North Sea Energy offshore system integration

4.2

North Sea Energy 2020-2022

# Carbon footprint of offshore structures

North Sea Energy 2020-2022

# Unlock the low-carbon energy potential North Sea with optimal value for society and nature

The North Sea Energy program and its consortium partners aim to identify and assess opportunities for synergies between energy sectors offshore. The program aims to integrate all dominant low-carbon energy developments at the North Sea, including: offshore wind deployment, offshore hydrogen infrastructure, carbon capture, transport and storage, energy hubs, energy interconnections, energy storage and more.

Strategic sector coupling and integration of these low-carbon energy developments provides options to reduce CO2 emissions, enable & accelerate the energy transition and reduce costs. The consortium is a public private partnership consisting of a large number of (international) partners and offers new perspectives regarding the technical, environmental, ecological, safety, societal, legal, regulatory and economic feasibility for these options.

In this fourth phase of the program a particular focus has been placed on the identification of North Sea Energy Hubs where system integration projects could be materialized and advanced. This includes system integration technologies strategically connecting infrastructures and services of electricity, hydrogen, natural gas and CO2. A fit-for-purpose strategy plan per hub and short-term development plan has been developed to fast-track system integration projects, such as: offshore hydrogen production, platform electrification, CO2 transport and storage and energy storage.

The multi-disciplinary work lines and themes are further geared towards analyses on the barriers and drivers from the perspective of society, regulatory framework, standards, safety, integrity and reliability and ecology & environment. Synergies for the operation and maintenance for offshore assets in wind and oil and gas sector are identified. And a new online Atlas has been released to showcase the spatial challenges and opportunities on the North Sea. Finally, a system perspective is presented with an assessment of energy system and market dynamics of introducing offshore system integration and offshore hubs in the North Sea region. Insights from all work lines have been integrated in a Roadmap and Action Agenda for offshore system integration at the North Sea.

The last two years of research has yielded a series of 12 reports on system integration on the North Sea. These reports give new insights and perspectives from different knowledge disciplines. It highlights the dynamics, opportunities and barriers we are going to face in the future. We aim that these perspectives and insights help the offshore sectors and governments in speeding-up the transition.

We wish to thank the consortium partners, executive partners and the sounding board. Without the active involvement from all partners that provided technical or financial support, knowledge, critical feedback and positive energy this result would not have been possible.

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# Carbon footprint of offshore structures


Prepared by:

TNO
Mara Hauck
Lia de Simon
Jonna Snoek

Bureau Veritas
Pim Reuderink

TotalEnergies
Mathieu Nemec
Corstiaan Teeuwen
Tjabbo Oudkerk

Checked by:

NEC
Miralda van Schot
(previous versions)

Royal HaskoningDHV
Jens Odinga

Approved by:

TNO
Madelaine Halter



The project has been carried out with a subsidy from the Dutch Ministry of Economic Affairs and Climate, National Schemes EZK-subsidies, Top Sector Energy, as taken care of by RVO (Rijksdienst voor Ondernemend Nederland)

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# Executive summary

The aim of this report within the NSE project was to quantify and compare the carbon footprint (kg $CO_2$equivalent/$m^2$yr) of offshore structures available for hydrogen production (4GW) and other energy hub functions. The following structures were included: jacket platform, sand island (two versions: a 'full' version and one aligned to platform design) and hybrid island built of a sand island and floaters. The carbon footprints ranged from 40 (for unsheltered sand islands) to 80 $CO_2$equivalent/$m^2$yr (for platforms). Main contributors to carbon footprint were steel production (platforms) and installation fuel use (sand islands). The main options for reducing carbon footprint are therefore use of recycled steel (almost 40% reduction potential for platforms) and alternative low-carbon fuels (25%-40% reduction potential for sand island when replacing half of the diesel with blue or green hydrogen). Carbon footprints of all structures were within a factor of 2 over a range of sensitivity scenarios. Therefore, while taking all efforts to reduce carbon footprints, other considerations are expected to dominate structure choices.

# 1 Introduction

The North Sea provides opportunities for large-scale wind energy and hydrogen production and underground carbon storage. By connecting the infrastructure of wind energy, hydrogen, CO2 and natural gas, we can save money, time and space. An integrated approach to the energy system and identifying and investigating the benefits of linking these energy functions is core of the North Sea Energy research programme. Including different perspectives is part of this integrated approach. Technology, market, society, ecology, logistics, spatial planning, regulations and integration in the (national) energy system are important angles - as reflected in the various work packages of the North Sea Energy Programme. At the same time, the program aims to limit the costs for society and the impact on nature. Starting from the integration of increasing offshore wind activities with existing gas infrastructure and activities ('platform electrification'), the scope of the North Sea Energy Programme has widened since 2017 to include more functions, such as Carbon Capture and Storage and hydrogen production and transport. The current research project, North Sea Energy (NSE) 4, additionally adds spatial integration ('hubs') and a joint vision (roadmap). Details of the programme and work packages are described elsewhere (North Sea Energy (north-sea-energy.eu))

