North Sea Energy
offshore system integration

D4.4

North Sea Energy 2023-2025

Comparing embedded carbon for central and decentral offshore hydrogen

Navigating the North Sea transition!

For centuries, the North Sea has been a source of economic strength, ecological richness, and international cooperation. Always subject to change, yet steadfast as a connector of nations, cultures, and economies. Today, it once again takes center stage—this time as a lighthouse region for the transition to a sustainable, affordable, and reliable energy system. The North Sea Energy program marks an important step in this development.

North Sea Energy is a dynamic research program centered around an integrated approach to the offshore energy system. Its aim is to identify and assess opportunities for synergies between multiple low-carbon energy developments at sea: offshore wind, marine energy, carbon capture and storage (CCS), natural gas, and hydrogen. At the same time, the program seeks to strengthen the carrying capacity of our economy, society, and nature.

The offshore energy transition is approached from various perspectives: technical, ecological, societal, legal, regulatory, and economic. Our publications provide an overview of the strategies, innovations, and collaborations shaping the energy future of the North Sea. They reflect the joint efforts of companies, researchers, and societal partners who believe in the unique potential of this region as a hub for renewable energy and innovation.

What makes this program truly distinctive is not only its scale or ambition, but above all the recognition that we are operating in a dynamic field of research. The energy transition is not a fixed path, but a continuous process of learning, adapting, and evolving. New technologies, a dynamic natural environment, shifting policy frameworks, and changing societal insights demand flexibility and vision. Within this program, we work together to ensure that science and practice reinforce one another.

This publication is one of the results of more than two years of intensive research, involving over forty (inter)national partners. This collaboration has led to valuable insights and concrete proposals for the future of the energy system in and around the North Sea. All publications and supporting data are available at: https://north-sea-energy.eu/en/results/

We are deeply grateful to all those who contributed to the realization of this program. In particular, we thank our consortium partners, the funding body TKI New Gas, the members of the sounding board, the stakeholders, and the engaged public who actively participated in webinars and workshops. Their input, questions, and insights have enriched and guided the program.

At a time when energy security, climate responsibility, and affordability are becoming increasingly urgent, this work offers valuable insights for a broad audience—from policymakers and professionals to interested citizens. The challenges are great, but the opportunities are even greater. The North Sea, a lasting source of energy, is now becoming a symbol of sustainable progress.

With these publications, we conclude an important phase and look ahead with confidence to the next phase of the North Sea Energy program. In this new phase, special attention will be given to spatial planning in the North Sea, European cooperation, and the growing importance of security in the energy system of the future.

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Executive summary

This study aims to investigate the difference between ‘centralised’ and ‘decentralised’ systems for green hydrogen production offshore. Centralised here refers to a system where electricity from one or several wind farms is gathered and applied in larger centrally located electrolyser systems, from where the hydrogen is transported onshore. In a ‘decentralised system’ electrolysis is performed directly at each turbine and only hydrogen is transported offshore. Due to the different configurations also the materials required for these systems will be different. The carbon footprint of hydrogen production via different routes had already been investigated in NSE 3, showing clear advantages of using (exclusively) green sources and less differences between production technologies or location (onshore – offshore) for a MJ of hydrogen produced. The focus of this report is comparing the carbon footprints embedded in the central vs decentral systems - as expert consultation had not hinted on difference in process performance. To this end, first, two specific systems are defined that represent ‘decentral’ and ‘central’ hydrogen production, then the major material inputs of the different components were gathered. These materials are translated into carbon footprints using the life cycle assessment method.

Carbon footprints were similar for the two and were dominated by impacts from wind turbines due to the large amounts of steel for building a wind farm. Differences between the designs were negligible in comparison. It must be kept in mind that due to the new nature of many of the designs inventory data must be considered as indicative. Recall, that no differences in system performance, lifetime and maintenance requirements were expected. Potential differences arising from different installation and maintenance options were thus not investigated. An important consequence is that, if differences in any if these aspects would occur, mainly when leading to changes in overall lifetime hydrogen production, this could make decisive differences between the systems. Options for reducing carbon footprints are optimizing pipeline and cable demand. Independent of design enhancing contribution of secondary steel is a good option.

1 Introduction

This report is drafted as part of the LCA studies carried out within Work package 4 of the North Sea Energy (NSE) 5 research program. The NSE research programme strives to outline routes to the energy transition in the North Sea that have positive societal and ecological impacts. It integrates knowledge from technological, economical, policy, participation and ecological and environmental expertise. While navigating the transition to a climate neutral energy system, insights into available technologies and innovations needs to exceed techno-economic information and for instance include estimations of the material demands and emission arising from the use of specific technologies.

For a range of energy transition technologies and infrastructures (platform electrification, hydrogen from different sources and locations, platforms and islands) the carbon footprints have been assessed in previous NSE projects. North Sea data for some technologies are still lacking. In particular, different configurations for green offshore hydrogen production are currently discussed. These are mainly related to the location of the electrolyser, implying different transportation modes and distances and different technical configurations. For instance, NSWPH (2024) distinguishes between platform, island and turbine based designs. Although many of the major technological components, like electrolysers, wind turbines, gas platforms and pipelines are already more or less well known, the system designs, sizes, functioning are largely still under development, in particular under offshore conditions, with few exceptions (such as Hywind in Tampen and Scotland). As a consequence, little is known about the effects on carbon footprint of these different designs.

