North Sea Energy
offshore system integration

D4.5

North Sea Energy 2023-2025

Material Flow Analysis and Criticality Assessment

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

Material, in particular, metals play a central role in successfully building Europe's clean energy technology and digital technology value chains and meeting the EU's 2050 climate-neutrality goals. The North Sea has a significant role to play to achieve the EU's energy demand. The nine countries participating in the North Seas Energy Cooperation (NSE-C) have set a target of 76 GW by 2030, 193 GW by 2040 and 260 GW of offshore wind by 2050. These targets accounts for a deployment of at least 6 GW per annum, a significant step up from the current 3.4 GW/year. This study offers an initial assessment of the anticipated material demand for energy technologies and infrastructure in the North Sea through 2050. The study also assesses which bottlenecks might arise to meet the material demand.

To model the material flows associated with the energy technologies and infrastructure in the North Sea up to 2050 a stock-driven dynamic stock model (DSM) is used. The analysis includes the following technologies: offshore wind power, offshore natural gas, offshore floating solar, offshore hydrogen production, and carbon capture utilization and storage.

The results of the DSM show that the demand for materials is projected to rise significantly between 2020 and 2050. Material outflows from energy technologies reaching end-of-life are considerably lower than the inflows required to meet the demand for new technologies. In a hypothetical scenario where the North Sea energy system operates as a fully circular economy, the secondary materials generated would still cover only a fraction of total material demand. Consequently, reliance on primary materials or secundary materials from outside the NSE system will remain substantial. Furthermore, a significant amount of critical raw materials (CRMs) is required. CRMs are essential materials with high economic importance and significant supply risks, vital for industries like renewable energy, digital technologies, and defense, and often facing challenges in sustainable sourcing and recycling.

Most (refined) critical raw materials are concentrated in a limited number of countries, creating significant risks of supply disruptions due to geopolitical tensions, export restrictions, or environmental issues. The EU's Critical Raw Material Act aims to mitigate these risks by enhancing mining, refining, and recycling capacities in Europe while diversifying import sources. However, if demand for certain materials grows rapidly outpacing supply, market dynamics could still lead to significant price increases, causing supply chain disruptions and manufacturing delays. This scenario may prompt industries to intensify efforts to explore alternative materials or technologies that rely less on scarce resources. However, it is unlikely that these alternatives can be produced at sufficient scales in the short term to replace existing technologies.

For the North Sea energy system to achieve its deployment targets, a continuous balancing act will be required between the cost, efficiency, and availability of energy technologies and infrastructure. It is recommended to regularly assess risk, vulnerabilities and dependencies associated with supply disruptions, geopolitical factors, and market fluctuations to inform decision-making. Additionally, it is recommended to develop and build out strategic partnerships with a diverse range of key suppliers across various countries, and to explore partnership with emerging producers of low-CRM energy technologies.

1 Introduction

“North Sea Energy is a public-private research programme, which benefits from the cooperation of almost 40 international parties from the energy value chain. These parties are active in and around the North Sea. The programme was launched in 2017 and investigates the North Sea’s potential for an integrated energy system. The North Sea Energy programme consists of several research projects at the heart of which is an integral approach to the energy system and its benefits.” [1]

One of the research projects (within work package 4) focusses on assessing the environmental impacts of the energy technologies and infrastructure to be deployed in the North Sea. In the last years, carbon footprint analysis has already been conducted for several energy technologies using life-cycle assessment (LCA). These assessments included: offshore wind, offshore natural gas, green/blue/grey hydrogen (Hauck, 2020), and offshore structures (Hauck et al., 2022). In 2024, additional life-cycle assessments have been conducted for floating solar and decentral hydrogen. These assessments focus on single technological units and mainly emissions and energy consumption whereas this research focusses on the total material demands as a bottleneck to affect feasibility of building a low-carbon energy system.

This research builds upon these life-cycle assessments to model to the material flows associated with the expected energy technology and infrastructure deployment in the North Sea.

1.1 Relevance

Metals play a central role in successfully building Europe’s clean energy technology and digital technology value chains and meeting the EU’s 2050 climate-neutrality goals. Recent geopolitical events, energy price volatility, regulatory changes, and financial market conditions have underscored Europe's and the Netherlands' lack of resilience in meeting this growing demand for critical raw materials (CRMs) and strategic raw materials (SRMs). This issue has become a strategic concern, as reflected in the EU's Critical Raw Materials Act and the Dutch "Nationale Grondstoffenstrategie".

Action is needed to avoid supply chain bottlenecks by the end of this decade. For Europe to become resilient, insights into vulnerable value chains related to the supply and demand of CRMs and SRMs for key sectors is needed. This research focusses on filling a knowledge gap on the demand side of CRMs and SRMs for the energy technology sector. Within the energy technology sector, the North Sea has a significant role to play to achieve the EU’s energy demand. The nine countries participating in the North Seas Energy Cooperation (NSE-C) have set a target of 76 GW by 2030, 193 GW by 2040 and 260 GW of offshore wind by 2050. These targets accounts for a deployment of at least 6 GW per annum, a significant step up from the current 3.4 GW/year. The North Sea will account for a large fraction of the total EU offshore

[1] North Sea Energy (north-sea-energy.eu). About us. Retrieved: 21-10-2024.

energy capacity which is aimed at 88 GW in 2030 and 360 GW in 2050[2]. Furthermore, the North Sea energy system will be critical in achieving the EU's minimum target of a 42.5% share or renewable energy in 2030, up from 24.1% in 2023[3].

1.2 Goals

The goal of this study is twofold:

- Assess the material demand of energy technologies and infrastructure deployment in the North Sea up to 2050.
- Assess which bottlenecks might arise for timely energy transition in the North Sea related to materials demand.

[2] Offshore renewable energy. Retrieved at 23-12-2024.
[3] Share of energy consumption from renewable sources in Europe. Retrieved at 23-12-2024.

2 Methodology

This chapter contains a description of the methods used to achieve the research goals. The chapter is divided into a description of the scope (2.1), an explanation of dynamic material flow analysis (2.2) and criticality assessments (2.3), a detailed description of data collection and processing (2.4), and a description of the model and its data flows (2.5).

2.1 Scope

The following sections outline the key aspects of the material flow analysis, including system boundaries, geographic scope, temporal scope, technologies, and materials considered in this study.

- System boundaries: the material flow analysis focus solely on the material inflow due to construction activities, stock accumulation and material outflow due to demolition activities. Material flows related to repair activities are excluded in this iteration of the research.
- Geographic: the spatial scope is governed by the North Sea countries, which include Belgium, Denmark, France, Germany, the Netherlands, Norway, Sweden, and the United Kingdom.
- Temporal: the material flow analysis covers 2023-2050 with yearly intervals for construction and demolition.
- Technologies: the technical scope includes most offshore energy commodities (natural gas, electricity, hydrogen and CO2) and with it their main marine energy assets including natural gas production, wind energy, floating solar, offshore energy storage, CO2 transport and storage, including the infrastructure for landfall of these commodities. Table 2.1 provides an overview of each technology, and their components included in the analysis.
- Materials: all CRMs, SRMs and bulk materials associated with the technologies and components are included in the analysis. Several other materials, such as chemicals, are present in the material intensity data, but are not reported on in detail in this study. Table 2.2 shows a qualitative overview of the materials included in the analysis and which technologies contain them.

Table 2.1 Technology scope

Technology	Component	Description
Offshore wind power	Wind turbine	Offshore wind turbines harness wind energy from oceanic environments, benefiting from stronger and more consistent wind patterns. They vary in size, capacity, and mounting, all of which impact the material required per unit of produced power.
	Internal array cabling	Internal array cabling in offshore wind power systems refers to the network of cables that connect individual wind turbines within a wind farm.
	External cabling	External cabling connects the offshore wind park to the onshore grid, transmitting electricity over long distances. Connection to consumers within the North Sea, e.g., hydrogen platforms, were not considered.
Offshore natural gas	Platforms	Platforms support drilling and production operations, engineered to withstand harsh marine environments. They are predominantly made of steel. Efforts to remove out-of-service platforms from the sea started in the last couple of years.
	Wells	Offshore wells are drilled through the seabed to extract natural gas or oil, often reaching depths of several thousand meters. These wells are designed to ensure efficient and safe resource extraction and are therefore resource intense components.
	Pipelines	Pipelines transport natural gas or oil from offshore wells to onshore facilities or connect gas networks between countries. The existing pipeline network in the North Sea spans several tens of thousands of kilometres.
Floating solar	Modules	Floating solar systems consist of photovoltaic modules, including the solar cells, frames, and junction boxes. These systems can be mounted on various floating structures, impacting their resource efficiency. It was assumed that all solar panels are mounted on steel structures high above the sea level.
Offshore Hydrogen production	Electrolysers	Electrolysers split water into hydrogen and oxygen using electricity. These systems consist of electrodes, membranes, and power supply units.
	Platforms	Electrolysers will be placed on several platforms throughout the North Sea close to wind parks which can produce the electricity for the hydrogen production.
	Pipelines	Pipelines transport the hydrogen from offshore production facilities to shore and connect the future hydrogen networks of countries. Several gas pipelines will be repurposed for the transport of hydrogen.
Carbon capture utilization and storage	Compressors and pumps	Carbon dioxide produced by industry will be stored in old oil and gas fields. Compressors and pumps will generate the necessary pressure to inject the CO_2 into these geological formations.
	Wells	New wells will be drilled to reach former oil and gas fields. Those wells can be several thousand meter deep.
	Pipelines	Pipelines will be built to transport CO_2 from carbon emitting onshore industry to the storage facilities offshore.