## 1.1 Aim and research questions

The North Sea is expected to contribute to a reduction of carbon emissions and the success of the European energy transition. Therefore, estimations of the greenhouse gas emissions of the investigated pathways have been included from the very beginning of the research programme. These have been integrated in work package (WP) 4 by means of life cycle assessment (LCA). In line with an interdisciplinary approach and following the broadening of the NSE scope and the techno-economic insights, carbon footprints have been estimated for platform electrification and hydrogen production. Although aligned as much as possible with other work packages in terms of assumptions and physical descriptions, the LCAs of WP4 aim to provide generic insights into the advantages and disadvantages of using specific technological configurations rather than providing location-specific assessments. These previous carbon footprint assessments focussed on the emissions related to processes and energy generation related to gas or hydrogen production (Hauck, 2019; Hauck, 2020). The impacts of large scale infrastructures, such as platforms or islands were either ignored or their contributions to the considered functions were negligible due to long life times. However, extension to and integration of various energy functions in the North Sea will call for (newly built) large infrastructures that will be impactful for the (surrounding) environment. The choice of type of infrastructures might influence the impacts generated. How different types of platforms or islands compare in terms of their carbon footprints is currently unknown. Therefore, the aim of this report is to compare carbon footprints of offshore constructions including their end of life by using LCA. The terms constructions and structures will be used throughout these report to indicate platforms as well as islands, regardless their exact engineering and legal descriptions.

The main research question of this report is:
**How do the carbon footprints of offshore constructions including end of life compare?**

To answer this overall research question, the following auxiliary research questions have to be answered:

- What is the material and energy requirements over the lifetime of each structure type?
- What are the carbon footprints of the different structures?
- What are the main contributors to their carbon footprints?

## 1.2 Outline

As it is embedded in the larger research programme, WP4 Environment has relations with several other work packages, these are described in the appendix A.1.

Chapter 2 outlines the methodology in more detail. Chapter 3 describes and discusses the results and chapter 4 the conclusion and recommendations.

# 2 Method

## 2.1 Life cycle assessment

Life cycle assessment (LCA) is a method to systematically quantify and compare the effects of a product, system, service or geographical entity. As the name suggests, an important characteristic of LCA is that it takes into account the complete life cycle of a product (cradle-to-grave) from resource extraction to waste treatment, including transport in between. 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). Another important characteristic of LCA is that a wide range of environmental problems can be addressed, such as climate change and toxicity to humans or ecosystems. This way, trade-offs between life cycle stages and/or environmental problem areas are prevented. Finally, LCA is generally considered a comparative rather than an absolute tool. LCA is conducted in four interrelated steps: 1) Goal and scope definition; 2) life cycle inventory; 3) impact assessment; 4) interpretation and conclusions (ISO 14040/44). Each of these steps is described in more detail below for the case of offshore structures.

Other methodologies than LCA can be used to assess the environmental consequences of an innovation, technology or project. Environmental Impact Assessment (EIA, milieu effect rapportage (MER) in Dutch) is one of the most frequently used methods. EIAs are often compulsory when new works take place. LCA can be applied as a part of an EIA (Commissie MER, 2013), depending on the type and goal of the EIA. In general, EIAs are conducted to assess the effects of a specific project (e.g. one new facility) or location (e.g. of a road trajectory). These involve assessment of actual, local environmental effects and knowledge of temporal and small scale spatial changes at the location. Such specific local questions are generally not included in the generic effect of potential damage in LCA. However, if the environmental effects of a whole system, including also indirect effects and on a larger scale are of interest, LCA is a more appropriate tool (within EIA or standalone, Tukker, 2000).

## 2.2 Goal and scope

In the goal and scope definition, where the products to be compared are defined, the functional unit, the type of LCA, system boundaries, and impacts and impact assessment methodology are set. A functional unit (FU) is the unit of comparison to which all flows in the inventory are related. It is important that the functional unit is defined in such way that all systems under comparison fulfil the same function. For comparison of natural gas production, this is generally 1 m3 of gas, for hydrogen production 1 MJ of hydrogen and for electricity generation 1 kWh. The type of LCA refers to attributional vs. consequential LCAs. In attributional LCAs, it is assumed that a small amount of the product under consideration would not change the economy and average data are used. In consequential LCA, the change that the production of an additional amount of a product would infer to the economy (e.g. by replacing a competing product) is considered. Data gathering in this case includes modelling of the market consequences.

### 2.2.1 Goal and FU

The goal of this LCA study is to compare the carbon footprint of offshore structures over their life cycle. The functional unit in this study is the provision of a specified area (defined in the project together with WP1) of useful surface in the Dutch North Sea over a specified number of years [m2*yr]. The surface area was defined so that the functions defined for Hub West in WP1 can be fulfilled: **4GW dedicated hydrogen production**. Due to differences in design principles between platforms and islands, different scenarios were defined for the islands. The fulfilment of these functions and the required infrastructure is not part of this research. For platforms it is assumed that a larger area requires the building of additional identical platform and therefore, results will be scaled linearly with the area. The base platform is expected to be for **500 MW** dedicated hydrogen production. Islands however are designed to the required sizes and estimates of the required area/mass were derived in cooperation with WP 1 and consortium partners. The study is cradle-to-grave, meaning all life cycle stages including end of life were included. Using attributional LCA is deemed appropriate for this goal.

### 2.2.2 Scope

The geographic scope is the (Dutch) shallow North Sea. The temporal scope is a full life cycle starting between 2020 and 2030, but assuming current market relations. With an estimated life time of 50-100 years, the temporal scope is in line with the period also covered by the Hub definition in WP1. The technical scope is current (expected) state of the art. As a minor exception, some sensitivity scenarios relating to future fuel use and steel production were included. Results are presented per structure, showing contributions of materials and life cycle stages.