1.1 Aim and Research questions

This study aims to investigate the difference between 'centralised' and 'decentralised' systems for green hydrogen production offshore. Centralised refers to a system where electricity from one or several wind farms is gathered and applied in larger centrally located electrolyser systems, from where the hydrogen is transported onshore. In a 'decentralised system' electrolysis is performed directly at each turbine and only hydrogen is transported offshore. Due to the different configurations also the materials required for these systems will be different. The carbon footprint of hydrogen production via different routes had already been investigated in NSE 3, showing clear advantages of using (exclusively) green sources and less differences between production technologies or location (onshore – offshore) for a MJ of hydrogen produced. Whereas that report (Hauck, 2020) was mainly focussed on energy and emissions arising from the direct production of hydrogen, neglecting infrastructure demands, in NSE 4 the carbon footprints of building an island or a platform for that hydrogen production where compared, showing steel production and transportation fuels as the main options for reducing carbon footprint. Therefore the focus of this report is comparing the carbon footprints embedded in the material of the two systems - as expert consultation had not hinted on difference in process performance. To this end, first, two specific systems are defined that represent 'decentral' and 'central' hydrogen production, then the major material inputs of the different components are gathered. These materials are translated into carbon footprints using the life cycle assessment method. Finally, the carbon footprints of the two systems are compared and sensitivity analysis are conducted.

Based on these results recommendations for reductions of emission reductions can be identified.

Results of this report can be used in hub design decisions as well as support for technology developers and project developers. The material balance compiled in this report will also serve as input to a material flow assessment, also conducted within the NSE program in this work package.

1.2 Outline

Chapter 2 outlines the methodology, system definitions, life cycle assessment, main assumptions and data sources and the inventory data modelling approach. Chapter 3 describes and discusses the results, including sensitivity scenarios. Chapter 4 draws conclusions and provides first recommendations.

2 Material and methods

2.1 Carbon footprint assessment

A general description of life cycle assessment has been provided in several previous NSE reports (e.g. Hauck, 2020). In short, as the name says, the total life cycle and all according emissions and resource extraction are intended to be included. In some cases (e.g. if the environmental performance of a company making consumer products is assessed), the analysis is constrained to the production phase (cradle-to-gate). LCA encompasses four stages (goal and scope definition, data inventory, impact assessment and interpretation). Next to methods that strive to be as complete as possible in their coverage of potential environmental problems, also specific problem categories (so called single issues) can be addressed – with the carbon footprint being by far the most applied. Although referred to as the carbon footprint for convenience, it encompasses emissions of all (also non-carbon) greenhouse gases that are re-calculated to kg CO2-equivalents (CO2-eq) by using Global Warming Potentials (GWP) that express the contribution of a gas to radiative forcing relative to that of CO2.

2.2 Goal and scope

The goals of this LCA is to compare the carbon footprint embedded in the materials required to build a system for ‘centralised’ vs. ‘decentralised’ offshore green hydrogen production. Therefore the system boundary is cradle-to-gate (excluding installation, use and end of life). Both systems are sized to 2 GW of wind electricity generation capacity. As the main function in this case is to have the system in place, the functional unit is per piece of hydrogen production system which implies assuming the same production per system. This seemed justified because discussions with experts did not indicate a differences in process performance between the two systems. To ease interpretation of the carbon footprint numbers, results are expressed ‘per turbine’ (by dividing the carbon footprint of the 2 GW system by the number of turbines). In this report, the GWPs from the latest IPCC report were used (IPCC 2021 GWP 100a).

2.3 System definition and inventory data

As the systems investigated here are under ongoing development, several configurations and designs are still possible. Specific configurations have been developed to allow insights in the required materials. This selection has been based on publicly available reports and discussions with experts (mainly within TNO). In the centralized system electricity from the wind turbines is connected via an transformer station and cables to a platform that serves for desalination, electrolysis, and compression. From there hydrogen is transported via pipelines onshore. In the decentralized system, hydrogen is produced at the platform, meaning the main electrolyzer and desalination units are located on a platform attached to the transition piece of the wind turbine (‘hydrogen ***at*** turbine’). The hydrogen is gathered and jointly brough onshore from a compressors station. This design is based on the decisions described by Moreno (2021). Some alternatives to this design are discussed in the section on ‘sensitivity analysis’. Appendix A shows a flow chart of the main components and data sources for the two systems. Table 2.1 shows per component the capacity of a single unit and the number of units included in each system. The sources of inventory data for each component are also shown in the last column of Table 2.1. Major assumptions, proxies chosen and data adaptations are explained in the next section.