Table 2.2 Material scope

Material	Category	Offshore wind power	Offshore natural gas	Floating solar	Offshore hydrogen production	Carbon capture and storage
Activated carbon	Other				x	
Aluminium	CRM	x	x	x	x	x
Baryte	CRM		x			x
Bentonite	Other		x			x
Bitumen	Other	x				
Boron	CRM, SRM	x				
Cement	Other		x			x
Chemicals	Other	x	x	x	x	x
Concrete	Bulk		x		x	x
Copper	CRM, SRM	x	x	x	x	x
Dysprosium	CRM	x				
Fluoride	Other	x				
Glass	Bulk	x		x		
Iridium	CRM				x	
Iron/steel	Bulk	x	x	x	x	x
Lead	Metal	x		x		
Lignite	Other		x			x
Natural Rubber	Other	x				
Neodymium	CRM	x				
Paper	Other			x		
Plastic	Bulk	x		x	x	
Platinum	CRM, SRM				x	
Silicon metal	CRM, SRM		x	x	x	x
Stone	Other	x				
Tin	Metal			x		
Titanium metal	CRM, SRM	x			x	
Wood	Other	x				
Zinc	Metal	x	x		x	x

Source: Classification of critical raw materials and strategic materials from: RMIS - Critical, strategic and advanced materials: CRM list – 2023, retrieved 30-10-2024. Material composition data from multiple sources, as explained in the table in Appendix 0.

2.2 Material flow analysis

To model the material flows associated with the energy technologies and infrastructure in the North Sea up to 2050 a dynamic stock model (DSM) is used. A DSM is a scientific framework used to analyze and understand the flow and accumulation of resources or substances within a system over time. Two types of DSM exist: inflow- driven and stock-driven models. In an inflow driven model, the stock and outflow are calculated using (historic) inflows and lifetime distributions. In a stock driven model the inflow and outflow are calculated using (historic) stocks and lifetime distributions.

In this research a stock driven DSM is used because detailed data on the current installed capacity of the energy commodities and their future deployment projections are available. A stock driven model requires at least the following data components:

- Stock: historic, current, and future installed capacity of offshore energy commodities and their associated infrastructure
- Lifetime distribution function of each energy commodities (e.g., Weibull distribution, see Box 1.1)

The DSM results provide insights into the inflows, stocks, and outflows for each energy technology and its associated infrastructure. These stocks and flows are then integrated with the material composition data of each energy commodity (e.g., kg of silicon per MW of installed capacity for floating solar, or kg of aluminum per installed capacity of wind turbines) to calculate overall material flows.

It's important to note that the DSM also facilitates a more detailed analysis at the (sub)component level, rather than just the energy commodity level. This approach allows for the inclusion of material flows from activities like repairs before an energy commodity reaches the end of its life. For instance, an offshore wind turbine typically has a lifespan of 30 years, but its wiring must be replaced every 10 years. However, these (sub)component-level material flows are currently outside this research's scope.

2.3 Criticality assessment

To put the material flows resulting from the DSM into perspective, the economic importance (EI) and supply risk (SR) indicators of the European Commission (EC) are used (Blengini, et al., 2017). The EI describes the vulnerability to supply disruptions, and the SR describes the risk of supply disruptions.

Economic importance is calculated as a function of the economic value added of the use of materials in an economic sector and their material substitution potential. Supply risk is calculated as a function of the concentration of mining and refining of materials, an index on country specific governance risks, export challenges, and potential material substitutability. See Blengini et al. (2017) for a detailed description of all formulae used to calculate the EI and SR.

In this research, the EI and SR are used to indicate which materials are associated with considerable risk. A scaling method is proposed to calculate the overall risk of the demand of a material for the North Sea energy system (EQ1).

$$\text{EQ1: } OR, mat, y = (SR, mat) * \sqrt{inflow, mat, y}$$

where:

OR, mat, y = The overall risk score per material in a certain year
SR, mat = the supply risk per material
Inflow, mat = the material demand resulting from the DSM in a certain year

The root of the material demand is taken to emphasise the role of the supply risk in the overall risk calculation. This ensures that materials with relatively low demand (e.g. most of the CRMs) are not overshadowed by high-volume materials, such as steel or aluminium.

The main data source for the criticality assessment is the Study on the Critical Raw Materials for the EU 2023 commissioned by European Commission (2023). The study includes a comprehensive evaluation of the EI and SR for all critical raw materials essential to the EU's economy. Together with the results of the MFA, these indicators are used to evaluate the criticality of the material demand of the North Sea Energy system. This evaluation considers the total inflow of CRMs and SRMs over the entire future temporal scope across all technologies, combined with the current supply risk (see section 2.4, EQ1).

Furthermore, the study of the European Commission (2023) provides data on the countries of origin differentiating between extraction and processing stage. This data is utilized to map the upstream value chain of individual CRMs and SRMs, identifying the countries involved in their mining and processing.

2.4 Data collection and processing

The MFA requires data on the historic stock, future stock projections, lifetimes, and material intensities are required for each technology and component. The historic stock was compiled from various sources, primarily the OSPAR database (OSPAR, 2023), the North Sea Energy Atlas (2024), and the North Sea Transition Authority (2024). Stock projections were based on data provided by NSE5 - Work Package 7 from the file *North Sea Energy – WP7 – Country overview GA scenarios.xlsx* (WP7) or internal expert judgment. Regressions of the historic stock with other data were sometimes necessary to extrapolate the data. Lifetimes and material intensities were sourced from literature or from LCAs performed for NSE projects (Wernet, et al., 2016). Detailed explanation on data sources, data processing, and taken assumptions can be found in Appendix 0.

Challenges related to the data and assumptions used in the project were identified, with potential improvements outlined in Appendix 0.

The DSM uses a lifetime distribution to derive the stocks and flows of the system. In this research a Weibull distribution is used. Box 1.1 explains in detail what a Weibull distribution is and how it is used in this research. Figure 2.1 shows an example of a Weibull distribution and how the probability of a product reaching end-of-life is translated across various metrics like a survival curve.

Box 2.1 What is a Weibull distribution?

The Weibull distribution is a versatile continuous probability distribution commonly used to model product lifetimes and time-to-failure of systems. Its flexibility allows it to represent a wide range of failure behaviours, making it a popular tool in reliability engineering for analysing and predicting the lifespan of components and systems. The distribution's ability to capture different hazard function shapes makes it well-suited for describing various failure patterns observed in real-world scenarios. Additionally, its mathematical simplicity and adaptability enable it to fit data across different products and systems, further enhancing its utility in reliability analysis.

The probability density function (PDF) of the Weibull distribution is given by EQ2:

$$\text{EQ2: } f(x;k,\lambda) = \{\frac{k}{\lambda} * \left(\frac{x}{\lambda}\right)^{k-1} e - \left(\frac{x}{\lambda}\right)^{k}, 0, x \geq 0x < 0$$

where:

- *x* = the variable representing time to failure
- *λ>0* = the scale parameter
- *k>0* = the shape parameter

T (characteristic life) is often used to refer to a specific point in the distribution, typically the point at which approximately 63.2% of the population will have failed if the shape parameter k = 1. In general usage,
T can represent the average or characteristic life associated with the scale parameter, particularly in contexts where reliability is discussed.

Using the characteristic life (T) and scale parameter (*k*) the scale parameter *(λ)* can be derived as follows (EQ3):

$$\text{EQ3: } \lambda = \frac{T}{\Gamma(1 + \frac{1}{k})}$$

where:

- *λ>0* = the scale parameter
- *k>0* = the shape parameter
- T = the characteristic life
- Γ = represents the gamma function evaluated at 1+(1/k)

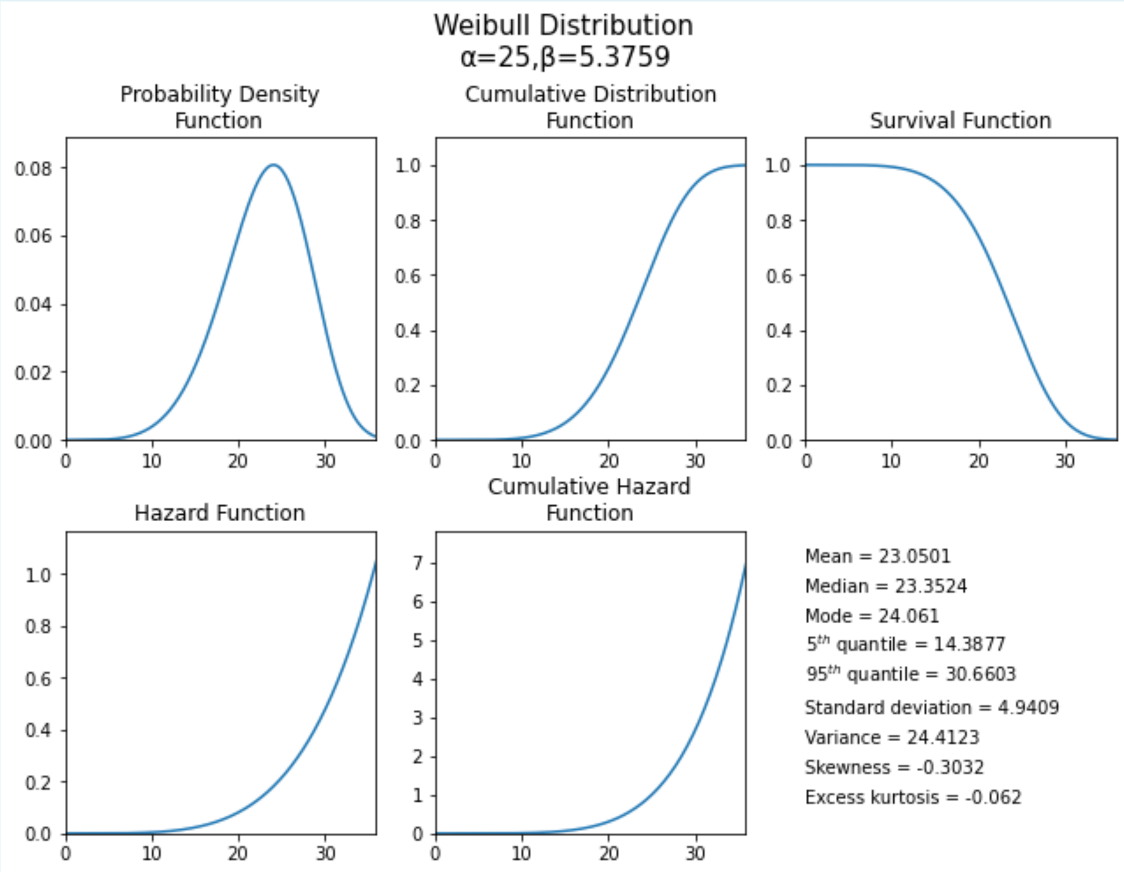

Figure 2.1 A Weibull distribution visualised. The figure shows an example probability density function of a Weibull distribution for a scale parameter of 25 (25-year average lifetime of a PV-panel) and a shape parameter of 5.3759 (source).