#### 2.2.2.1 Structure selection

Two basic types of structures are currently investigated to provide functional surface area in the North Sea (e.g. NSE 3, RWS 2018): platforms and artificial islands. The North Sea Wind Power Hub (NSWPH, 2019) distinguishes four hub foundation types: caisson island, sand island, and jacket based platforms and gravity based platforms. These are taken as starting points for conceptual design types in this study. Different types of structures are applicable at different water depths. For all the hub locations, currently a water depth of 30-40 m is assumed. Table 2.1 shows the water depth restrictions per type according to the North Sea Wind Power Hub and whether these restrictions indicate suitability for the hub locations considered in WP1. As can be seen, gravity based platforms and caisson islands as described by NSWPH are not well aligned with the hub water depth. Gravity based platforms are hardly used in the Dutch North Sea and are more suitable for locations with larger water depth further offshore and are therefore not included in this study. Likewise, caisson islands are not considered appropriate for these hubs. A combination of sand island and caisson might be feasible for the larger water depth, but has not been included within the NSE research. As an alternative, the inclusion of floating islands was considered. A hybrid island, combining floaters and fixed sand part is investigated in another TKI project HybridEnerSeaHub, for which data became available within TNO. Therefore this type of island was included next to sand island, and jacket based platforms. They are described in more detail in the next section.

*Table 2.1 Water depth per structure type and relation to hubs*

| Structure type | Max water depth [m] | Appropriate for Hub |
|---|---|---|
| Caisson Island | 25[1] | To be investigated |
| Sand Island | 40 | East, West, North |
| Jacket based platform | 45 | East, West, North |
| Gravity based platform | More than 100m | none |

Source: NSWPH, 2019, WP1, own interpretation
1 According to NSE experts, Caisson islands could be an option as well, even for deeper waters. In this case, a rock foundation layer will be pre-installed to raise the seabed.

#### 2.2.2.2 System description and boundary

*Jacket platform*

Jacket based platforms with steel topsides are included in this report. For the substructures, jacket based platforms use steel piles to be anchored in the sea bed. According to a study by DNVGL (2018) a platform for power to X in the North Sea is likely to have multiple tiers. For comparison with the island, the total surface area of the platform, including helicopter decks and several tiers is to be taken into account in this study. Equipment, cladding, cranes, roofing and rooms generally needed on a platform are not included in this study because their specific design is expected to be function-specific. For jacket based platforms, substructures consist of (low-alloyed) steel jacket legs, protected by anodes (aluminium zinc based on ecoinvent, Wernet et al., 2016) and coating (epoxy resin, ecoinvent) and concrete piles, anchoring the jacket structure in the seabed (foundation) (NSE 3 Deliverable in Energy Transport and Energy Carriers (Kee et al., 2020). Piles can be drilled in the seabed by relief drilling or vibro pile installation. According to the DNVGL study, the jacket is constructed onshore and transported to the site by heavy vessels where it is installed by jacket launch / lift and upending, positioning, pile installation, jacket levelling and grouting. For topside installation DNVGL assumes installation by heavy lift (in one or two parts) or float over requiring (floating) crane vessels. Other ways are floating or self-installing. For end of life treatment reverse handling is assumed.

*Sand island*

The main difference between a sand (revetment) and a caisson island is the type of protection: a caisson island is included in a steel or concrete box, whereas a sand island is basically a sand hill reinforced by gravel or concrete (e.g. Fang & Duan, 2018; NSWPH, 2019). For a (sand) island, the following components can be distinguished (Quickscan RWS, NSE 3 Deliverable on Offshore energy Islands (Van der Veer, 2020):

1. A revetment to keep the island in place and protected by rock and concrete (pre-cast blocks and slabs);
2. A breakwater to protect the harbour, and quay walls for the port basin itself from rock and concrete;
3. A basis for the island 'pancake': from gravel and sand
4. The filling of the total island with sand.

*Hybrid island*

To cover a range of island types a hybrid island, which is a combination of a sand island and floaters, has been included as well. Information on this type of island has been taken from another project (https://www.marin.nl/en/jips/hybridhub) and extrapolated to the 4 GW capacity. A hybrid island consists of various large and small floating modules and a fixed sand island. The island is surrounded by a breakwater. The floating modules are connected to each other by mooring lines. Between the floaters are tubular piles with protecting fenders on their sides. Fenders also protect the floating modules where they are connected to the fixed island.

The following components can be distinguished in the design described here:

1. Floaters: 11 large and 4 small floaters, made of steel and mooring components: tubular piles, mooring lines, fenders
2. Fixed sand island: covered by a pavement of a concrete slab on top of an infilled cement bed with on the harbour side a steel combi wall surrounded by a revetment of sand, gravel and rock
3. Breakwater (sand, gravel, blocks)

*Comparability of construction types*

The designs of the structures investigated in this report would generally be optimized to different goals, e.g. an offshore platform would generally be designed to use as few space as possible, whereas for an island space would be less restricting and for instance flexibility of functions or more accessibility (e.g. sheltered harbour) could be a goal. To make the carbon footprints as comparable as possible, several scenarios (expressed in areas required for specific functions) have been developed for the sand islands that represent the originally preferred design and the design adapted to maximal comparability with platforms. An overview of these scenarios and related total areas is given in Table 2.2. One design is presented for the platform. For the sand island a full option island has been designed that includes a sheltered harbour, laydown area and more space for storage. This island also makes use of 9 concrete caissons. In the 'unsheltered' island design that aims to mimic functions and assumptions for the platform as closely as possible ('like for like' comparison), these have been excluded or reduced in area. A comparison of the areas per construction in each scenario is shown in Appendix 0. Data for the hybrid island were deduced from a design that included 2 GW hydrogen production and other functions, namely aquaculture, visitor and data centres and extended living quarters. To allow for a comparison to 4 GW platforms and a sand island, these functions have been replaced by hydrogen and the same area requirements for specific functions have been assumed as in the 'like for like' island. As the fixed part of the hybrid island is designed for electrical equipment, the corresponding area is not included in the floaters. A comparison of the areas in the original 2 GW design and the adapted version is also included in Appendix 0. Possible extra measures due to this adapted design, like a blast wall for protection between power to gas equipment and living buildings have not been included.