Table 2.1 Units and capacities included in the two systems

	Unit	Amount per unit	Nrs per system	Source	Inventory source per component
For both systems					
Capacity per turbine	MW	15	133	Dighe et al., 2024; NSWPH, 2024a; Gaertner et al., 2020	
Capacity wind farm	GW	2	1	Calculated	
Capacity electrolyser stack	MW	5	399	Moreno, 2021	Gerloff, 2021
Pipeline to shore	km	150	1	NSE4 (Kawale et al., 2022)	Ecoinvent
Centralised system only					
Capacity electrolyser platform	MW	500	4	NSE 4 (Hauck et al., 2022)	NSE 4 (Hauck et al., 2022)
Desalination unit	MW	500	4	Fit to electrolyser	NSWPH, 2024b; Razman et al., 2023
Substation	GW	2	1	Dighe et al., 2024;	
Cable array	km		432	Kamps and Elbing, 2024	
Cable to platform(s)	km		20	NSE 3 (Hauck, 2020)	Ecoinvent
Decentralised system only					
Desalination unit	MW	15	133	Fit to electrolyser	Moreno, 2021, Razman et al., 2023
Compressor platform capacity	GW	2	1	Expert estimate (NSE 5 WP1)	NSWPH, 2024a
Compressor capacity	MW	500	4	Expert estimate (NSE 5 WP1)	NSWPH, 2024a
Gathering pipeline length	km		500	Estimate based on NSWPH, 2024c; Moreno, 2021	Adapted from ecoinvent

2.3.1 Main assumptions

Inventory data for the wind turbines and substations in the centralised system are directly taken from Dighe et al. (2024). Array cable length per MW was taken from Kamps and Elbing (2024). They based masses for the wind turbines components on Gaertner et al. (2020), that reports 100 tonnes of steel for the transition piece. For the hydrogen at turbine platform, these 100 tonnes are replaced by 365 tonnes for transition piece including platform based in

NSWPH (2024b) data. The inventory of the electrolyser platform, cable length and cable inventory have been directly taken from Hauck (2020) and ecoinvent. Inventory data per 1 MW of electrolyser stack have been taken from Gerloff (2021) and scaled following the scaling equations given in the same source (see Appendix A details).

Less detailed data was available for the decentralized system due to its new nature. Masses of major materials for compressors and compressor platforms have been taken from NSWPH (2024a) and modelled following the same approach as in NSE 3 electrolyser platforms and some additional approximations. In short, anodes have been modelled as built up of aluminium and steel and coating has been added using the same proportion to steel mass as for the electrolyzer platform. Additionally, gathering pipelines haven been taken from long-distance gas pipelines from ecoinvent but adapted to smaller diameters (25.4 mm (Moreno, 2021) instead of 1000 mm (ecoinvent). The resulting inventories are shown in Table 2.2.

As no inventory data for desalination units to scale could be found, materials and their relative mass contributions were taken from Razman et al. (2023) and scaled to the weights for desalination units for 15MW (for the decentralised system) and 500MW for the centralised system. The resulting inventories are given in Table 2.3. Exact back-up power approaches for the systems are still under development, therefore all systems are modelled using batteries (see section 2.4 and Appendix C).

Table 2.2 Inventory table for compressor platform, including compressor, and gathering pipeline based on NSWPH, 2024a; Moreno, 2021

	Unit	Amount	Comment
Compressor platform	**piece**	**1**	Including equipment by weight
topside			
Steel	tonnes	7,608	
Epoxy resin	m2	58,747	Rough estimate based on mass relation compared to electrolyser platform
Steel working		41	
jacket			
Steel	tonnes	4,190	
Aluminium, cast alloy	tonnes	25	31% of anode mass
Aluminium, wrought alloy	tonnes	53	66% of anode mass
Zinc	tonnes	2	3% of anode mass
Epoxy resin	m2	9,609	
Steel working	tonnes	4,190	
Gathering pipeline	km	1	
Offshore natural gas pipeline	km	0.102	Scaled from 1000mm to 25.4mm (4 inch)

Table 2.3 Inventory table for desalination units adapted from Razman et al. (2023)

	Unit	Amount	Comment
Desalination unit 500MW	**piece**	**1**	Total mass from NSWPH, 2024b
stainless steel	t	83	
fibre galss reinforced plastic	t	129	
polyethylene	t	49	
polypropylene	t	1	
filament wound epoxy glass	t	24	
Desalination unit 15MW	**piece**	**1**	Total mass from Moreno, 2021
stainless steel	t	0.58	
fibre galss reinforced plastic	t	0.90	
polyethylene	t	0.34	
polypropylene	t	0.01	
filament wound epoxy glass	t	0.17	

2.3.2 Inventory data modelling

Background data linking materials to emissions over the product chain are taken from the life cycle inventory database ecoinvent (Wernet et al., 2016). Ecoinvent provides ‘production’ and ‘market’ datasets for several locations. Market datasets combine several specific production datasets as well as transportation. If not explicitly specified in the underlying data sources or the regions therein where unavailable (global) market data sets were chosen. If these were not available, region of Europe datasets were selected, no other transport was included on top of the ones already included in ecoinvent. Additionally, the following proxy processes were chosen were no exact datasets were available in ecoinvent:

- Metal working for steel for wind turbine power and foundation and platforms where adapted from the ecoinvent pocess where the amount of steel loss during processing was reduced to 5% (compared to 22.7% in ecoinvent) based on expert judgement (Van Dinghe et al., 2024).
- Primary copper was modelled as copper anode as this resembles most closely the production process.
- GHG emission data for production of iridium were taken from Ashby (2021) as these were not available in ecoinvent.