Data sources and processing methods of the criticality assessment are described in section 2.3.

2.5 Model description

This chapter contains a high-level description on how the model uses the data discussed in section 2.4 to produce the results for the material flow analysis and criticality assessment. Figure 2.2 shows a schematic overview of the model with its two sub systems, the material flow analysis, and the criticality assessment.

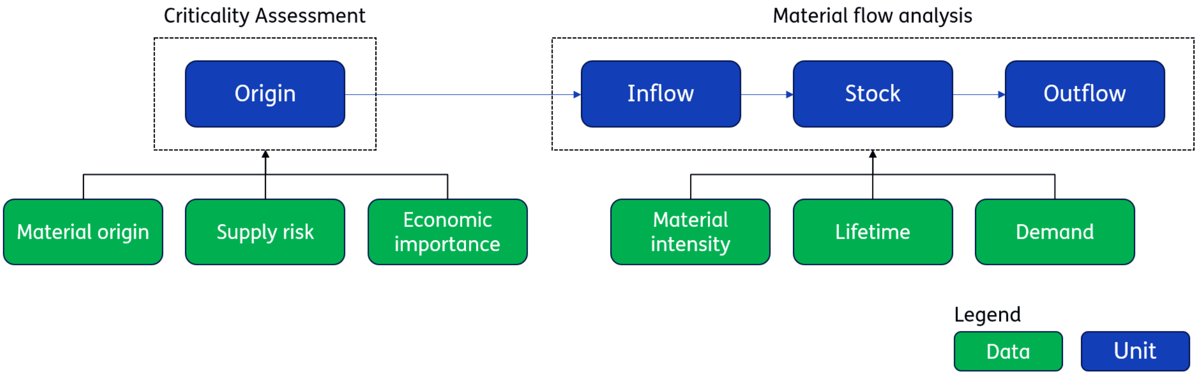

Figure 2.2: Schematic overview of the model including subsystems and required data.

Looking at the data processed in the MFA, the demand defines the stock in installed capacity (GW). The lifetime distribution is used to calculate the inflow and outflow in installed capacity. The material intensity converts the inflow, stock, and outflow into mass per material. The criticality assessment leverages the calculated inflow looking at the demand of specific materials and its supply risk, economic importance, and origin.

2.5.1 Material flow analysis

The goal of the material flow analysis is to quantify the material stocks, inflows, and outflows of energy technologies and their respective infrastructure in the North Sea up to 2050. For most technologies, the historic and current stock is provided in the form installed capacities in megawatts (MW); the demand provides the future installed capacities.

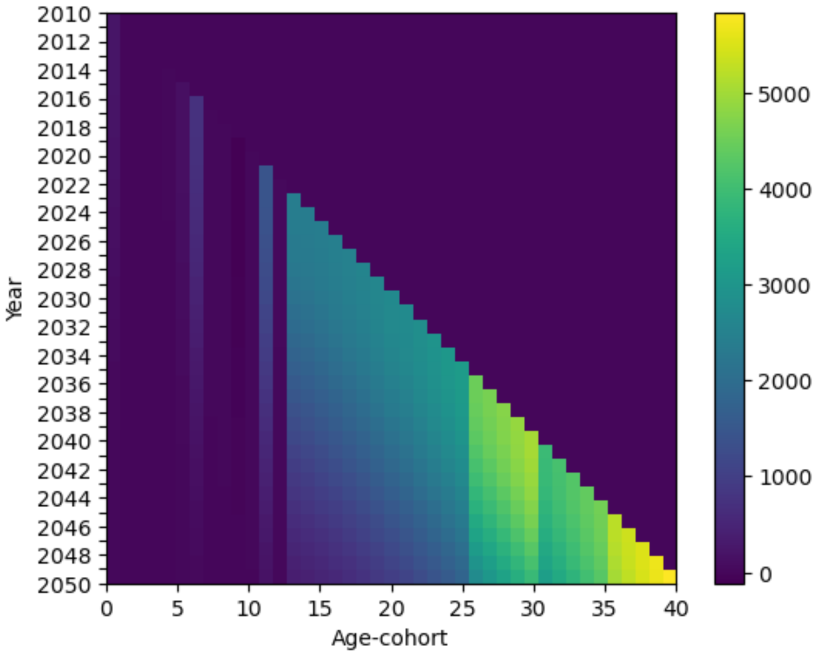

Figure 21.3: Stock by age-cohort matrix on the example of offshore wind turbines in the Netherlands in MW.

The inflow and the outflow, also in installed capacity (MW), need to be determined via the stock-driven dynamic stock model (DSM). A DSM requires the stock (installed capacity) of the system for each year and how long this stock will remain within the system – its lifetime. The lifetime is defined by the Weibull survival function (see Box 1.1). Figure 2.3 represents this for the years 2010 to 2050 using the example of offshore wind turbines in the Netherlands. On the diagonal axis, we see the inflow into the system for each year (cohort). Below each of these inflows, we can observe the stock depleting over time. This way, the inflow, outflow, and stock are defined for each year. The outflow in a particular year is the sum of the outflows of all previous cohorts. Therefore, years that lie before the temporal scope of the study need to be modelled as well to avoid underestimating the outflow. Using data on material intensities, mostly in the unit kg/MW, subsequently enables us to derive the mass of the materials in the stock and flows.

Details how the criticality was assessed can be found in section 2.3.

3 Results

3.1 Material flow analysis

In this section the results of the material flow analysis are presented. The results are divided into two main sections: an overview of the developed dashboard, and an overview of the total material flows of the North Sea energy system, including a comparison between stocks and flows. See appendix A.1 for an overview.

3.1.1 Dashboard

Figure 3.1 shows a screenshot of the MFA-NSE5 app. The app was developed to have the opportunity to explore inputs and outputs interactively. It offers the following features:

- A scenario explorer which allows the user to explore visualizations of model inputs and to choose scenarios accordingly.
- The functionality to execute the model in the application or to load previously produced results.
- A results section for stocks and flows where materials, technologies and countries can be selected to be mapped on various charts.
- A results section to explore the data around supply and criticality.

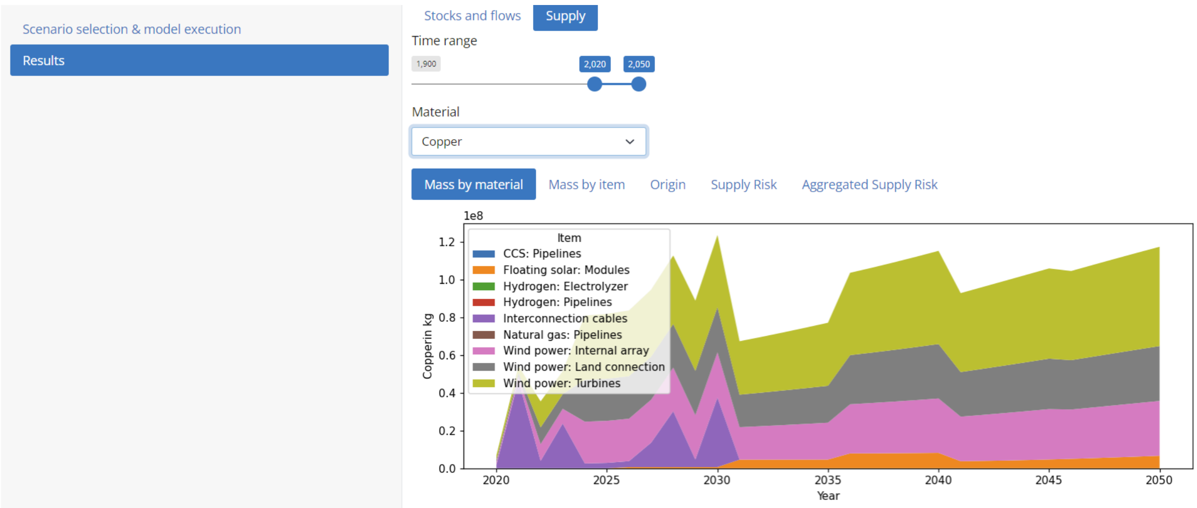

Figure 3.1 Screenshot of MFA-NSE5 app. The application is not yet accessible.

3.1.2 Material flows

Figure 3.2 shows the summed inflow, outflow, and remaining stock of all CRM, SRM, and bulk materials within the North Sea. The total height of the bars represents the total stock in the respective year. The main observations are:

- The present stock in 2020 is already large, especially compared to the predicted yearly inflows and outflows.
- The stock grows linearly and is projected to increase by about 65% by 2050.
- The material inflow and outflow vary on a yearly basis but in general appear to be growing over time.
- The outflow is considerably smaller than the inflow.

