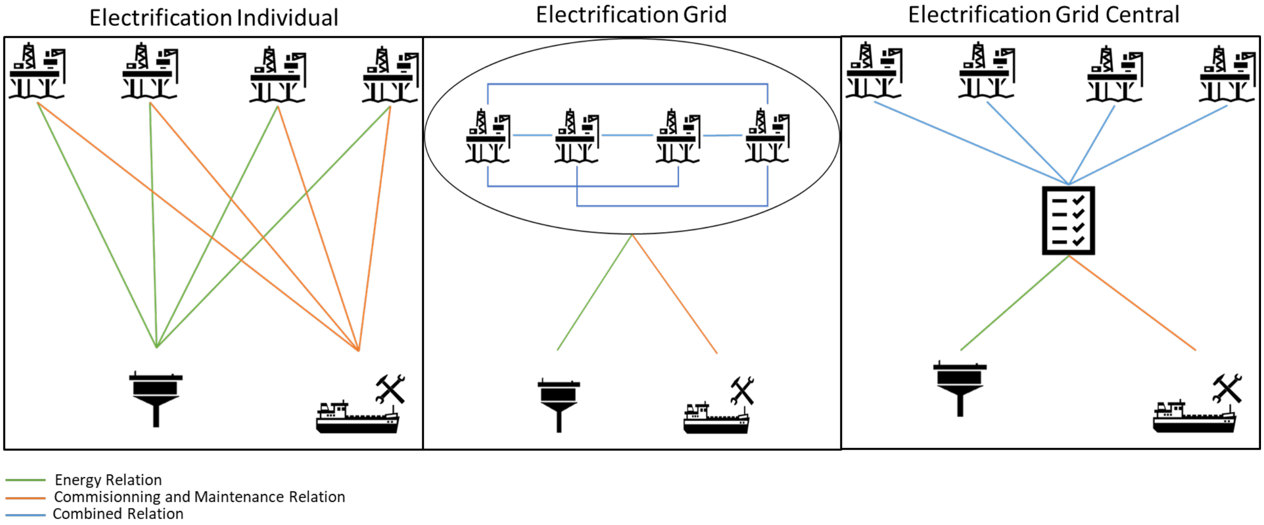
The analysis into the amount of relations in the ecosystem leads to the following result:

Incorporating a power grid instead of individual connection to power sources reduces the organizational complexity of electrification and CO_2-storage only when a central party coordinates the development and operation of the power grid. Separating the development of the power grid and a CO_2-storage business model has a positive effect of the complexity in the development phase.

Developing a power grid without central coordination will increase the organizational complexity.

When energy is supplied to the platforms through a power grid, the platforms will become dependent on each other for developing and operating the power grid. This means they will together have to tender for the power grid design, construction, operation and maintenance, and they have to negotiate with each other how the costs of the power grid will be divided. When the grid is realized, agreements have to be made who will operate the grid and how operational costs will be shared among users. In addition, due to the demanded security of supply for all platforms, stakeholders involved need to agree on a distribution of responsibilities and liabilities regarding safety and reliability aspects of the grid. The relations between platform operators already exist, however working together in shared ownership of electricity infrastructure is a new cooperation area. Amongst other aspects, mutual trust, dependability and shared risk management becomes inevitable. This greatly increases the organizational complexity compared to individual electrification[10].

An example of stakeholder relationships for individual, collaborative and collaborative with central party for four platforms is shown in Figure 10. When more platforms and operators are involved, the complexity increases greatly.



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[10] Internal relations between X parties is X!, relations between X parties and two suppliers is 2X.

Figure 10 Schematic description of organizational complexity in the Electrification Scenario. Three coordination options are depicted: a) Individual decision for power connection, b) Collective power grid organized by platform operators and c) Collective grid organized by a central party.

Introduction of a central party that is responsible for the development and operation and maintenance of the power grid will decrease the organizational complexity.

This will mean that all platform operators will only need to maintain relations with this central party and that energy suppliers and maintenance operators will also have a single point of contact. In order to develop a power grid with central coordination, a minimum viable number of participants need to be guaranteed to create a sound business case for the central coordinator. This amount strongly depends on the individual platform situations and the context in which the grid will be embedded. In Table 7, the number of relations for each described situation is shown. The number of offshore platform stakeholders change with each scenario, 5 stakeholders in the electrification scenario and 4 in the CO_2-storage and combined scenario.