2.4 Sensitivity analysis

Uncertainties in modelling are related to the fact that different data sources had to be combined and different system designs are still possible, therefore a number of sensitivity scenario have been calculated. These have been based on existing data and must therefore be seen as a very first indication:

- To account for the fact that using different data sources for the different types of platforms, in particular the electrolyser and compressor platform that share similar functions, an additional approach was taken: the compressor platform was set equal to the electrolyser platform and a proxy compressor was taken from ecoinvent. Details of the alternative modelling approaches are shown in Appendix C.
- Instead of a grid connection back up by batteries (based on ecoinvent data for stationary applications) could also have been assumed. These batteries are reported to have a power density of 27Wh/kg. A battery capacity of 1.8 MWh/MW was assumed based on consultation with TNO experts and required mass of battery was linearly scaled to MWh capacity, which could be a strong worst case approach. The modelled processes and masses per system are shown in Appendix C.

Gathering pipelines were roughly approximated by reducing the mass of offshore pipeline for transportation. However, it might be possible that instead small pipes made of polymers and fibres could be used. Next to that, according to discussions with experts, it might also be possible to forgo compressor station (with our without integrating small compression steps at the turbine) and a large pipeline and have several small running pipes onshore directly from a number of turbines. Due to large data uncertainties including modelling this option has not been attempted.

3 Results and discussion

Figure 3.1 shows a comparison of the carbon footprint of the centralised and decentralised system and the contribution of the major components. Differences between the two systems are small, with the central system showing a slightly larger footprint. More than half of the footprint of both systems is built up of the wind turbine system itself, with the foundation contributing most, followed by tower, hub & nacelle and blades. These relative contributions are line with Allekotte & Garrett (2024). In total the amount of steel required for building a 2 GW wind farm exceeds those of the added platforms. Other electronics (transformers and converters not included in the nacelle and hub) have a minor contribution. Differences in electronics between the two systems could not be modelled, however, considering the small contribution, they are not expected to lead to large differences in carbon footprints.

When assuming the same electricity outputs, wind farm footprints are also comparable to Dinghe et al. (2024) (results not shown). On a per MW basis, however results are higher than Allekotte & Garrett (2024), probably due to different choices in inventory database or dataset that cannot be verified from the report. The electrolyser systems including desalination units and batteries were the second largest contributor to carbon footprints. Batteries and desalination units were a first approximation and further more detailed modelling is recommended if differences between the systems are expected and data become available. Differences between the systems arise from the different types of platforms and offshore transport. Having electrolysers integrated with the transition piece seems to be more efficient in terms of carbon footprint than having a separate electrolyser platform. Likewise the compressor platform compares favourably with the transformer station. Both effects lower the carbon footprint of the decentral system compared to the central one. However, these results should be considered with care because data for both systems have been taken from different sources and the specific designs therein might affect material quantities and therefore the carbon footprint. Where possible, this has been addressed in the ***sensitivity analysis.*** Changing transformer platform from NSWPH data to using the electrolyser platform from NSE increased the carbon footprint of the decentralised system by roughly 1%. Although the housing and equipment modelling for the transformer station modelling from Dinghe et al. (2024) must be seen as a first approximation, no alternative was modelled here as 50% of the impact could be attributed to the steel for the platform. These results also indicate that elimination of compressor platforms would lead to small reduction in carbon footprint. Only the amount of gathering pipelines in the decentralised system have a higher carbon footprint than the cable arrays and platform connection in the central system, mainly due to the longer estimated distance (Table 2.1). However, considering the first estimation nature of the data, these differences are negligible.