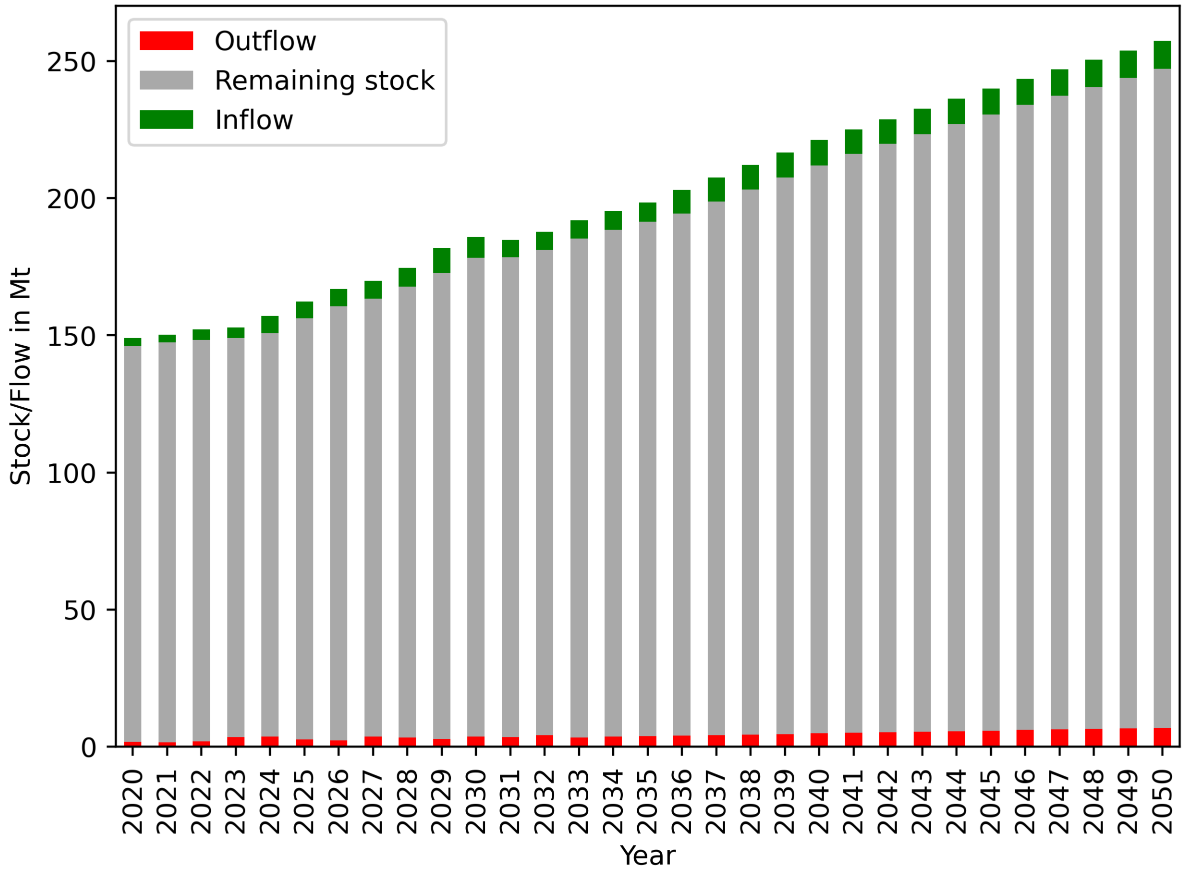

Figure 3.2 Accumulated inflow, outflow, and remaining stock of all CRM, SRM, and bulk materials

Figure 3.3 shows the inflows broken down into CRM, SRM, and bulk materials in 2020, 2030, and 2050, mapped onto technologies and components. The main takeaways are:

- Not all technologies are present in the system 2020 (CCS, floating solar, and hydrogen).
- The inflow related to natural gas pipelines appears constant, while for natural gas wells, it is declining.
- The floating solar inflow increases after 2030. The inflow due to wind turbines grows most notably. All other inflows are minor in comparison.
- The most visible materials are the bulk materials iron & steel and concrete, driven by the construction of pipelines and wind turbines.
- Floating solar introduces large inflows of glass in 2050.
- Visible CRMs are baryte and neodymium. Baryte is only visible in 2020, looking at the inflow for natural gas wells. The neodymium inflow is driven by wind turbines.

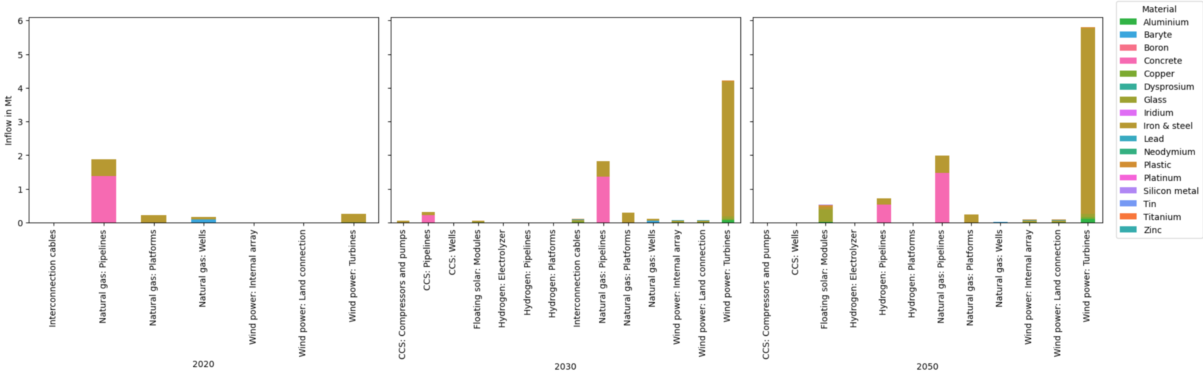

Figure 3.3 Inflows by technologies and components, and CRM, SRM, and bulk materials in 2020, 2030, and 2050

Figure 3.4 shows a Sankey diagram of the accumulated inflows and outflows between 2025 and 2050. It provides the following insights:

- More than half of the mass of inflowing materials is due to wind power, followed by natural gas. Therefore, the most contributing components are wind turbines and pipelines. Pipelines are required for the technologies natural gas, CCS, and hydrogen.
- Iron & steel make up more than half of the total demand, followed by concrete and glass.
- Aluminium represents the largest inflow of CRMs, followed by copper, lead, baryte, neodymium, and silicon metal. Other inflows of CRMs and SRMs are too small to be analysed with this visual representation.
- The outflow is less than half as large as the inflow. Most of the outflow is allocated to natural gas, followed by wind power. More than half of the outflowing material is iron & steel, followed by concrete from pipelines. CRMs and SRMs with a noticeable outflow are aluminium, copper, lead, and neodymium.

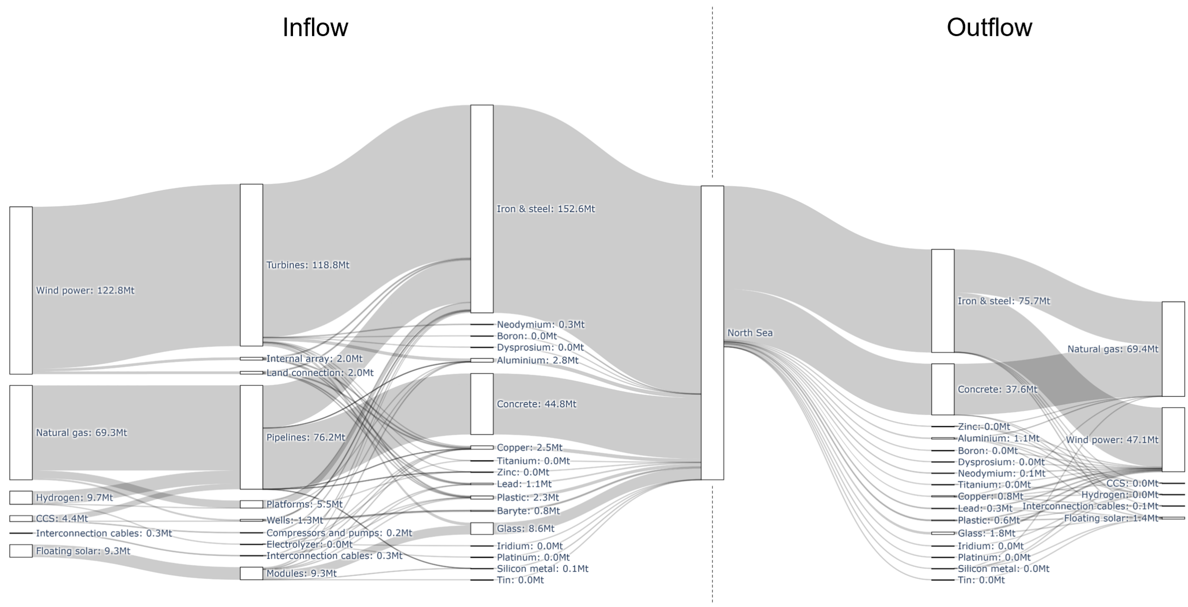

Figure 3.4 Accumulated inflows and outflows from 2025 till 2050 by technologies, components, CRMs, SRMs and bulk materials