*Table 2.2 Construction and areas*

| | Platform | Sand island (full option) | Sand island (like for like) | Hybrid island |
|---|---|---|---|---|
| Circumference | 80 m x 40 m *4tiers | 600 x 570 m | 500 x 480 m | 490 x 750 m (including port basin) |
| Area | 1.3 ha for one platform, 10ha for 8 platforms | 34 ha | 24 ha | 37 ha |
| Area for hydrogen production | 14 ha (8*1.8ha) | 20 ha | 20 ha | 21 ha[A] |

Source: [NSE and HybridEnergSeaHub], assuming the same are is used for electric equipment on the fixed part of the hybrid island as on the other islands.

### 2.2.2.3 End of life scenarios

The lifetime of platforms and islands still to be built is highly uncertain. For gas and oil platforms, the life cycle inventory database ecoinvent (Wernet et al., 2016) assumes a lifetime of 30 years, but many platforms in the North Sea have already exceeded this lifetime. Rijkswaterstaat (RWS, 2018) assumes 100 years for islands in the Quickscan. Default lifetimes of 30-35 years for floating modules, 50 years for platforms (with a sensitivity for 10 and 100 years) and 100 years for sand islands and breakwaters were used in this report.

What will happen at the end of this life, is also not yet well defined. The OSPAR Decision 98/3 on the Disposal of Disused Offshore Installations distinguishes several options:

1. Dumping, leaving partly/wholly in place
2. Re-use all or part
3. Recycling all or part
4. Final disposal on land

The first option is not currently allowed in the North Sea, but is nonetheless included in this report to cover the full spectrum of possibilities. Following Ekins et al. (2005), who, next to leaving in place and recovery distinguish shallow removal, we interpret 'in parts' as referring to topside vs. jacket/socket.

Rijkswaterstaat (2018) suggests removal of the hard protection by ship for each layer for re-use and leaving the sand body for erosion as most likely end of life scenario for sand islands. The default end of life treatment modelled in this report is shown in Table 2.3 alongside alternative possibilities.

*Table 2.3 End of life scenarios*

| Structure | Default | Alternative scenarios | |
|---|---|---|---|
| Platform | Remove all and recycle on land | Shallow removal (put topside on seabed) | Abandon all |
| Sand island | Remove concrete, recycle on land | | Abandon all |
| Hybrid island | Remove concrete and floaters, recycle on land | Recycle floaters, abandon fixed parts | |

## 2.3 Inventory

Inventory refers to the data gathering phase, were all inputs and outputs of the product system are compiled. These encompass resource extractions as well as emissions into the environment and are summarized under the term interventions. This report focusses on the interventions that have an influence on the emissions of greenhouse gases related to the life cycle of platforms and islands. These are expected to be:

- the amount (in mass or volume) and type of material used over the life cycle of the structure: steel, concrete, rock, sand and gravel but also the specific types, e.g. recycled or virgin steel, from blast or electric furnace and level of alloyment or coating, reinforced concrete or incorporation of waste and type and amount of cement incorporation, and sources of sand and gravel excavated. Where no details on the materials was available, an average product, available from databases, was chosen.
- the amount and type of fuel used for transporting the materials and/or structure components (e.g. topside or caisson), before and after its life at sea, but also for construction and installation and dismantling and removal and for maintenance. These are likely influenced by the type of vessel, the transport distance, the amount of material to be transported and the type of construction, installation and dismantling and removal activity.

Secondary infrastructure material such as to build the ship, vessels or cranes is not included in the analysis. For both types of data (materials and fuels), the data gathering approach is described in more detail below.

### 2.3.1 Data sources and modelling approach

In life cycle inventory, often distinction is made between foreground data that are compiled by the practitioner specific to the case study and background data that are taken from databases. In this study, foreground data to be gathered within the NSE project are material needs for each of the structures, fuel (and replacement material) consumption for transport, construction, installation, maintenance and dismantling and removal and direct emissions, e.g. from losses. Data on the hybdrid island are gathered from HybridEnergSeaHub project, data for floaters are taken from Wernet & Van den Brink (2021). Background data are the environmental profiles related to these materials and fuels. These were taken from ecoinvent 3.6 (Wernet et al., 2016). If data remain unknown, assumptions will also be transferred from ecoinvent, such as the percentage of anode loss.

#### 2.3.1.1 Materials

Table 2.4 gives an overview of material data gathering: from the capacity and depth definition as in WP1 on hubs, the required areas can be derived. These are translated by calculation rules derived from NSE 3 reports and the DNVGL (2018) report as far as possible.