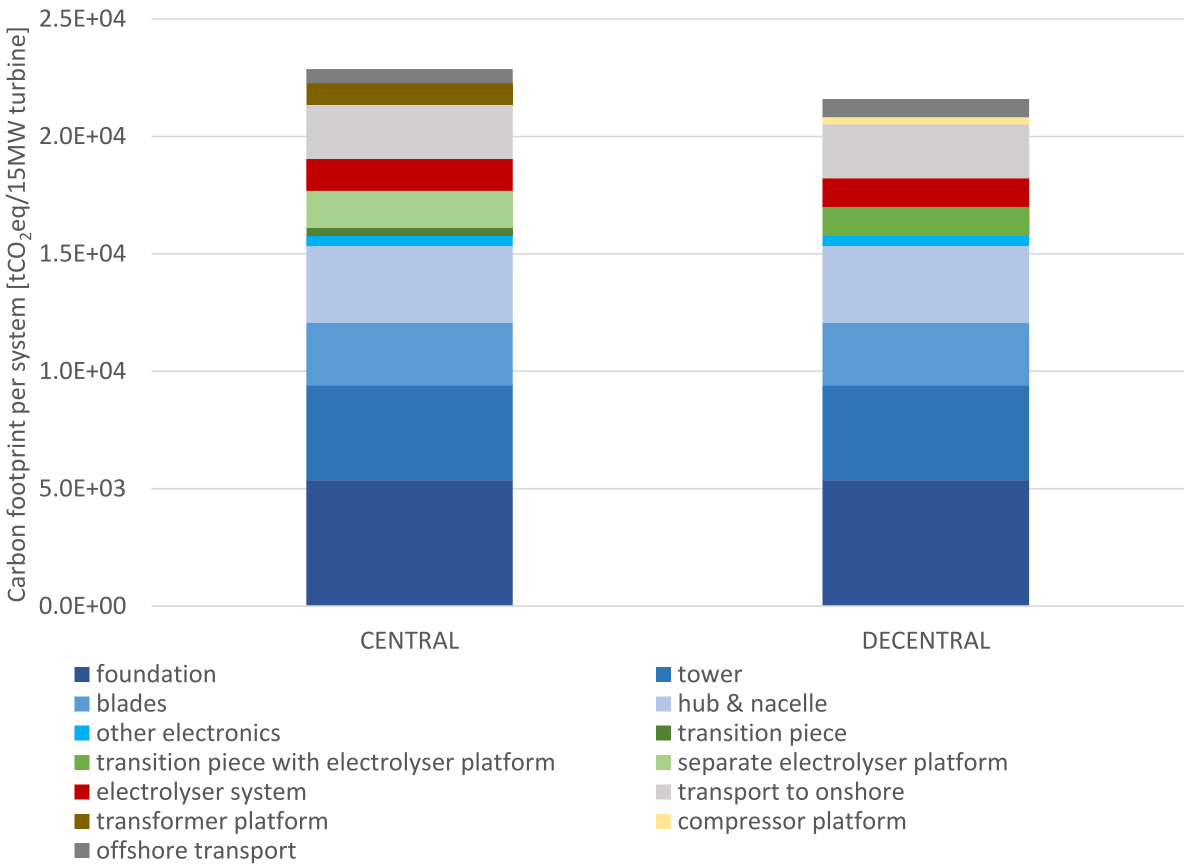

Figure 3.1 Comparison of carbon footprints for the centralised and decentralised (hydrogen at turbine) system. Compressor and transformation platforms include equipment, the electrolyser system includes desalination.

3.1.1 Alternative designs

Next to the design investigated here (hydrogen ***at*** turbine), hydrogen ***in*** turbine is also a possible design, where also the electrolyser system is placed on additional platforms within the turbine. The design modelled here had been identified as most feasible by Moreno (2021) and data for alternatives are even scarcer. Main reasons not to perform hydrogen treatment within a turbine are safety risks. In our analysis, 265 tonnes of extra weight have been added to the transition piece for an external platform. In turbine designs could differ in carbon footprint if masses for additional internal structures, would deviate substantially from this amount. It should be noted, that existing internal structures have been modelled as aluminium based in this case, which represents a worst case assumption in terms of carbon footprints (Dinghe et al., 2024).

In case that offshore pipeline would be replaced by a string of polymer pipes, the carbon footprint for pipeline materials, could decreased substantially. However, not enough data were available to model the pipelines and their offshore installation, therefore it cannot be said at this state how these could affect the offshore transportation system carbon footprint. It can merely be indicated that investigating alternative pipe materials and less platforms could reduce carbon footprint. If batteries were used instead of grid connection, carbon footprints would increase slightly under the current worst case assumptions (Figure 3.2 shown in the Appendix). Considering substantial battery pack might still be needed, this supports the need for further research into back-up power.

4 Conclusion and recommendation

This report aimed to compare the carbon footprints of different offshore green hydrogen production designs: central via electrolyser platforms and decentral via hydrogen at turbine. Carbon footprints were dominated by impacts from wind turbines due to the large amounts of steel for building a wind farm. Differences between the designs were negligible in comparison. It must be kept in mind that due to the new nature of many of the designs inventory data must be considered as indicative. Recall, that no differences in system performance, lifetime and maintenance requirements were expected. An important consequence is that, if differences in any if these aspects would occur, mainly when leading to changes in overall lifetime hydrogen production, this could make decisive differences between the systems. Options for reducing carbon footprints are optimizing pipeline and cable demand. Potential differences arising from different installation and maintenance options were not investigated. Independent of design enhancing contribution of secondary steel is a good option (see also Hauck et al., 2022). The new nature of the designs is also an opportunity to include circular design, end of life strategies and material information with new assets.

References

Allekotte, Lukas, Garrett, Peter, 2024. Life cycle Assessment of a electricity production from an offshore V236-15 MW wind plant.

Ashby, M. F. (2021). Appendix B – Eco- and supply-chain data. *Materials and the environment: eco-informed material choice*. Eco-Informed Material Choice. 2021, Pages 403-429. https://doi.org/10.1016/B978-0-12-821521-0.15002-9

Chico Moreno, F. D. (2021). Design of an Electrolyzer Integrated in an Offshore Wind Turbine System. [EngD Thesis, University of Twente]. University of Twente. From: https://research.utwente.nl/en/publications/design-of-an-electrolyzer-integrated-in-an-offshore-wind-turbine-

Gaertner, Evan, Jennifer Rinker, Latha Sethuraman, Frederik Zahle, Benjamin Anderson, Garrett Barter, Nikhar Abbas, Fanzhong Meng, Pietro Bortolotti, Witold Skrzypinski, George Scott, Roland Feil, Henrik Bredmose, Katherine Dykes, Matt Shields, Christopher Allen, and Anthony Viselli. 2020. Definition of the IEA 15-Megawatt Offshore Reference Wind. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-75698. https://www.nrel.gov/docs/fy20osti/75698.pdf

Gerloff, 2021. Comparative Life-Cycle-Assessment analysis of three major water electrolysis technologies while applying various energy scenarios for a greener hydrogen production. Journal of Energy Storage 43 (2021) 102759

Hauck, 2020. D4.1-Report-on-life-cycle-comparison-of-environmental-performance-of-grey-blue-green-hydrogen-pathways. From: https://north-sea-energy.eu/static/1a8004c68fb16f7ed588ef2d10ea51bf/9.-FINAL-NSE3_D4.1-Report-on-life-cycle-comparison-of-environmental-performance-of-grey-blue-green-hydrogen-pathways.pdf

Hauck, Mara, Lia de Simon, Jonna Snoek, 2022. D4.2 North Sea Energy 2020-2022.Carbon footprint of offshore structures. https://north-sea-energy.eu/static/3c920aae741c4fbead4234fd716f5e53/NSE-2020-2022-4.2-Carbon-footprint-of-offshore-structure-corr-29-11.pdf

Kamps and Elbing, 2024. NSE Material Flow Analysis and Criticality Assessment.