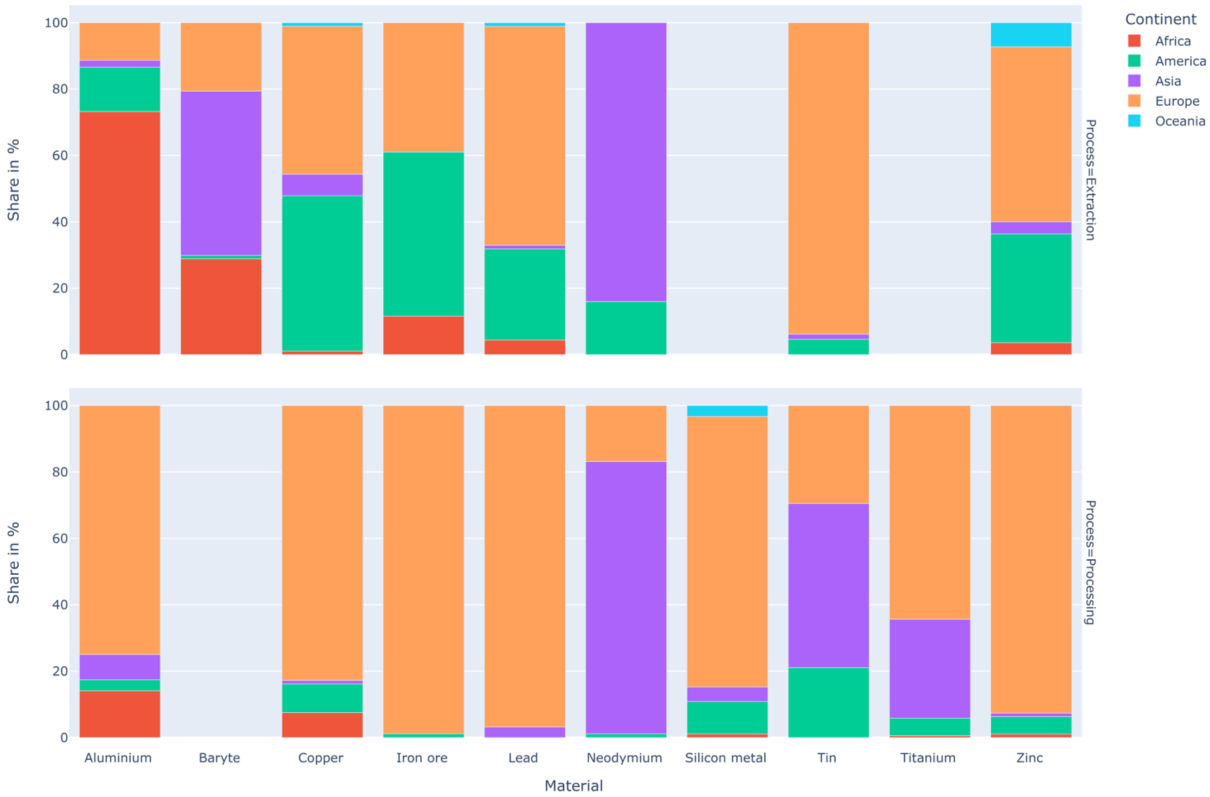

Figure 3.5 Current extraction and processing locations of CRMs, SRMs, and bulk materials.

Figure 3.5 illustrates the current extraction and processing locations of CRMs, SRMs and bulk materials. The results are available on country level but grouped by continent for visualisation purposes. The main findings are:

- (Critical) raw materials are extracted globally. For most materials, there are primary locations where more than half of the total mass is extracted. The strongest concentration is seen for tin, with over 90% sourced in Europe, followed by neodymium, with about 85% extracted in Asia.
- Materials are predominantly processed in Europe. Exceptions include neodymium, where approximately 82% of processing occurs in Asia, and tin, where about half is processed in Asia.
- This figure does not say anything about potential future extraction and processing locations, therefore, as supply chain evolve its likely these ratios and the associated supply risks will change.

3.2 Criticality

In this section the results of the criticality assessment are presented. See Appendix A.2 for an overview.

Figure 3.6 maps CRMs and SRMs based on economic importance and supply risk. The size of the bubbles is relative to the inflow in the period from 2025 to 2050. Hence, the bubbles give an indication of the importance in the context of the North Sea. The main takeaways are:

- Materials with a high economic importance and a high supply risk are neodymium and iridium. The inflow of iridium is small while neodymium is needed in large quantities.
- Dysprosium is the material with the highest supply risk. However, the required mass and its economic importance are comparatively low.
- The material with the highest economic importance is iron ore, which is also the material of which the most is needed.
- Aluminium has a high supply risk and economic importance.

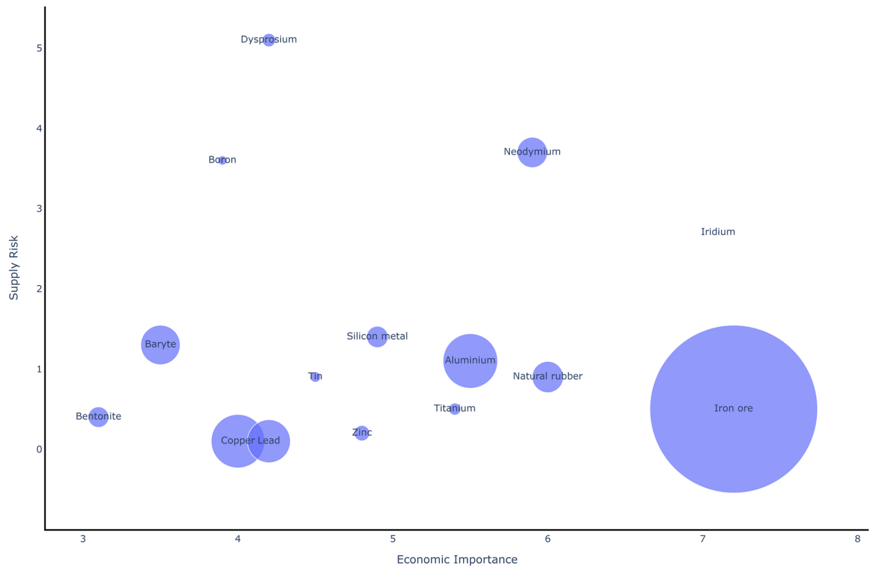

Figure 3.6 Supply risk and economic importance of CRMs and SRMs with bubbles relative to the square root of the inflow in the period of 2025 till 2050

Figure 3.7 displays the aggregate supply risk based on SR and the root of the accumulated inflow from 2025 till 2050. It is assumed that the required mass serves as an indicator for economic importance in the context of the North Sea. Main take aways are:

- The aggregated supply risk of iron ore is more than four times higher than the supply risk of the runner up, aluminium.
- Looking at CRMs and SRMs, neodymium has the highest aggregated supply risk followed by baryte, dysprosium, and silicon metal.
- The aggregated supply risk of all other CRMs and SRMs is less than half of the aggregated supply risk of silicon metal.

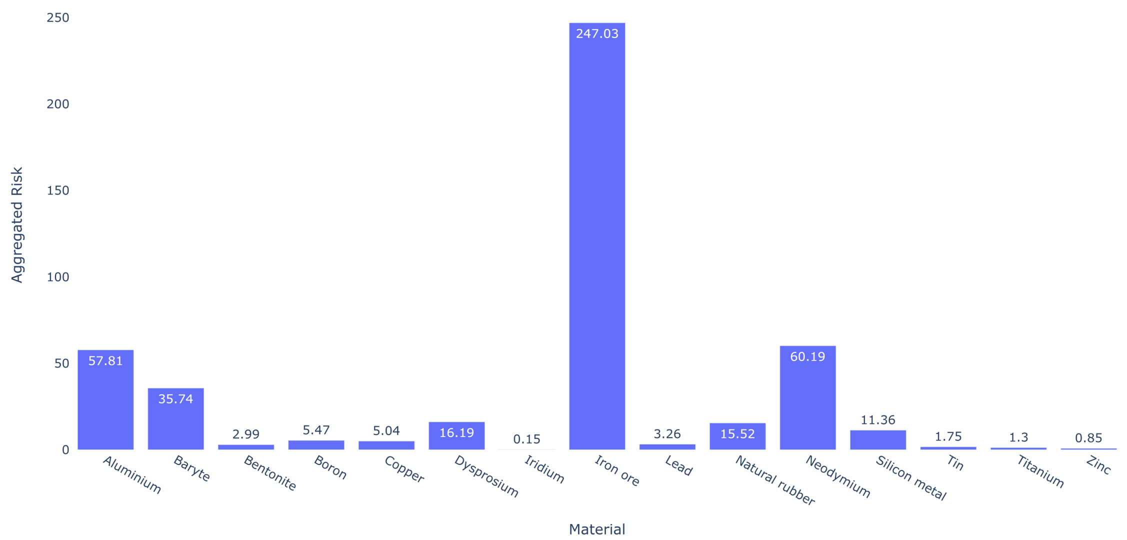

Figure 3.7 Aggregated supply risk based on SR and the root of the accumulated inflow from 2025 till 2050 $(\boldsymbol{AS,mat} = (\boldsymbol{SR,mat}) * \sqrt{\boldsymbol{inflow,mat}})$

4 Discussion

Assessing the material demand of energy technologies and infrastructure deployment in the North Sea up to 2050

This study provides a first indication of the expected material demand of energy technologies and infrastructure deployment in the North Sea up to 2050. In the whole European Union, it is expected that the renewable energy sector uses 40% of aluminium in 2030 compared to the ICT and E-mobility sectors (Carrara et al., 2023). For copper this equates to 62%, dysprosium (35%), iridium (100%), neodymium (42%) and zinc (99%). This study shows that the North Sea Energy system demands 16% of the aluminium demand of the European renewable energy sector. For some of the other CRMs and SRMs this accounts for: dysprosium (14%), iridium (0%), neodymium (41%), copper (25%) and zinc (0.4%). Especially the demand for aluminium, copper, dysprosium, and neodymium is high compared to the total demand of these materials for renewable energy in the EU, mainly because of the high amount of offshore wind turbines. Similarly, the demand for aluminium is mainly the result of the high material intensity of aluminium per MW offshore wind turbine, combined with the fact that offshore wind is the main energy technology deployed in the North Sea. The same story goes for dysprosium and neodymium that are used in the magnets of wind turbines. For copper there are high material intensities and deployment rates for offshore wind turbines as well as the associated internal cable arrays and the external land connection.

Assessing which bottlenecks might arise for timely energy transition in the North Sea related to materials demand

Using the aggregated risk score, it becomes apparent that the effect of high-volume materials, such as iron ore, also results in a disproportionate risk score. Metals like boron, with a very high supply risk score, and a low economic importance and demand still score low compared to for instance aluminium and iron ore. Looking solely at the supply risk indictor the supply of dysprosium, neodymium, boron, baryte and silicon metal seem most at risk.

Turkey (52%), US (18%) and Chile (7%) are the primary producers of boron. Boron is essential for glass and ceramics, detergents, and fertilizers, and it plays a role in advanced materials like boron fibres and semiconductors. Most of the global boron production comes from a few countries, notably Turkey and the United States. Turkey provides 99% of the EUs primary sourcing and 46% of the refined sourcing. The US and Germany are responsible for 25% and 20% respectively of the refined boron used in Europe. Increased demand for boron in clean energy technologies could strain supply. Supply risks may arise from geopolitical tensions or environmental regulations impacting mining operations (RMIS, 2024).

Baryte is mainly used for oil and gas drilling. The EU is responsible for only 1.2% of the baryte primary production and imports mainly from China (44%), Morocco (28%) and Bulgaria (11%). While baryte is more abundant than some critical raw materials, its supply can be affected by regional production limits, especially in countries with stringent mining regulations. Since China, India, and the United States are the main primary producers, geopolitical factors and trade policies could impact availability (RMIS, 2024).