*Table 2.4 Data sources material*

| Structure | Capacity | Water depth | area | Primary data source | Material list |
|---|---|---|---|---|---|
| Jacket based platform | 500 MW | 30 m | (80m*40m)*4decks* 8 platforms = ca. 16 ha | DNVGL, 2018; to be replaced later by calculations by IV-one (WP1) | Steel, concrete, anodes, coating |
| Sand island | 4 GW | 30 m | 24-35 ha | Calculated by DEME together with WP 1 | Sand, Gravel, Concrete, Stone |
| Hybrid island | 4 GW, extrapolated from 2 GW | 25 m | 22 ha | Info from other projects HybridEnerSeaHub | steel, coating, rubber, dyneema (=High Modulus Polyethylene), sand, gravel, rock |

#### 2.3.1.2 Fuel consumption

Data gathering for fuel consumption depended on the activity type and source and were derived as follows:

- Fuel consumption for transport and installation of sand islands: directly derived from cost estimations by DEME. These fuel data include the dredging of sand at the location, the transport of other materials form onshore to location and the construction of the island.
- Fuel consumption for transport and installation of platforms: According to IV-one information, the vessel 'Thialf' might be used for installation. Daily fuel consumption and the accompanying heavy lift vessel Aegir are taken from the Heerema sustainability report (Heerema Marine Contractors, 2020) and are assumed to be operated for one day per platform.
- Fuel consumption for transport and installation of floaters: It is assumed that tugs need two days an average daily fuel consumption of 15.140 liter per day[1] (bring and return) per floater to transport them to the island location. It is assumed that floaters need to be replaced 2 times, requiring 2 days for the old and new floaters together.
- Fuel consumption for transport and installation of fixed island: a working schedule for installing the fixed island and breakwater was derived from the HybridEnerSeaHub project consisting of running days and vessel types. These were multiplied by specific fuel consumptions (taken from databases available at TNO wind energy).
- Fuel consumption for decommissioning of platforms and islands: assumed equal to installation, no differentiation between scenarios was possible with the current data.
- Fuel consumption for operation and maintenance of both platforms and islands: derived from route information by Peterson. The following information was derived from data provided by Peterson on their supply vessels:
  - The composition of modes for an example voyage.

[1] From Fuel management for tugs becoming an increasing challenge - Professional Mariner.

- The average fuel consumption per nautical mile above ground for sailing, the average fuel consumption per second for other activities, such as waiting, handling, moving in or out.
  The total fuel use during the lifecycle has then been calculated as:

  $$F_{O\&M} = \left(\sum_i tA_{t,i} + dA_d\right) \cdot rLT \qquad \text{equation 1}$$

  Where F: fuel use over life cycle (ton); t: time for operation i (h); $A_{t,i}$: average fuel use for activity i (ton/h); $A_d$: average fuel use for distance d over ground (ton/km); d: distance (km); r: frequency of maintenance trips (/year); LT: lifetime (50 years for platforms, 100 years for sand islands). The underlying activities for these calculations are summarized in Appendix A.3.

The distance to shore has been assumed as 150km (in alignment with WP1), the assemble of platforms has been modeled as one. A sensitivity analysis on the distance was envisaged, but has not been performed due to a lack of detail in other fuel data (not attributable to voyage part). Inland transport from quarries or market to shore has not been added to the modelled due to relatively short distances.

For maintenance of platforms/islands, it has been assumed that only maintenance that requires shut-down can be considered as referring to the structure itself and not the equipment. According to (Peet, 2021), they occur once in 2 years with 6 visits (= 3 visits *per year).*

#### 2.3.1.3 End of life modelling

In the default scenarios, structures are dismantled and brought onshore. For the platform this refers to topside as well as jacket, for the sand island this only refers to the concrete parts. Sand, gravel and stone were assumed to be left at sea. For the hybrid island this refers to all materials, except for the sand. Sand is assumed to be left on the sea floor. Using cut-off principles ((i.e. all the benefits and burdens of recycling are assigned to the second life cycle of the material) , the burdens and benefits of recycling were not allocated to the current life cycle, but modelling was cut-off after transport to shore. This means that re-use of materials after decommissioning will not affect results. This will be addressed in a sensitivity scenario. Steel is modelled following ecoinvent. Accordingly, about 40% of the steel produced is already made from secondary materials (Classen et al., 2009). Energy use for dismantling and transport to shore is set equal to installation and transport energy use, due to lack of better data.

### 2.3.2 Inventory tables

The inventory tables as used for the calculation are shown in the following section.

#### 2.3.2.1 Inventory data

Below, the inventory tables for sandy islands, jacket platforms and a hybrid island for a 4 GW dedicated hydrogen scenario at 150km from the coast and a water depth of 25-30m are shown. Platform data are the same as in the midterm report, except for the addition of metal working as a proxy for platform construction. Sand island data have been updated for better comparability and consistency. The following lines of reasoning were followed to select the appropriate materials from the life cycle inventory database ecoinvent:

- It was expected that most of the steel used is construction steel. Construction steel is mostly unalloyed steel, but in the offshore application it is expected that high strength steel is applied, such as steel type S355 (Wortel et al., 2008)[2]. The steel type S355 is a high-strength low-alloy standard structural steel (S355 European standard Steel). For this reason, all steel used in the platforms and

[2] Confirmed by Internal TNO experts

floaters has been modelled as low-alloyed steel, unless more specific information was provided by the partners.