Kawale, Dugesh, Aravind Satish, Ellen van der Veer, Yeshambel Melese, Thomas Hajonides van der Meulen, Rob van Zoelen, Shubhra Chaudhry, Miralda van Schot, Salar Mahfoozi, Joris Kee, 2022. D1.1 Energy Hubs & Transport Infrastructure. https://north-sea-energy.eu/static/2fd1407691ef2b058666b7f5e5c93d05/NSE-2020-2022-1.1-Energy-Hubs-and-Transport-Infrastructure-v2.pdf

North Sea Wind Power Hub (NSWPH), 2024. Offshore Energy Hubs: Blueprints with Offshore Electrolysis. Discussion Paper #2. Part of: North Sea Wind Power Hub feasibility and preparation studies. From: https://northseawindpowerhub.eu/files/media/document/2024.09.16_NSWPH_Offshore%20Energy%20Hubs%20Blueprints%20with%20Offshore%20Electrolysis_Technical%20feasibility_Discussion%20paper%20%232.pdf (downloaded October 10th, 2024)

North Sea Wind Power Hub (NSWPH), 2024a. WTG H2 Concept Design Report: Offshore Structures. 2209-SLP-ST-RPT-0002 https://northseawindpowerhub.eu/files/media/document/Hydrogen%20Turbine%20Electrolysis%20%28WP6AB%20WP14%29.zip

North Sea Wind Power Hub (NSWPH), 2024b. Size and Weight Assessment. 424532-N-RP-0002. https://northseawindpowerhub.eu/files/media/document/Platform%20based%20electrolysis%20%28WP-2B%20WP-2E%29.zip

North Sea Wind Power Hub (NSWPH), 2024c. Functional Block Diagram. 424532-T-DR-0003 https://northseawindpowerhub.eu/files/media/document/Hydrogen%20Turbine%20Electrolysis%20%28WP6AB%20WP14%29.zip

Razman, Khalisah Khairina, Marlia M. Hanafiah, Abdul Wahab Mohammad, Sergey Agashichev, Sgouris Sgouridis, Faisal Al Marzooqi, 2023. Environmental performance of a photovoltaic brackish water reverse osmosis for a cleaner desalination process: A case study. Science of the Total Environment 896 (2023) 165244

Schaefer, Juni Marie Lerøy, 2022. Concept analysis and life cycle assessment of large-scale, offshore hydrogen production, storage and distribution options. Master Thesis in Energy. University of Bergen, Department of Physics and Technology. https://bora.uib.no/bora-xmlui/bitstream/handle/11250/3000765/FINALMASTER.pdf?sequence=1

Vinit V. Dighe, Aaradhya Bansal, Kamiel Jansen, Joep Breuer and Harald van der Meijer, 2024. A prospective life cycle assessment of drivetrain technologies in offshore wind. In preparation.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21(9), pp.1218–1230.