Silicon metal is crucial for producing silicon-based materials like semiconductors, solar panels, and aluminium alloys. The EU is responsible for only 3.8% of refined silicon metal production. China is the main producer of refined silicon metal with 73%, followed by Brazil and Norway with 6% each. The EU sources 34% of refined Silicon metal from Norway, 29% from France, and 9% from Brazil. The rapid growth of the renewable energy sector and semiconductor industry is driving up demand, leading to potential supply shortages. Shortages could be exuberated by environmental and human rights concerns related to silicon production, particularly energy consumption related emissions and worker conditions, which may lead to regulatory pressures that could impact supply chains. And, since China is the dominant producer of silicon metal, any disruptions (due to environmental regulations, energy shortages, or trade disputes) could significantly affect global supply (RMIS, 2024).

While the other metals have a lower score on the indicators SR and EI, they each face their own potential supply risk. Dysprosium is a rare earth element essential for producing strong permanent magnets, used in electric vehicles, wind turbines, and various electronic devices. As demand for electric vehicles and renewable energy systems increases, dysprosium's supply could become increasingly strained. Since China dominates global dysprosium production (40.4%), any geopolitical tensions or export restrictions could severely impact supply. Like dysprosium, neodymium is crucial for making high-performance magnets used in motors, generators, and electronics. Neodymium also experiences a significant increase and demand and is also primarily sourced from China (43%), leading to similar risks as dysprosium. Efforts to recycle neodymium from old electronics and magnets are ongoing, but the current capacity is limited, leaving supply vulnerable. Copper is essential for electrical wiring and renewable energy technologies. Its supply risks arise from geopolitical factors, aging mines, and increasing demand from green energy technologies. Tin is used in electronics and soldering and its supply can be affected by geopolitical instability in producing countries, particularly in Southeast Asia. Aluminium, while abundant, faces supply risks related to energy costs and environmental regulations, especially in key producing regions. Iridium is a rare earth metal used in high-temperature applications, spark plugs, and as a catalyst in chemical reactions. Iridium is primarily produced as a byproduct of platinum mining, mainly in South Africa and Russia, making its supply closely tied to these countries' mining operations. Its rarity and high demand in electronics and green technologies (like hydrogen fuel cells) create a significant risk of supply constraints, especially considering potential political instability and environmental regulations in the producing countries. Platinum is widely used in catalytic converters for vehicles, jewellery, and various industrial applications, including electronics and medical devices. Platinum is expected to experience an increase in demand, especially for electric vehicles. Most platinum is produced in South Africa and Russia, resulting in a supply chain susceptible to geopolitical issues. Titanium is essential in aerospace, medical implants, and military applications, but also used for offshore wind and electrolysers. The titanium supply chain is complex, with challenges in sourcing raw materials like ilmenite and rutile, which can lead to fluctuations in availability. Availability could be further strained because of geopolitical tensions and trade policies since the major producers include China, Russia and the US. Zinc is primarily used for galvanizing steel to prevent corrosion, as well as in alloys and batteries. While zinc is generally abundant, its demand is expected to increase, especially for construction and infrastructure. Supply risks could stem from geopolitical decisions, as the major producers are China, Australia and Peru (RMIS, 2024).

When the supply of metals decreases because of the risks described above and demand increases several consequences can occur. Likely prices will increase significantly because of market dynamics. Supply reductions and price increases can result in supply chain disruptions and manufacturing delays as industries might faces difficulties sourcing the materials. As a result, it is possible that industries will increase efforts in actively seeking alternative materials or energy technologies that require less or no scarce materials. However, it is unlikely these alternative materials and technologies in the short term can be produced at sufficient rates to substitute current market technologies. Furthermore, it is expected that recycling and recovery initiatives will gain ground.

The role of recycling

Recycling will be increasingly important in meeting the demand for metals such as iridium, dysprosium, neodymium, platinum, titanium, and zinc in Europe. Recycling helps reduce reliance on primary extraction, which can be environmentally damaging and geopolitically risky. By recovering metals from end-of-life products, Europe can lessen its dependence on imports and therefore mitigate supply risks. At the same time recycling reduces the need for new mining, conserving natural resources and protecting ecosystems. Furthermore, the recycling process typically requires less energy than mining and processing of virgin materials (EC, 2021), resulting in lower overall greenhouse gas emissions and diverting waste from landfills. The Critical Raw Materials Act aims to recycle at least 25% of annual metal consumption in the EU. For some of the metals in scope this target seems to have already been achieved. For instance, aluminium has an average end-of-life recycling-input-rate (EoL-RiR) of 32% in the EU and for copper and zinc this is 30% and 40% respectively. But for other metals recycling is low or non-existing: iridium (16%), platinum (12%), titanium metal (1%), neodymium (1%), boron (1%), baryte (0%), dysprosium (0%) (RMIS, 2024). In a hypothetical scenario where the North Sea energy system operates as a fully circular economy, the secondary materials generated would cover only a fraction of total material demand (inflow-outflow ratio). Consequently, reliance on primary materials will remain substantial or the amount of secundary material from other sectors needs to be increased.

Further research

Further research could involve including end-of-life scenarios on collection and recycling for the energy commodities reaching the end of their lifetime. This enables the calculation of the potential EoL-RIR for the North Sea energy system (European Commission, 2018). The EoL-RIR provides insight into the fraction of the demand for materials that could met by recycling the supply of materials originating from the North Sea energy system. In other words, it describes the self-sufficiency or degree to which this system can operate as a closed-loop. Another topic for further research would be the inclusion of repair activities in the material flow analysis. It is expected that repair especially contributes to the demand for CRMs and that the change in high-volume materials is relatively insignificant. An additional material demand of around 5-20% is expected (IRENA, 2016; Fraunhofer ISE, 2021; NREL, 2016; IEA, 2019; Hydrogen Council, 2020; European Commission 2020); which be significant for CRMs with a high supply risk. Another topic for further research could be the refining of the criticality indicator to address the material demand of the North Sea Energy system more specifically in relation the current and future supply chains of materials, components, and energy technologies. The current indicator still leans quite heavily on the mass which overshadows the risk indicators. Additionally, the risk indicators provide a present-day snapshot, but by understanding future supply-demand dynamics the risk indicators could potentially be estimated over time to refine the criticality indicator.

5 Conclusion

This study offers an initial assessment of the anticipated material demand for energy technologies and infrastructure in the North Sea through 2050. The demand for critical raw materials is projected to rise significantly between 2020 and 2050, driven by the installation of offshore wind power, offshore natural gas, floating solar panels, offshore hydrogen production, and carbon capture and storage.

Material outflows from energy technologies reaching end-of-life are considerably lower than the inflows required to meet the demand for new technologies. In a hypothetical scenario where the North Sea energy system operates as a fully circular economy, the secondary materials generated would still cover only a fraction of total material demand. Consequently, reliance on primary materials will remain substantial.

Most (refined) critical raw materials are concentrated in a limited number of countries, creating significant risks of supply disruptions due to geopolitical tensions, export restrictions, or environmental issues. The EU's Critical Raw Material Act aims to mitigate these risks by enhancing mining, refining, and recycling capacities in Europe while diversifying import sources. However, if demand for certain materials grows rapidly outpacing supply, market dynamics could still lead to significant price increases, causing supply chain disruptions and manufacturing delays as industries struggle to source the necessary materials. This scenario may prompt industries to intensify efforts to explore alternative materials or technologies that rely less on scarce resources. However, it is unlikely that these alternatives can be produced at sufficient scales in the short term to replace existing technologies.

For the North Sea energy system to achieve its deployment targets, a continuous balancing act will be required between the cost, efficiency, and availability of energy technologies and infrastructure. It is recommended to regularly assess risk, vulnerabilities and dependencies associated with supply disruptions, geopolitical factors, and market fluctuations to inform decision-making. Additionally, it is recommended to develop and build out strategic partnerships with a diverse range of key suppliers across various countries, and to explore partnership with emerging producers of low-CRM energy technologies.