- Concrete is used in the sand and hybrid islands for different purposes; e.g. for the concrete ring road, concrete blocks and caissons. The caissons and the ring road were modelled using reinforced concrete. The caissons are hydraulic structures that have to withstand vertical and horizontal loads underwater (Voorendt et al., 2011), and therefore reinforced concrete is the appropriate choice. The reinforced concrete used in these applications could be concrete based on cement types CEM III/B or CEM II/B, i.e. cements where part of the Portland cement is substituted with other materials such as fly ash or furnace slag. Only CEM II/B, which has a fraction of Portland cement of above 45%, is available in ecoinvent. This cement type was chosen after confirmation with TNO experts that this type could be a reasonable choice for many EU countries (though less in the Netherlands). For simplicity, concrete blocks have been modelled based on the available ecoinvent process for concrete blocks using the major type of concrete available in there.
- Diesel consumption in vessels has been modelled with the ecoinvent process card "Diesel, burnt in fishing vessel" due to similarity of CO2 emission profiles of different vessels, ships and modelling approaches. Details on modelling of concrete and emission factors can be found in the appendix A.5.

*Table 2.5 Sand island (source: DEME): 4GW dedicated hydrogen capacity, lifetime 100 years (bold numbers are included in the LCA model)*

| Material | Unit | Quantity | | Database process |
|---|---|---|---|---|
| | | Without sheltered harbour (24ha) | With sheltered harbour (34ha) | |
| SandC | $m^3$ | 17,809,711 | 23,823,327 | Adapded_Sand {RoW}\| sand quarry operation, extraction from river bed \| Cut-off, U3, A |
| QRN/GRAVEL | tonnes | 7,371,398 | 7,355,807 | Gravel round {RoW}\| gravel and sand quarry operation \| Cut-off, U |
| Rock 40-200kg | tonnes | 175,333 | 140,242 | |
| Rock 0.3-1.0T | tonnes | 1,068,721 | 4,467,534 | |
| Rock 10-1000 kg | | | 63,254 | |
| Rock 10-60 kg | | | 249,785 | |
| Rock 3 -6 Tonnes | tonnes | 1,468,102 | 1,679,154 | |
| Rock 10-15 Tonnes | tonnes | 235,776 | 297,696 | |
| sum | tonnes | 2,947,932 | 6,897,665 | Diesel, burned in building machine {GLO}\| market for \| Cut-off, UD |
| X-Block 43.2T | Units | 13,125 | 19,602 | |
| X-Block 43.2T concrete | $m^3$ | 236,255 | 352,845 | Adapted_Concrete block {DE}\| market for concrete block \| Cut-off, U |
| Ringroad concrete | $m^3$ | 34,260 | 30,931 | 2% reinforcing steelB<br>98% Concrete, high exacting requirements {CH}\| concrete production, for building construction, with cement CEM II/B \| Cut-off, |

[3] Density of sand reported in Table A.1 in Appendix A.2

| | | | | |
|---|---|---|---|---|
| | | | | U, Reinforcing steel {RER}\| production \| Cut-off, U) |
| CAISSONS (22.5x22x55m) | Units | | 9 | |
| CAISSONS $m^3$ concrete | $m^3$ | | 25,135 | 2% reinforcing steelB<br>98% Concrete, high exacting requirements {CH}\| concrete production, for building construction, with cement CEM II/B \| Cut-off, U, Reinforcing steel {RER}\| production \| Cut-off, U) |
| Energy use for caisson construction | MJ | | 0.0216MJ/kg concrete = 1440000 MJ | Diesel, burned in building machine {GLO}\| market for \| Cut-off, U |
| Energy use for caisson construction | kWh | | 0.002 kWh/kg concrete = 133000 kWh | Electricity, medium voltage {NL}\| market for \| Cut-off, U |
| Fuel use for transport and installation | liters | 133,000,000 | 175,000,000 | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U |
| Fuel use for maintenance | liters | 4,284,451 | 4,284,451 | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U |
| Fuel use for decommission in default scenario | liters | 133,000,000 | 175,000,000 | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U |

A: this process has been adapted to exclude fuel use and quarrying machinery to avoid double counting with the fuel data derived from DEME.
B: based on CE Delft, 2020.
C: potential replacements and losses are included in the total numbers.
D: Rubble stone: Modelled as inert rock (input from nature) and the energy necessary to produce it (0,051 MJ/kg), modelled following the process "0171-fab&Breuksteen, waterbouwsteen, exc.transport naar de bouwplaats" (i.e. armourstone) available in the Dutch Nationale Milieu Database.

*Table 2.6 Jacket based platform (source: DNVGL, 2018): 500MW hydrogen production (3200m2*4), lifetime 50 years*