Appendix A: Flow chart data sources

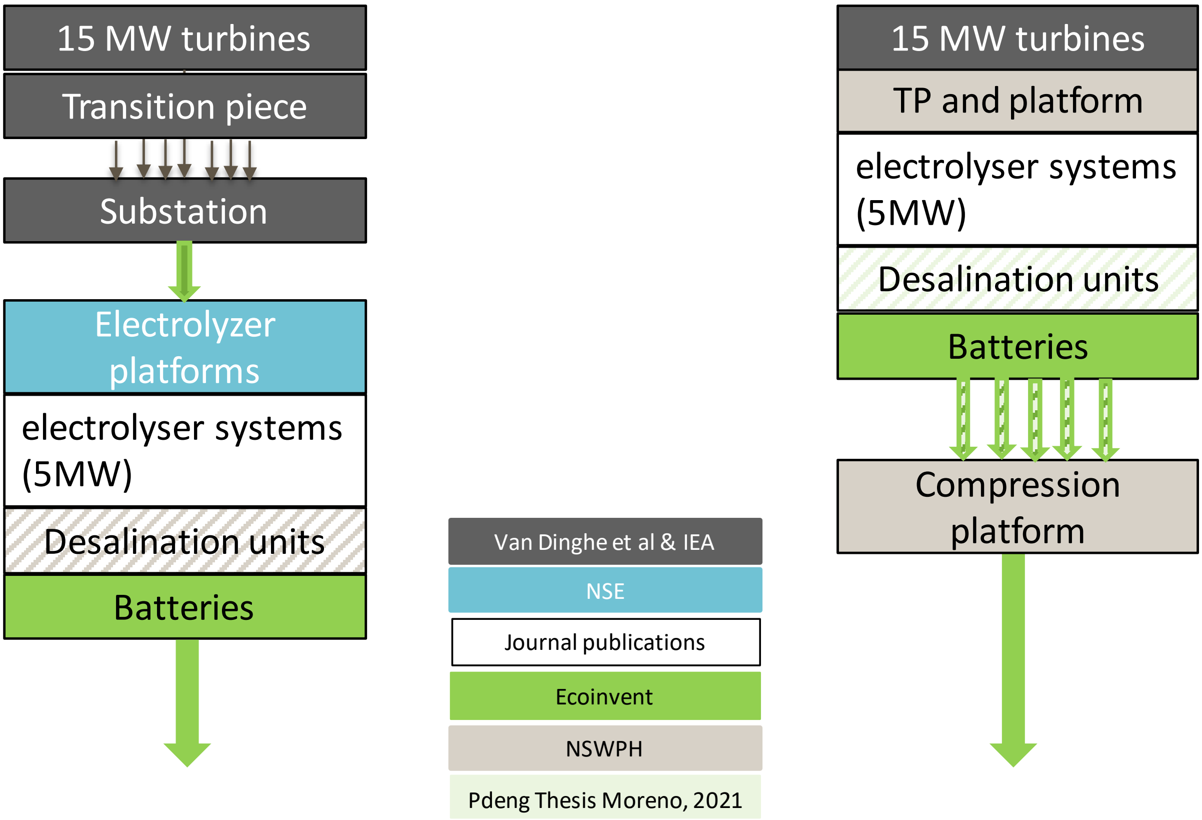

Figure A1. Inventory data sources per component used in this report for a 5 MW electrolyser system, central on the left, decentral on the right.

Appendix B: Electrolyser scaling and inventories

Inventory data per 1 MW of electrolyser stack have been taken from Gerloff (2021) and scaled following the approach in the same paper. Component weights were scaled with electrolyser capacity following Equation A1:

$$M_2 = M_1 \cdot \left(\frac{C_2}{C_1}\right)^b \qquad \text{Equation A1}$$

Where: M_2: unknown weight of the component [kg], M_1: known weight of the component [kg]; C_2: electrolyser capacity belonging to component 2 [MW], C_1: electrolyser capacity belonging to component 1 [MW], b: scaling factor [-] (0.95 for PEM stack; 0.98 for balance of plant; 0.9 for power electronics) (Gerloff, 2021). The resulting inventory for a 5 MW electrolyser is shown in Table A1. Production regions were not given from Gerloff (2021) therefore global datasets were used and production datasets were replaced by market datasets. Copper processes are not available in ecoinvent any more and were approximated by copper anode.

Table A1. Inventory data for a 5 MW electrolyser system, based on Gerloff (2021)

Component	Ecoinvent process	Amount 5 MW system [kg]
Power electronics		
	market for aluminium, wrought alloy {GLO}	426
	market for copper-rich materials {GLO}	851
	market for reinforcing steel {GLO}	2554
	market for sheet rolling, aluminium {GLO}	426
	market for sheet rolling, steel {GLO}	2554
	market for tube insulation, elastomere {GLO}	426
	market for wire drawing, copper {GLO}	851
Balance of plant		
Control panel/electronics	market for electronics, for control units {GLO}	393
tubing and pump	market for steel, low-alloyed {GLO}	3535
	market for sheet rolling, steel {GLO}	3535
steel construction element	market for sheet rolling, chromium steel {GLO}	2946
	market for steel, chromium steel 18/8 {GLO}	2946
Purification (De-oxo) & water treatment	market for aluminium, wrought alloy {GLO}	393
	market for sheet rolling, aluminium {GLO}	393
water-gas separator	market for copper, anode {GLO}	393
	market for sheet rolling, copper {GLO}	393
valve	market for polypropylene, granulate {GLO}	1178
	market for injection moulding {GLO}	1178
back pressure regulator	market for lubricating oil {RER}	393
ion exchanger	market for zeolite, powder {GLO}	393

heat exchanger	market for sheet rolling, chromium steel {GLO}	4560
	market for steel, chromium steel 18/8 {GLO}	4560
water purifier and feed tank	market for extrusion, plastic pipes {GLO}	1825
	market for polyethylene, low density, granulate {GLO}	1825
	market for reinforcing steel {GLO}	912
	market for sheet rolling, steel {GLO}	912
frequency converter diaphragm compressor	market for aluminium, wrought alloy {GLO}	236
	market for copper-rich materials {GLO}	177
	market for reinforcing steel {GLO}	707
	market for tube insulation, elastomere {GLO}	59
	market for wire drawing, copper {GLO}	177
diaphragm for diaphragm compressor	market for cast iron {GLO}	2357
	market for ethylene glycol {RER}	27
	market for reinforcing steel {GLO}	5106
	market for sheet rolling, chromium steel {GLO}	1591
	market for sheet rolling, steel {GLO}	1571
	market for steel, chromium steel 18/8 {GLO}	1591
container with pipes and fittings for diaphragm compressor	market for reinforcing steel {GLO}	3928
	market for sheet rolling, chromium steel {GLO}	5891
	market for sheet rolling, steel {GLO}	3928
	market for steel, chromium steel 18/8 {GLO}	5891
Buffertank	market for sheet rolling, chromium steel {GLO}	2007
	market for steel, chromium steel 18/8 {GLO}	2007
Container	market for welding, arc, steel {GLO}	114
	market for sheet rolling, steel {GLO}	8837
	market for steel, low-alloyed {GLO}	8837
Stack		
end plate	market for aluminium, wrought alloy {GLO}	125
	market for sheet rolling, aluminium {GLO}	125
bipolarplate	market for titanium {GLO}	2436
membrane polymer	market for tetrafluoroethylene {GLO}	74
electrocatalyst anode	market for carbon black {GLO}	21
		4
electrocatalyst cathode	market for platinum {GLO}	0
	market for carbon black {GLO}	21
current collector	market for copper, anode {GLO}	21
	market for sheet rolling, copper {GLO}	21
bolts and screws	market for sheet rolling, chromium steel {GLO}	461
	market for steel, chromium steel 18/8 {GLO}	461
gasket	market for synthetic rubber {GLO}	22