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Supplementary tables

A1: Results: total material flows

Year	Aluminium	Baryte	Boron	Concrete	Copper	Dysprosium	Glass	Iridium	Iron & steel	Lead	Neodymium	Plastic	Platinum	Silicon metal	Tin	Titanium	Zinc
2020	10274	96435	5	1382691	6870	22	4475	0	1502197	3584	568	3313	0	8	0	10	298
2021	11937	78584	8	1147039	54095	33	6783	0	1377206	39755	861	22183	0	7	0	15	261
2022	34386	61787	30	1220097	35399	129	26722	0	2481960	16987	3390	17577	0	7	0	58	361
2023	31063	71516	26	1264972	51397	114	23579	0	2364122	30830	2992	23430	0	8	0	51	356
2024	78385	19147	73	1309527	80810	319	65987	0	4652423	36759	8372	40811	0	8	0	143	547
2025	78783	18201	74	1226175	81726	322	66632	0	4515498	37217	8454	41260	0	7	0	144	533
2026	81324	20093	75	1220287	83560	326	104365	0	4570447	37790	8572	47610	0	377	21	146	536
2027	83217	20093	76	1362353	94521	332	105578	0	4763081	45911	8726	52082	0	378	21	149	569
2028	85056	22929	78	1412768	112606	339	107064	0	4901582	59521	8914	59391	0	378	21	152	586
2029	92171	19147	80	2765533	88706	348	108820	0	5913217	40038	9134	50243	0	386	21	156	867
2030	89833	62753	82	1580936	123450	357	110847	0	5582884	66535	9385	64172	0	380	21	160	636
2031	76943	55519	61	1374717	67243	265	312628	0	4347754	27180	6959	72488	0	2596	149	118	512
2032	79658	52066	63	1397652	69557	276	315165	0	4485477	28042	7258	73748	0	2598	149	124	527
2033	82463	48613	66	1418661	71968	288	317918	0	4618061	28944	7568	75077	0	2601	149	129	542
2034	85344	45160	69	1437623	74463	300	320965	0	4761220	29881	7885	76482	0	2606	149	134	556
2035	88286	41707	72	1454436	77029	313	324419	0	4905681	30851	8210	77976	0	2616	150	140	571
2036	118359	38452	94	1551647	103472	408	529629	0	6078007	41140	10721	118803	0	4477	257	215	675
2037	121445	35548	97	1563919	106194	421	534400	0	6225392	42174	11058	120553	0	4498	258	221	689
2038	124666	32644	100	1573842	109041	434	540191	0	6376471	43257	11407	122504	0	4529	260	227	703
2039	128019	29741	103	1581392	112007	448	547252	0	6530629	44384	11766	124691	0	4571	262	233	716
2040	131503	26837	106	1586566	115087	462	555860	0	6687314	45552	12134	127153	0	4629	265	239	730
2041	106606	25093	90	2034363	92709	391	291116	0	6151227	37218	10280	78965	0	2121	121	382	758
2042	110320	23350	93	2038298	95959	406	303619	0	6312999	38441	10657	82075	0	2217	127	389	771
2043	114074	21606	96	2039990	99226	420	318360	0	6471627	39663	11029	85526	0	2335	134	395	784
2044	117866	19863	99	2039541	102504	434	335462	0	6626635	40882	11394	89336	0	2478	142	401	796
2045	121692	18655	103	2037068	105788	447	354936	0	6778273	42095	11753	93503	0	2645	151	407	808
2046	121218	17611	101	2032706	104424	442	372773	0	6713960	41223	11611	95647	0	2835	162	405	802
2047	125077	16567	104	2026605	107692	455	396483	0	6857502	42414	11955	100443	0	3046	174	411	812
2048	128915	15523	107	2018926	110926	468	421758	0	6996209	43587	12289	105460	0	3273	187	417	822
2049	132711	14479	110	2009841	114115	480	448054	0	7130202	44739	12614	110613	0	3511	201	423	831
2050	136449	13435	113	1999530	117249	492	474709	0	7260562	45871	12930	115799	0	3754	215	428	840

A2: Results: aggregated supply risks considering inflows from 2025 till 2050

Material	Supply Risk	Economic Importance	Mass in kt	Aggregated Risk
Aluminium	1.1	5.5	2762	18229.19
Baryte	1.3	3.5	755.7	3627.28
Bentonite	0.4	3.1	56	195.92
Boron	3.6	3.9	2.3	17.32
Copper	0.1	4	2541.2	10419.01
Dysprosium	5.1	4.2	10.1	93.69
Iridium	2.7	7.1	0	0.03
Iron ore	0.5	7.2	244099.7	1879568
Lead	0.1	4.2	1064.5	4577.55
Natural rubber	0.9	6	297.5	2052.95
Neodymium	3.7	5.9	264.7	2540.75
Silicon metal	1.4	4.9	65.8	414.79
Tin	0.9	4.5	3.8	20.34
Titanium	0.5	5.4	6.7	39.78
Zinc	0.2	4.8	18	89.85

A3: Data: Description of data for each technology and component

The table below provides an overview of the data collection and processing for each technology and their components. Additionally, a data quality indicator is used to provide additional qualitative insight of the uncertainties associated with each data point. The data quality indicator consists of three levels:

- High: primary data and/or measurements are available, uncertainty is low
- Medium: interpolation needed to fill data gaps, uncertainty is medium
- Low: extrapolation needed to fill data gaps, uncertainty is high

Technology	Component	Data type	Description	Data quality
Offshore wind power	Wind turbine	Historic Stock	The historic stock is modelled in megawatt (MW) installed capacity; it covers the years 2009 till 2023. All data was retrieved from OSPAR (2023).	High
		Stock Projection	Future installed capacities for the considered countries were provided by NSE5 - Work Package 7 (WP7). The used data is defined by the columns Commodity (Electricity – Supply (capacity)) and Commodity information (Offshore wind). The data spans over the years 2030 to 2050 in 5-year increments. Gaps between historical data and projected future capacities were interpolated using linear regression.	Medium
		Lifetime	Following Zimmermann et al. (2013) we assume that the failure behaviour of offshore wind turbines follows a Weibull distribution with shape factor $\mathrm{k} = 2$ (constant failure rate curve) and scale factor $T = 20$.	High
		Material intensity	The material intensity of a 15MW wind turbine was utilized to estimate the total material demand [TNO, manuscript in preparation]. The bill of materials considered is specific to a wind turbine with a monopile foundation. Therefore, it is assumed that all wind turbines within the system are 15MW units with monopile foundations. The scaling unit of the material intensity is kg/MW.	Medium
	Internal array cabling	Historic Stock	Geospatial data on the internal array for the wind parks Borssele, Egmond aan Zee, Gemini, Kavel V CrossWind, Luchterduinen, and Prinses Amalia Windpark was found in the North Sea Energy Atlas (2024) and provided by NSE5 - WP7. Combined with the known capacity of the wind parks it was calculated that there is on average 216 meter of internal array cable per MW installed capacity. This number was combined with the historic installed capacity as presented in the OSPAR (2024) database.	Medium
		Stock Projection	Future installed capacities for the considered countries were provided by NSE5 - WP7. The used data is defined by the columns Commodity (Electricity – Supply (capacity)) and Commodity information (Offshore wind). The data spans over the years 2030 to 2050 in 5-year increments. Gaps between historical data and projected future capacities were interpolated using linear regression. The average length of array cable per MW installed capacity was used to calculate the total length of array cables in the system.	Medium
		Lifetime	It was assumed that the lifetime of array cables can be describe with the Weibull distribution. A scale factor of $T = 25$ and a shape factor of $k = 2$ (constant failure rate curve) were assumed.	Low
		Material intensity	Material intensities for offshore cables could be derived from the LCAs performed the previous NSE projects (Wernet, et al., 2016). Data for a 32kV cable and a 132kV cables was available. Data on the voltage of internal array cables was sparse but always larger than 100kV. Therefore, the material intensities of a 132kV cable was used. The conversion factor 216m/MW (see above) was used to compile a bill of material which scales to kg/MW.	Low
	External cabling	Historic Stock	Geospatial data on the land connection of multiple wind parks was provided by the North Sea Energy Atlas (2024) and NSE5 - WP7. The wind parks Borssele, Egmond aan Zee, Gemini, Kavel V CrossWind, Luchterduinen, and Prinses Amalia Windpark were considered. Accounting for the fact that those wind parks are close to shore the wind parks Solige N, Area 6/7, EN11, EN12, and Dogger Ban were also taken into consideration. Combined with the known capacity of the wind parks it was calculated that there is 207 m/MW of external cabling. This number was combined with the historic installed capacity as presented in the OSPAR (2024) database.	Low
		Stock Projection	Future installed capacities for the considered countries were provided by NSE5 – WP7. The used data is defined by the columns Commodity	Low

			(Electricity – Supply (capacity)) and Commodity information (Offshore wind). The data spans over the years 2030 to 2050 in 5-year increments. Gaps between historical data and projected future capacities were interpolated using linear regression. The average length of array cable per capacity was used to calculate the total length of array cables in the system.	
		Lifetime	It was assumed that the lifetime of offshore cables can be describe with the Weibull distribution. A scale factor of $T = 25$ and a shape factor of $k = 2$ (constant failure rate curve) were assumed.	Low
		Material intensity	Material intensities for offshore cables could be derived from the LCAs performed the previous NSE projects (Wernet, et al., 2016). Data for a 32kV cable and a 132kV cables was available. Data on the voltage of internal array cables was sparse but always larger than 100kV. Therefore, the material intensities of a 132kV cable was used. The conversion factor 207m/MW (see above) was used to compile a bill of material which scales to kg/MW.	Low
Offshore natural gas	Platforms	Historic Stock	Geospatial data on offshore installations from OSPAR (2024) and the North Sea Energy Atlas (2024) was used to model the historic stock from 1900 to 2024. The OSPAR data includes weights for both above and below sea level structures. Using this data, a linear regression function was created to estimate the weight of subsea structures based on water depth. For the NSE Atlas data, which provides water depth information, the weight of subsea structures was calculated using the regression function. The average weight of above sea level structures was assumed for the NSE Atlas data.	High
		Stock Projection	The future natural gas demand for North Sea countries was provided by NSE5 – WP7. The used data is defined by the columns Commodity (Natural Gas – Demand (annual energy)) and Commodity information (Demand natural gas). The data spans over the years 2030 to 2050 in 5-year increments. Any gaps between historical data and projected future capacities were interpolated using linear correlation. The data was analysed by correlating the inflowing weights of offshore installations from 2015 to 2023 with the gas demand of these countries (Eurostat, 2024). The projected future demand spans from 2030 to 2050 in 5-year increments.	Low
		Lifetime	The removal of end-of-life offshore structures has only recently begun, and data on this subject is limited. The primary source is a report by Nexstep (2023), which provides figures for the removal of offshore structures in the Netherlands from 2018 to 2032. For other North Sea countries, this data was extrapolated using the total weight in 2018 as a baseline.	Low
		Material intensity	It was assumed that the majority of the platforms are made of steel, and that other materials are negligible. The amount of steel per platform is provided by OSPAR.	Medium
	Wells	Historic Stock	The historic stock of wells is based on data from the North Sea Transition Authority (2024), which lists over 10,000 wells drilled from 1965 to 2024, including their depths in meters. Since the dataset does not specify the country, each well belongs to, the average gas demand of the North Sea countries was used to allocate the stock (Eurostat).	High
		Stock Projection	The future natural gas demand for North Sea countries is provided by NSE 5 - WP7. The used data is defined by the columns Commodity (Natural Gas – Demand (annual energy)) and Commodity information (Demand natural gas). The data spans over the years 2030 to 2050 in 5-year increments. Any gaps between historical data and projected future capacities were interpolated using linear correlation. The data was analysed by correlating the inflowing meters of offshore wells from 2015 to 2023 with the gas demand of these countries (Eurostat, 2024). The projected future demand spans from 2030 to 2050 in 5-year increments. Any gaps between historical data and projected future capacities were interpolated using linear regression.	Medium