| Material | unit | Quantity | comment | Database process |
|---|---|---|---|---|
| **Topside** | | | | |
| steel | tonnes | 6,624C | | Steel, low-alloyed, hot rolled {GLO}\| market for \| Cut-off, U |
| Coating area | m2 | 126,448*6,604/16,326 = 51,149 | Assumed proportional to mass, only take into account supporting steel, not equipment | Epoxy resin, liquid {RER}\| market for epoxy resin, liquid \| Cut-off, U |
| Fuel use | litres | 86893 | One day of Thialf (48.4tonnes)+ one day of Aegir (28.5tonnes) | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U |
| Platform construction | ton | 6,624 | Average used due to lack of data on energy requirements, assumed to be in Europe | Adapted_Metal working, average for steel product manufacturing {RER}\| processing \| Cut-off, UB |
| Jacket | | | | |
| primary steel | tonnes | 8547C | | Steel, low-alloyed, hot rolled {GLO}\| market for \| Cut-off, U |
| anodes | tonnes | 88 | Aluminium-zinc as modelled for anodes in an offshore platform in ecoinventA | 31% Aluminium, cast alloy {GLO}\| market for \| Cut-off, U;<br>66% Aluminium, wrought alloy {GLO}\| market for \| Cut-off, U;<br>3% Zinc {GLO}\| market for \| Cut-off, U |
| Coating area | m2 | 9,609 | | Epoxy resin, liquid {RER}\| market for epoxy resin, liquid \| Cut-off, U |
| Fuel use for installation | litres | 86893 | One day of Thialf (48.4tonnes)+ one day of Aegir (28.5tonnes) | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U |
| platform construction | ton | 8547 | Average used due to lack of data on energy requirements, assumed to be in Europe | Adapted_Metal working, average for steel product manufacturing {RER}\| processing \| Cut-off, UB |
| **Energy** | | | | |
| Fuel use for maintenance | tonne | 2142225,71 | As in the case of the sand islands, this is modelled based on the data delivered by the project partner Peterson. | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U |
| Energy use for EoL (ships) in default scenario | litre | 173785 | Two days of work on the Thialf and the aegir | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U |
| Preparation for recycling of steel (default scenarios) | tonne | 15198 | Steel from topside and Jacket is recycled on shore. | Iron scrap, sorted, pressed {RER}\| sorting and pressing of iron scrap \| Cut-off, U |

A: anodes are assumed to be utilised for 85% and substances released to water. Because these are not related to the carbon footprint, these processes are ignored in the current version.
B: This process has been modified excluding the input of steel and keeping only the energy use for the metal working process.
C: These numbers are confirmed by the latest estimates from IV Offshore & Energy b.v. (10,575 tonne for jacket and 5510 tonne structural steel in the topside). These numbers exclude the weight of the equipment placed on the platform.

*Table 2.7 Hybrid island (source: HybridEnerSea project, data to be published summer 2022): 4 GW hydrogen production (extrapolated) (213.850 m2 floaters, 137.500 m2 fixed part), lifetime 30-35 years for floaters, 100 years for fixed part and breakwater*

| Material | unit | Quantity | comment | Database process |
|---|---|---|---|---|
| **Fixed part** | | | | |
| Sand | tonne | 27.829.595 | for sand island and breakwater | Adapted_Sand {RoW}\| sand quarry operation, extraction from river bed \| Cut-off, UA |
| Concrete | m3 | 12.500 | for sand island | 2% reinforcing steelB<br>98% Concrete, high exacting requirements {CH}\| concrete production, for building construction, with cement CEM II/B \| Cut-off, U, Reinforcing steel {RER}\| production \| Cut-off, U) |
| Steel | | | steel combi wall on island | Steel, unalloyed {GLO}\| market for \| Cut-off, U |
| Rocks | tonne | 5.619.279 | revetment and breakwater, See above | Diesel, burned in building machine {GLO}\| market for \| Cut-off, U |
| Gravel | tonne | 1.089.345 | revetment and breakwater | Adapted_Gravel, round {RoW}\| gravel and sand quarry operation \| Cut-off, UA and Transport, freight, sea, bulk carrier for dry goods {GLO}\| market for transport, freight, sea, bulk carrier for dry goods \| Cut-off, U, assuming a distance of 1000 km (quarrying along Norwegian coast) |
| fuel use for building | litres | 119347388 | | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U4 |
| fuel use for decommissioning | litres | 119.347.388 | | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U3 |
| Fuel use for Pavement replacement | litres | 1260 | | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U3 |
| Pavement replacement | m3 | 12.500 | Replacement of the concrete volume once | 2% reinforcing steelB<br>98% Concrete, high exacting requirements {CH}\| concrete production, for building construction, with cement CEM II/B \| Cut-off, U, Reinforcing steel {RER}\| production \| Cut-off, U) |
| **Large floater** | | | of which 11 + 22 | |
| Steel | tonnes | 11921 | | Steel, unalloyed {GLO}\| market for \| Cut-off, U |
| epoxy resin | tonnes | 36 | | Epoxy resin, liquid {RER}\| market for epoxy resin, liquid \| Cut-off, U |

[4] See Appendix A.5

| | | | | |
|---|---|---|---|---|
| fuel use for transport of floaters (installation) | litres | 30.280 | 2 days for installation, decommissioning each, 15.140 litres per day; | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U3 |
| fuel use for transport of floaters ( replacement ) | litres | 60.560 | Two replacements in the lifetime, (2 days of work each time). | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U3 |
| fuel use for transport of floaters (decommissioning ) | litres | 30.280 | | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U3 |
| Steel working for floater construction | ton | 11921 | Average used due to lack of data for lack of data on energy use, assumed to be in Europe | Adapted_Metal working, average for steel product manufacturing {RER}\| processing \| Cut-off, UC |
| Transport floaters from ChinaD | ktkm | 265732 | Calculated multiplying the average distance by sea between Port of Rotterdam and port of Shanghai (22224 km) by the total weight of 1 floater. | Transport, freight, sea, container ship {GLO}\| transport, freight, sea, container ship \| Cut-off, U |
| **Small floater** | | | of which 4 + 8 | |
| Steel | tonne | 7.944 | | Steel, unalloyed {GLO}\| market for \| Cut-off, U |
| epoxy resin | tonne | 31 | | Epoxy resin, liquid {RER}\| market for epoxy resin, liquid \| Cut-off, U |
| fuel use for transport of floaters (installation) | litres | 30.280 | 2 days for installation, 1 replacement, decomissioning each, 3 replacements over lifetime, 15.140 liters per day; total days of tug: 10 | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U3 |
| fuel use for transport of floaters ( replacement ) | | 60.560 | | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U3 |
| fuel use for transport of floaters (decomissioning) | | 30.280 | | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U3 |
| Steel working for floater construction | ton | 7.944 | Average used due to lack of data for lack of data on energy use, assumed to be in Europe | Adapted_Metal working, average for steel product manufacturing {RER}\| processing \| Cut-off, UC |
| Transport floaters from ChinaB | ktkm | 177236 | Calculated multiplying the average distance by sea between Port of | Transport, freight, sea, container ship {GLO}\| transport, freight, sea, container ship \| Cut-off, U |