	Individual	**Grid**	**Grid Central**
Electrification (5 operators)	10	26	7
CO2-storage (4 operators)	8	8	6
Electrification and CO2-storage (4 operators)	8	8	6

Table 7 Number of relations between stakeholders in different situations. The number of offshore stakeholders change with each scenario.

Separation of developing the power grid and the CO_2-storage supply chain reduces the organizational complexity for platform operators.

When the platform operators adopt the CO_2-storage business model new relations have to be developed. Agreements have to be made between the platform operators, CO_2 emitters and CO_2 transportation services. In the development phase of CO_2-storage, the number of new relations will further increase if the operators also have to develop a new power grid for operating the CO_2-storage. In the scenario of electrification and CO2-storage, the operators can build the relations for the power grid and the CO_2-storage supply chain separately. This separation results in fewer relationships that need to be maintained simultaneously within decision-making rounds.

7. Conclusions & Recommendations

Based on the analysis presented in the previous chapters, we can draw conclusions on the research question:

What is the value of a coordinated development of the offshore power grid in the Netherlands to serve both the offshore wind and oil & gas sector?

In paragraph 7.1, we will discuss the conclusions and translate these to recommendations in chapter 7.2.

7.1 Conclusions

From the analysis in the previous chapters the researchers conclude the following:

Developing an offshore power grid reduces the investment costs for connecting an offshore platform to the IJmuiden Ver substation. The investment reduction because of an offshore power grid therefore increases the chance of a positive business case for system integration. In assessing the value of an offshore power grid both positive effects related to the investment reduction and negative effects due to increased complexity should be considered.

The conclusion is supported by the following analyses:

Developing an offshore power grid will reduce the investment costs in electric infrastructure.

In all three scenarios considered in the analysis, the cable investment costs per platform are 54 - 66% lower for a power grid compared to an individual connection to the platform. This leads to a reduction of 21-26 million euro per platform. Based on business case analysis conducted for several platforms in NSE2 [3], this can result in an average CAPEX reduction of approximately 20% for the electrification business case or the CO_2-storage business case. The business case of a combined scenario has a higher investment in equipment, therefore the improvement resulting by a power grid is lower at approximately 10%. The business case depends on several more factors, such as CO_2 and energy prices, incentive and possible margins. The investment reduction because of an offshore power grid therefore increases the chance of a positive business case for system integration.

Enabling system integration through a power grid can increase the economic lifetime of offshore platforms.

An indirect effect of enabling platform electrification and CO_2-storage can be to increase the economic lifetime of offshore platforms. Platform electrification can expand the operational lifetime of the natural gas production CO_2-storage can induce a completely new business model for the platform operator after gas production seizes. This is a positive effect for platform operators, the effect on a system scale should be analyzed further, for instance with regards to space requirements on the North Sea

Since the power demand for CO_2-storage is a significantly lower than for electrification purposes, the decision of storing CO_2 in depleted fields can be made after the power grid is already constructed.

Additional platform electrification and CO_2 storage on the North Sea has an effect on value added to the Dutch economy, depending on the amount of additional platforms that are investing in system integration solutions due to the offshore power grid.

From macro-economic reasoning it follows that the power grid can have both an increasing or a decreasing effect on the value added to the Dutch economy. The actual effect depends on the amount of system integration realized due to the power grid compared to the saved costs on infrastructure.

Platform electrification and CO_2-storage reduce the direct emissions on platforms and can reduce the GHG and NO_x emissions in the Netherlands.

Electrification of platforms eliminates the consumption of fuel gas and thereby the direct CO_2-emissions that are allocated to the platform. By limiting the scope of the system under consideration to the platform fuel gas emissions due to gas turbine operation only, an indication of locally reduced CO_2-emissions is found. In the electrification scenario this local reduction could be up to 480 kiloton CO_2 reduction for the 10 platforms combined, based on the fuel gas consumption in 2017. Allocation of CO_2 emission outside the local scope due to carbon intensive electricity consumption back into the local scope would reduce this reduction potential. This step is not performed within this study.

When the platforms close to IJmuiden Ver offshore wind park replace fuel gas-based electricity supply with green electricity supply, the total GHG and NOx emissions attributed to one m3 NG produced on the Dutch North Sea may potentially be reduced by approximately 13 to 16% (GHG) and 21 to 25% (NOx). The actual emission reduction will strongly depend on the renewable share within the electricity mix throughout the year.