Appendix C: Sensitivity Analysis

Table A2. Masses and processes for alternative modelling approaches on own calculations and assumptions as explained in text.

	Unit	Amount	Ecoinvent process
Alternative compressor station	p	1	Electrolyser platform 500MW
With compressors	p	84	84 units of 'market for air compressor, screw-type compressor, 300kW' based on Schaefer (2022)
Battery for 1MW system	tonnes	66.7	Ecoinven process: market for battery, lead acid, rechargeable, stationary
Batteries for decentral system	p	133	Battery for 15MW system
Batteries for central system	p	4	Battery for 500MW system
Non-central hydrogen transport onshore	km	150*19	ecoinvent process 'market for polyethylene pipe, DN 200, SDR 41 {GLO}',

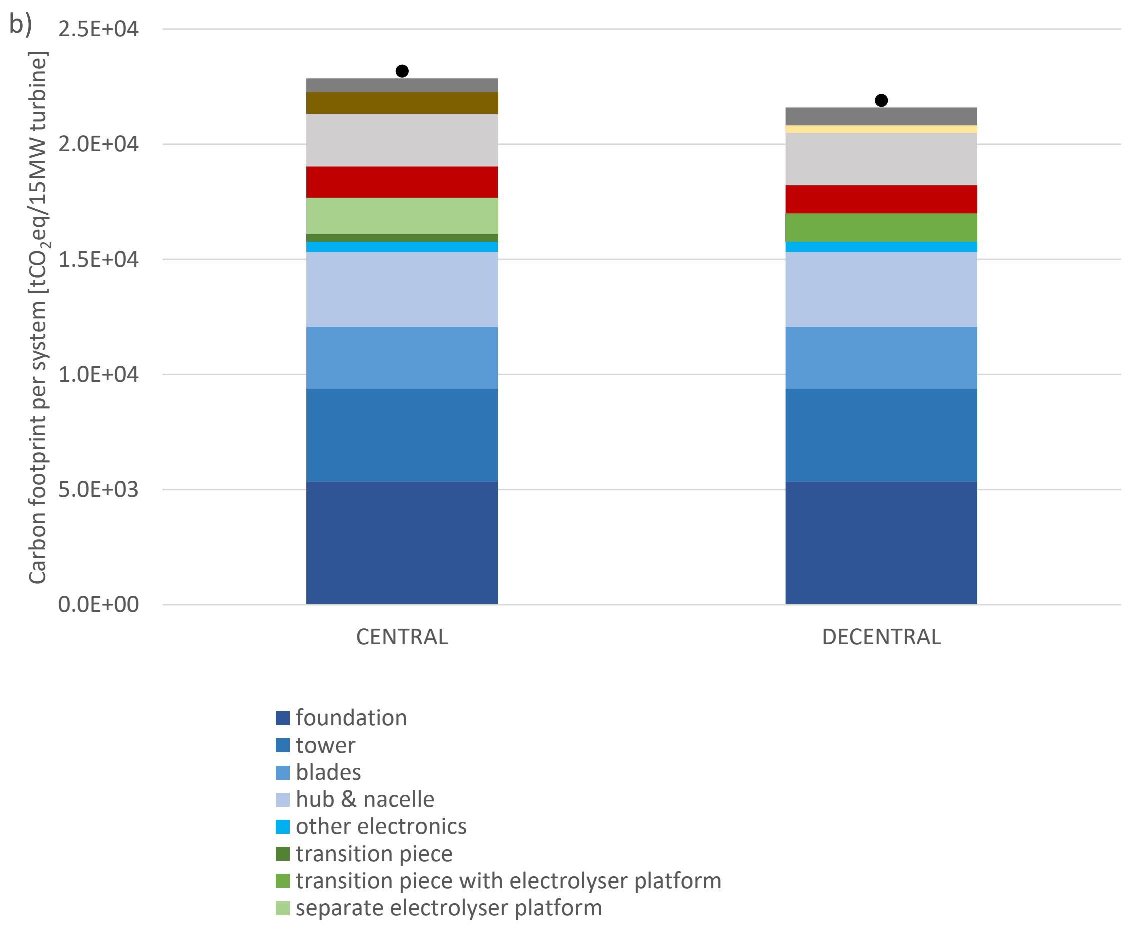

Figure 3.2 Comparison of the carbon footprints of the two systems with batteries (worst case) instead of cables.

North Sea Energy offshore system integration

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