		Lifetime	When wells reach the end of their life, they are sealed, leaving the construction materials in the sediment. In the context of material flow analysis, this means that these materials remain part of the stock and do not exit the system. For this specific case, an inflow-driven DSM was utilized because the demand was correlated with the inflowing meters, and the stock lifetime of wells is considered eternal..	High
		Material intensity	Material intensities for wells could be derived from the LCAs performed in previous NSE projects. A bill of material could be derived which was scaled to kg/m.	Medium
	Pipelines	Historic Stock	The current total stock of oil and gas pipeline was derived from the North Sea Energy Atlas (2024). It does not provide sufficient information on construction years. Hence, also the historic stock needed to be modelled (see stock projection).	Low
		Stock Projection	The assumption was made that the length of the pipeline network directly correlates with number of offshore platforms. Hence, the data described above for offshore platforms was used to derive the historic and projected stock of pipelines in km.	Low
		Lifetime	Ecoinvent (pipeline construction, natural gas, long distance, high capacity, offshore) indicates the expected lifetime of an offshore pipeline to be 45 years. On this basis, it was assumed that the lifetime of a pipeline follows a Weibull distribution with $T = 45$ and $k = 3$ (progressively increasing discard rate)	Medium
		Material intensity	Material intensities for pipelines can be derived from previously conducted LCAs in the NSE project (Wernet, et al., 2016). This allows for the creation of a bill of materials that scales to kilograms per kilometre (kg/km).	Medium
Floating solar	Modules	Historic Stock	There is currently no floating solar in the North Sea. Hence there is no historic stock.	
		Stock Projection	An expert at TNO provided the future projections for the installed floating solar capacity in the Netherlands and the rest of the North Sea. The total future demand for solar energy, both onshore and offshore, was provided by NSE 5 - WP7. The data is defined by the columns Commodity (Electricity – Supply (annual energy)) and Commodity information (Offshore solar). The comment column provides the information that the data is not actually only the predicted offshore capacity, but onshore and offshore combined. The data spans over the years 2030 to 2050 in 5-year increments. Any gaps between historical data and projected future capacities were interpolated using linear correlation. This prediction of the future total demand was used to distribute the offshore solar demand over the North Sea countries.	Medium
		Lifetime	Based on Tan et al. (2022) it is assumed that the lifetime of a solar module follows a Weibull distribution with a scale factor $T = 28$ and a shape factor $k = 5.3759$ (regular loss scenario). It is assumed that the same behaviour applies at sea. This is an optimistic estimate, as conditions at sea might deteriorate the solar panels more rapidly.	Medium
		Material intensity	Material intensities for floating solar panels were derived from previously conducted LCAs in the NSE project. The LCAs allowed for the development of a bill of materials that scales to kilograms per gigawatt peak (kg/GWp). There are 5 different mounting scenarios available: high above sea level in aluminium or steel, just above sea level in aluminium or steel, and mounted on ring membrane modules. Currently, only the scenario high above sea level in steel is considered.	High
Offshore Hydrogen production	Electrolysers	Historic Stock	There is currently no hydrogen production in the North Sea. Hence there is no historic stock.	
		Stock Projection	The future hydrogen production capacity was provided by NSE5 - WP7. The data is defined by the columns Commodity (Hydrogen – Supply (annual energy)) and Commodity information (Electrolysis - offshore). Numbers are provided for 2040 and 2050. Years in between were filled using a linear regression. An alternative scenario was provided by an expert at TNO which describes the future offshore hydrogen capacity of	Medium

			the Netherlands and Germany. Currently, the scenario as provided by WP7 is used.	
		Lifetime	It is assumed that the lifetime of an electrolyser follows a Weibull distribution with a scale factor of $T = 30$ (KU Leuven, 2022) and a shape factor of $k = 5$ (Lallana et al., 2024)	Medium
		Material intensity	The material intensities are derived from Bareiß et al. (2019). This publication provides a current and future scenario. The current scenario is used as it is the more conservative choice. The bill of materials has a scaling unit of kg/GW.	High
	Platforms	Historic Stock	There is currently no hydrogen production in the North Sea. Hence there is no historic stock.	
		Stock Projection	The stock projection follows the demand for electrolysers. Each platform can facilitate 4GW of electrolyser capacity. Hence, it is assumed that a whole new platform is installed every 4GW of added new capacity.	High
		Lifetime	Offshore hydrogen production starts appearing in the system after 2030. The temporal scope is until 2050. Therefore, it is safe to assume that no platform will reach it's end of life in the considered period. It is therefore assumed that the lifetime of a platform follows a Weibull distribution with a scale factor of $T = 50$ and a shape factor of $k = 2$ (constant failure rate curve).	High
		Material intensity	Material intensities for hydrogen production platforms are derived from the LCAs performed in previous NSE projects (Wernet, et al., 2016). A bill of material could be derived which scales to kg/GW.	High
	Pipelines	Historic Stock	There is currently no hydrogen production in the North Sea. Hence there is no historic stock.	
		Stock Projection	NSE5 - WP7 provided geospatial data on the final state of the hydrogen pipeline network in 2050. Some part of it reuse former gas pipelines. The total length of the future network was determined based on data provided by WP7. The length of reused gas pipelines was subtracted, leaving the length of the pipelines which need to build. It is assumed that the total length of the newly build pipelines grows linearly with the demand and that its full length is reached in 2050.	High
		Lifetime	Ecoinvent (pipeline construction, natural gas, long distance, high capacity, offshore) indicates the expected lifetime of an offshore pipeline to be 45 years. On this basis, it was assumed that the lifetime of a pipeline follows a Weibull distribution with T=45 and k=3 (progressively increasing failure rate)	Medium
		Material intensity	Material intensities for pipelines can be derived from previously conducted LCAs in the NSE project. This allows for the development of a bill of materials that scales to kilograms per kilometre (kg/km).	Medium
Carbon capture utilization and storage	Compressors and pumps	Historic Stock	There are currently no CC(U)S activities in the North Sea. Hence there is no historic stock.	
		Stock Projection	There are two future capacity projections. One based on the North Sea Energy 4 pathways, and one was provided by NSE5 - WP7 as geospatial data including injection rates per location The later data set is currently used. Both provide the future capacities in megaton per annum Mtpa.	High
		Lifetime	The lifetime is modelled as a Weibull distribution. Based on an internal LCA of a pumping station, a scale factor of $T = 70$ is assumed with a shape factor of $k = 2$ (constant failure rate curve)	Low
		Material intensity	Data on material intensities of compressors and pumps is sparse. The best source that could be found provides data about the use of steel for CC(U)S retrofits for coal fuelled powerplants US Department of Energy (2024) in kg/Mtpa.	Low
	Wells	Historic Stock	There are currently no CC(U)S activities in the North Sea. Hence there is no historic stock.	
		Stock Projection	NSE5 - WP7 provided geospatial data on the location of future carbon capture and storage locations including the year of construction. It is	Low

			assumed that each location has one well. The average depth of all wells in the North Sea Transition Authority (2024) of 3502m is applied to all wells.	
		Lifetime	When wells reach their end of life, they are sealed, leaving the construction materials in the sediment. In the context of material flow analysis, this means that these materials remain part of the stock and do not exit the system.	High
		Material intensity	Material intensities for wells could be derived from the LCAs performed in previous NSE projects (Wernet, et al., 2016). A bill of material could be derived which scales to kg/m.	High
	Pipelines	Historic Stock	There are currently no CC(U)S activities in the North Sea. Hence there is no historic stock.	
		Stock Projection	NSE5 - WP7 provided geospatial data on the final state of the CC(U)S pipeline network in 2050. The total length of the newly build pipelines was determined. It is assumed that the total length of the network grows linearly with the demand and that its full length is reached in 2050.	Medium
		Lifetime	Ecoinvent (pipeline construction, natural gas, long distance, high capacity, offshore) indicates the expected lifetime of an offshore pipeline to be 45 years (Wernet, et al., 2016). On this basis, it was assumed that the lifetime of a pipeline follows a Weibull distribution with T=45 and k=3 (progressively increasing discard rate)	Yellow
		Material intensity	Material intensities for pipelines can be derived from previously conducted LCAs (Wernet, et al., 2016). This allows for the creation of a bill of materials that scales to kilograms per kilometre (kg/km).	High

A4: Data: Limitations and potentials for improvement

The table below outlines identified data limitations and potential improvement points. When choosing what to address in the future, it needs to be considered which actions would have a significant impact on the overall results and what can be neglected.

Technology	Component	Description
Offshore wind power	Wind turbine	Wind turbine could be modelled in greater detail. It is assumed that all turbines are of the same type (15W capacity with monopile foundation). Smaller turbines and different foundations could be taken into account. Additionally, substations could be considered as they were out of scope for this study.
	Internal array cabling	The material intensity of an 132kV offshore cable was assumed to be applicable. As of the time of writing this report, an LCA including internal array cabling has become internally available. This LCA could be leveraged to derive an improved material intensity.
Offshore natural gas	Wells	The length of newly build wells was determined correlating the historic gas demand on national levels and meters of wells drilled. Predictions on national gas demand provided by WP7 were then used to predict how many meters of wells will be drilled in the future. It would be a better approach to correlate the meters of drilled wells with the national gas production ideally limited to the North Sea.
	Pipelines	An average lifetime of 45 years based on Ecoinvent (Wernet, et al., 2016) was used for pipelines. It is possible that this assumption is not applicable to the system. It would be possible to either model the stocks and flows of pipelines bottom up (considering the lifecycle of each pipeline individually) or to derive an individual Weibull distribution for this system based on existing data.
Floating solar	Platforms	Multiple scenarios for the mounting of the solar panels are available. Currently, the usage of steel platforms is assumed. The impact of other scenarios on the critical raw material demand could be explored.
Offshore Hydrogen production	Electrolysers	The material intensity of electrolysers can be improved. Firstly, the source for the material intensity needs to be harmonized with the source used for the LCAs within this project. Secondly, additional components as storage tanks, compressors, and desalination equipment could be considered.

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