Synergies exist between platform electrification and CO_2-storage which can increase the value of a power grid.

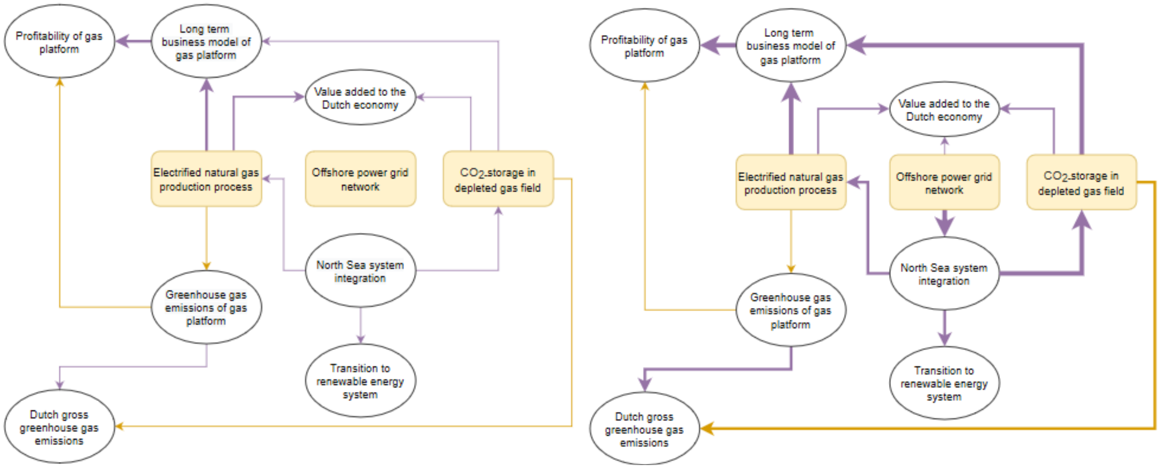
From the power grid design analysis, it follows that the power demand of CO_2-storage is significantly lower than the power demand for platform electrification. This implies that a power grid that serves both electrification and CO_2-storage has the same investment costs. When a power grid is developed for electrification, it is also dimensioned for CO_2-storage activities on the platforms.

Developing an offshore power grid requires the cooperation amongst a diverse stakeholder network.

In developing an offshore power grid, relations between platform operators, grid suppliers and renewable energy suppliers have to be maintained. With an increasing number of platform operators, the complexity of the cooperation will increase. There will have to be made agreements on operating the grid, sharing the costs and responsibility for grid security. The complexity for a platform operator is lower in the case where an individual cable is developed.

Introduction of a central party that is responsible for the development, operation and maintenance of the power grid will decrease the organizational complexity. This central party could organize the platform operators and communicate on their behalf to the electricity supplier and engineering party.

An integrated power grid has a reinforcing effect on platform electrification as the investment costs per platform are expected to decrease when developed in collaboration, compared to individual cable development. An integrated power grid can contribute to the transition towards a renewable energy infrastructure through increased offshore system integration.



Legend
Positive relationship: increase factor A = increase factor B, Negative relationship: increase factor A = decrease factor B,
Line thickness is indicative for relative size of impact.

Figure 11 Causal relation diagram – with individual cable connections (left) and with power grid network (right).

The causalities amongst a selection of key factors with an offshore power grid and with individual cable connections is visualized in **Error! Reference source not found.**. The actual causal result of an offshore power grid depends on the situation as only the possibility of a positive business case is increased, developing an offshore power grid does not guarantee an increased value.

Several considerations are valued in favor of an individual grid solution. These considerations were not analyzed in depth but should be considered.

The value selection has been performed by the project team. This means that the values are biased towards business analysis made in NSE 1 and 2 and towards values related to the offshore power grid. For a balanced and exhaustive value analysis, value ranking and selection has to be performed by a group of stakeholders. Several considerations for the individual grid have been identified during the research.

The offshore power grid design constructed in Chapter 2 considers K14 as a power hub. This will imply that on or close to K14, additional power electronics should be placed to facilitate the power hub. This space should be available and the effect on the power quality for the platform functioning as power hub should be analyzed. In an individual case, the transformer of IJmuiden Ver functions as a power hub.

The power grid as designed in Chapter 2 has a radial structure. This means that there is no redundancy in the grid to ensure security of supply. Failure in a supplying cable, for instance towards K14, will affect the entire grid. In the individual grid situation the security of supply from a design perspective is deemed to be higher, as each platform is connected by a dedicated cable. Failure of a cable will only affect the connected platform.

As mentioned in Chapter 6, the development of a power grid requires cooperation between several platform operators. The construction of the grid affects all operators, and the phasing of the grid can be out of synchronization with the strategic plans of the operators. This means that operators can be confronted with an investment in electric infrastructure before the system integration solution is being developed on the platform, or operators can be confronted with a connection which is supplied after the intended transition towards a system integration solution. In the individual grid case operators have more control over the timing of the electric connection.

7.2 Recommendations

Developing an offshore power grid requires the acknowledgement of, and anticipation on, a wide range of interests amongst a diverse stakeholder network. The first step toward an offshore power grid is to create a consortium willing to realize an offshore power grid.

The scenarios under consideration in this research are focused on techno-economic analysis of the grid design for serving offshore platforms. In the design coordinated planning of the electrification between the platforms, grid operator and offshore wind development is needed. The influence of a wide range of potential barriers (e.g. organizational, logistic, environmental, ecological, social, legal and institutional) may be of significant influence on the feasibility of the offshore power grid configuration.

While the costs of the offshore power grid is found to be significantly lower per platform, it remains unclear which reduction of costs is required to create individual positive business cases and related platform utilization strategies. As the business cases for platform electrification and possibly CO_2 storage should be analyzed on an individual platform level, future research is recommended to gain more insight on the relation between grid cost per platform and the willingness of that platform operator in the participation in an offshore power grid development consortium.

A holistic view on the development of a grid is required to move further towards a more detailed and concrete action plan. Defining a minimal viable grid size for offshore system integration as well as a minimum number of actors involved, can be highly beneficial to maintain the momentum needed to realize the offshore grid. In the development of a power grid, in-depth analysis about the design and construction of the power grid should be conducted.

Ijmuiden Ver and selected platforms are indicative for general conclusions. Site specific research is required to confirm the applicability of conclusions to other locations for offshore power grids
While the methodology followed can to a large extend be followed for other locations where both offshore wind farms and gas-fired gas platforms are operational, the data analyzed is site specific and should therefore not be extrapolated. The trend of lowering costs for a power grid solution over an individual solution can be generalized with sufficient platforms collaborating. Overall conclusions regarding platform electrification, CO_2 - storage business model synergy and the preference of a shared offshore grid may, for sites with comparable sizes, mutual distances between platforms and remaining useful lifetimes can be considered indicative for general conclusions.

The value of an offshore power grid is sensitive to time. Follow-up research with an explicit focus on time is therefore recommended to explore implementation scenario's
The relationship between the value of the grid and the timing of its implementation is found to be important. Each of the criteria (i.e. cable costs, added value for the Dutch economy, emission reduction, business model lifetime and organizational complexity) are uncertain over or sensitive to changes over time. The impact of time can be on costs but also on the remaining value of operating the platform, as described under business model lifetime. It is therefore recommended to include the timing of a project when assessing the feasibility of a grid solution.

References

[1] F. Berkers, “Orchestrating Innovation,” 2015.

[2] PBL and TNO, “Decarbonization Options for the Offshore Natural Gas Industry,” 2019.

[3] TNO and NEC, “Report on part A: Techno-economic scenarios and economic impact of offshore integration options at case study areas,” 2019.

[4] TNO, “North Sea Energy life cycle assessment of platform electrification”.

[5] TNO, “Offshore Platform Electrification: State of Play”.

Appendix A Power Grid Designs per Scenario

In this appendix, the power grid designs per scenario are shown visually. The power grid designs for the electrification scenario are shown in Figure 12. For the CO$_2$-storage scenario in Figure 13 and the combined scenario in Figure 14.

Power grid designs Electrification

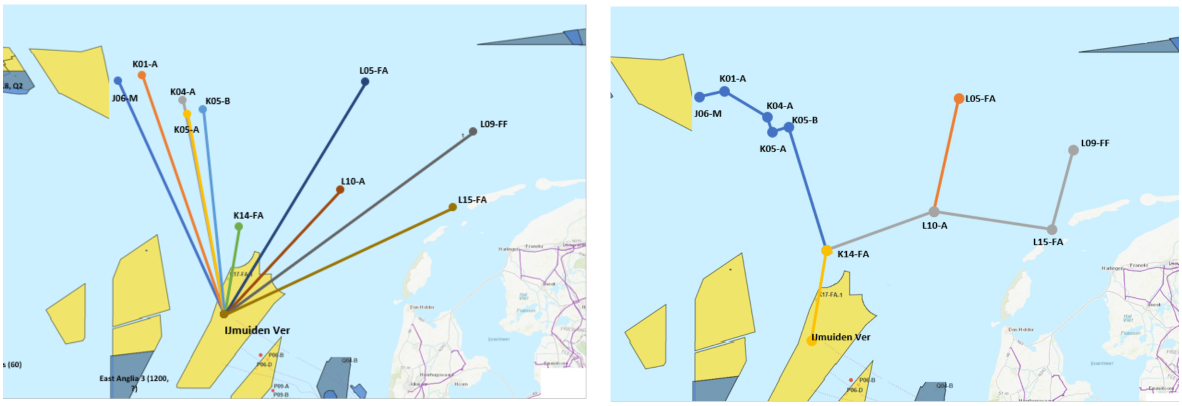


Figure 12 each platform is electrified individually (left) and an integrated offshore power grid (right) in the electrification scenario

Power grid designs CO$_2$-storage

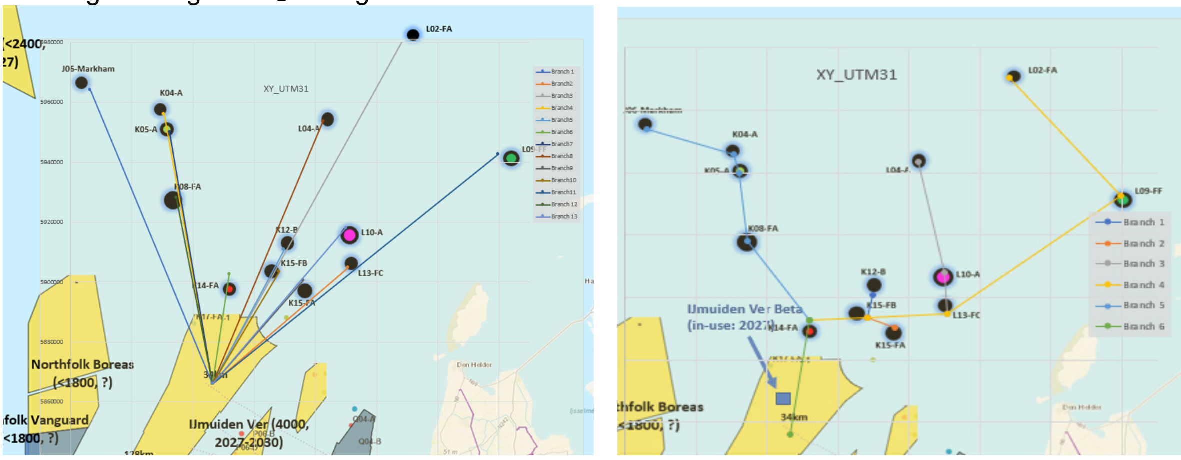


Figure 13 each platform is electrified individually (left) and an integrated offshore power grid (right) in the CO$_2$-storage scenario

Power grid designs Electrification + CO$_2$-storage

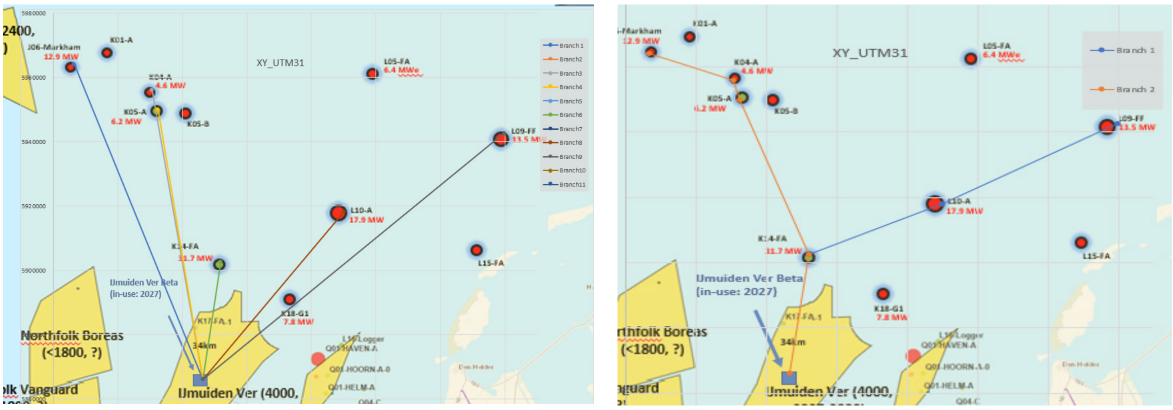


Figure 14 each platform is electrified individually (left) and an integrated offshore power grid (right) in the Electrification and CO_2-storage scenario

Appendix B Boskalis analysis

In the TNO and Boskalis cable costs analysis, the following assumptions were made. The assumptions are grouped in Topology, cable type and costs and shown in Table 8.

	TNO	Boskalis
Topology	Grid is connected to IJmuiden Ver transformer station. The connection onshore is out of scope	Grid is connected to IJmuiden Ver transformer station. The connection onshore is out of scope.
	Cable lengths based on the shortest distance between platforms + 10 %.	Cable lengths based on the shortest distance between platforms.
	Singular cable design between platforms.	Singular cable design between platforms.
	Double cable when the transported power exceeds 90 MW. This is the maximum capacity for a 630 mm^2 cable.	Power can exceed 90 MW for a single cable.
Cable type	Nominal voltage of 66 kV	Nominal voltage of 66 kV[11]
	Three core cables with a copper core	Three core cables with an aluminum core
	No cable joints	18 pieces of cable joints in the grid
	Core diameter between 95 and 630 mm^2.	Core diameter of 150 or 630 mm^2.
	Compensation reactive power: 50% on both cable ends. The reactive power is incorporated at each platform.	No reactive power compensation
Costs	Purchasing costs: anonymized project development data	Purchasing costs: current pricing data

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[11] The technological feasibility of 66 kV cables for a distance longer than 30-40 km has to be analyzed further

	No additional accessories	Additional accessories: 10% of cable costs
	Installation costs: 0.3 M€/km *Excluded*: electric equipment on platforms and changes to platforms	Calculated installation costs *including*: Pre lay grepnel run, pre- and post lay survey, cable transport, cable lay, cable burial, crossings, joints, pull in at offshore sub platform, support vessels, termination and testing, *Excluded:* Pre survey and UCO survey, pre trenching, boulder clearance, cable storage, dredging and post lay cable protection, cable transportation.
	Excluded electric equipment on platforms and changes to platforms	Excluded electric equipment on platforms and changes to platforms
	Excluded project development, licenses, financing and OPEX.	Excluded project development, licenses, financing and OPEX.

Table 8 Scope of cable costs calculations of TNO and Boskalis

The analysis from Boskalis is added to this report in a PDF:

200306_NSE-Power
grid_Estimation-and

Appendix C Thermal efficiencies of fuel gas consumption

Tabel 1 Table of mechanical power assumed for certain yearly fuel gas flow

Mechanical Power	Annual Energy	Thermal eff	Thermal power	Fuel flow
[MW]	[GWh pa]	[-]	[MWth]	[Nm^3/d]
1	8.76	0.24	4.2	9739
2	17.52	0.26	7.6	17688
3	26.28	0.29	10.5	24587
4	35.04	0.3	13.2	30856
5	43.8	0.32	15.7	36749
6	52.56	0.33	18.1	42428
7	61.32	0.34	20.5	48000

8	70.08	0.35	22.9	53533
9	78.84	0.36	25.2	59069
10	87.6	0.36	27.6	64627
11	96.36	0.37	30	70209
12	105.12	0.37	32.4	75796
13	113.88	0.37	34.7	81356
14	122.64	0.38	37.1	86837
15	131.4	0.38	39.3	92173

Appendix D Value Creation Canvas

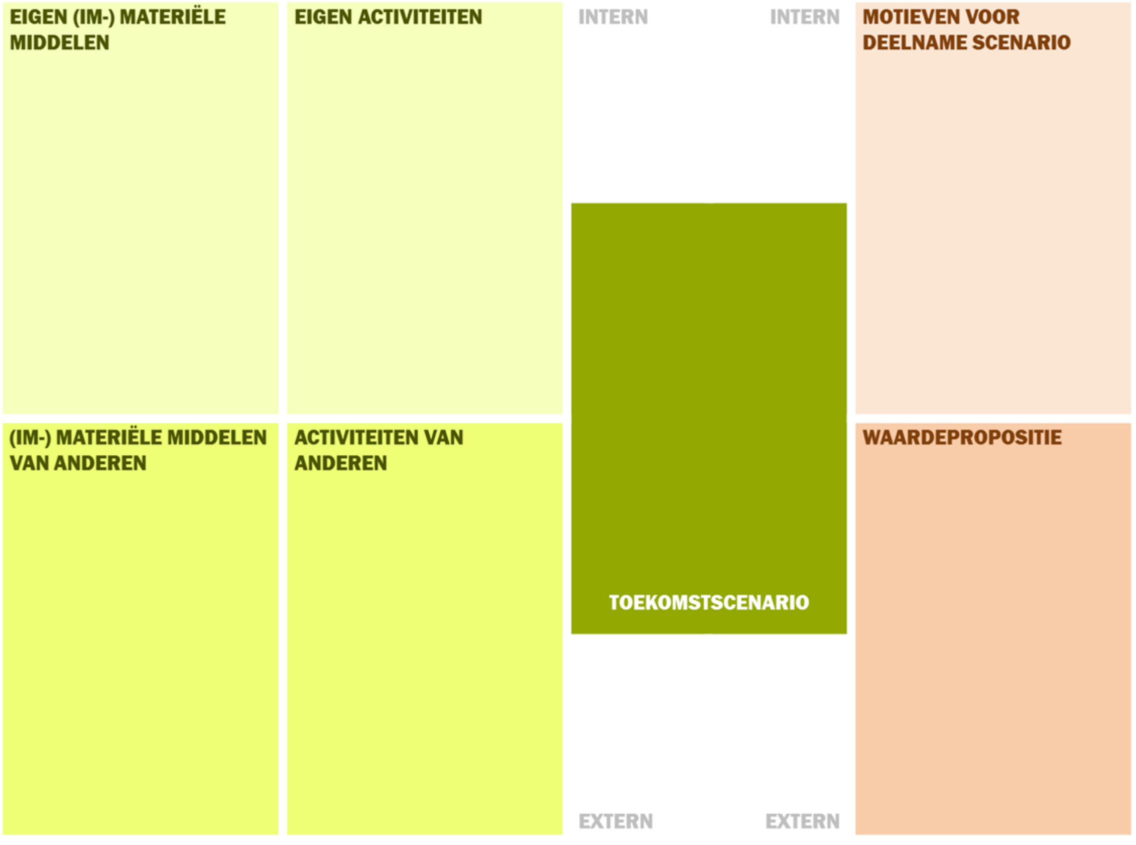

Figure 15 Example of Value creation Canvas

Appendix E CO_2 compression energy consumption

In order to transport the CO_2 to the platforms it is necessary to keep the CO_2 at a certain pressure. In this analysis we assume that every 50 km compression on sea is necessary to keep the CO_2 between 80 and 100 bar. The electricity need is assumed to be 1MW per 5Mt CO_2. This is an overestimation of the calculated electricity demand to account for fluctuations in the CO_2 flow. The calculation of the electricity demand is based on a flow rate of 5Mt CO_2 and a pressure increase from 80 to 100 bar. A pump efficiency of 75% is assumed. The electric power needed for this pressure increase is calculated by $P = \frac{Q*\Delta p}{\eta}$, where P is the power needed, Q the flow rate in m^3/s, η the efficiency of the pump and Δp the pressure increase. The flow rate is calculated by $Q = \frac{m}{\rho}$ where m is the mass flow in kg/s and ρ the density of the CO_2. The mass flow for 5 Mt per year is 158 kg/s. The density depends on the temperature:

- At 100 bar, 10 degrees Celcius the density is 920 kg/m^3.
- At 100 bar, 40 degrees Celcius the density is 628 kg/m^3.

This results in the following electric power demand:

- At 100 bar, 10 degrees Celcius the electric demand is 0.46 MW.
- At 100 bar, 40 degrees Celcius the electric demand is 0.67 MW.