| | | | | |
|---|---|---|---|---|
| | | | Rotterdam and port of Shanghai (22224 km) by the total weight of 1 floater. | |
| Other components to fix and connect all floaters | | | | |
| steel tubular pipes | ton | 234 | | Steel, unalloyed {GLO}\| market for \| Cut-off, U |
| rubber fenders | ton | 2 | 45 | Synthetic rubber {GLO}\| market for \| Cut-off, U |
| dyneema lines | ton | 9 | | Polyethylene, high density, granulate {GLO}\| market for \| Cut-off, U |

A: this process has been adapted to exclude fuel use and quarrying machinery to avoid double counting with the fuel data derived from DEME.
B: based on CE Delft, 2020.
C: This process has been modified excluding the input of steel and keeping only the energy use for the metal working process.
D: used as an approximation here, because details on transportation mode and distance were unknown

In order to translate the data presented above to mass data suitable for LCA modelling, some additional calculation factors have been used. These are summarized in Appendix A.2.

## 2.4 Impact assessment

Impact assessment describes the phase, where the long list of interventions is translated into a number of so-called midpoint impact categories by modelling the underlying environmental mechanism. This step allows to add all interventions that contribute to the same environmental problem in one common unit. For the carbon footprint, emissions of greenhouse gases are re-calculated to kg $CO_2$-equivalents ($CO_2$-eq) by using Global Warming Potentials (GWP) that express the contribution of a gas to radiative forcing relative to that of $CO_2$. More details on impact assessment levels and other impact categories have been given in previous NSE reports. In this report, the GWPs from the latest IPCC report were used (IPCC 2021 GWP 100a).

# 3 Results and discussion

## 3.1 Comparison of carbon footprints and contributions

Figure 3.1 shows the carbon footprints of two sand islands (sheltered and unsheltered), and of the jacket platforms per $m^2$ and year. The carbon footprint of the platform was about 80 $kgCO_2eq/m^2yr$), and about 40 $kgCO_2eq/m^2yr$ for the sand islands. Carbon footprints of a platform reported in ecoinvent largely exceed these numbers, mainly because it only had a lifetime of 11 years. Keep in mind that the areas estimated for a 4 GW capacity differ largely: 10 ha (8 platforms of 500MW) for platforms and 24ha and 34ha for sand islands. Figure 3.2 shows the carbon footprints for each structure for the total area and lifetime. Results per $m^2$ and year are shown in Appendix 0. As can be seen from Figure A2 in Appendix 0, the higher footprint of the platforms is largely due to the shorter lifetime.

The contributions of materials and fuels is shown in Figure 3.3. The carbon footprint of the platform was dominated by steel use whereas the footprints of the sand islands were dominated by fuel use for installation, and decommissioning. The second largest contributor for sand islands were the concrete blocks (see Figure A3 in Appendix A6). The contributions of the life cycle stages are compared in Figure 3.4. Fuel use for operation and maintenance is minor in all cases, but visible for the platforms and not for the islands. This is due to the fact that the same maintenance schemes (and absolute fuel uses) were assumed for both types of structures, but become lower per square meter for the sand islands due to the larger areas.

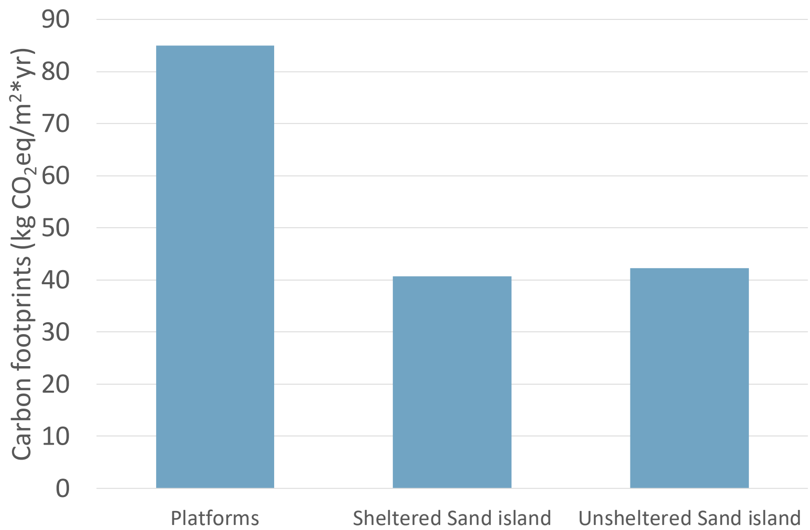


*Figure 3.1 Comparison of carbon footprints of sand islands and platforms for 4GW hydrogen production per $m^2$ and year based on 10 ha (8 platforms of 500MW) and a lifetime of 50 years for platforms and 24ha (as closely designed to platform as possible, unsheltered island) and 34ha (full functionality sheltered sand island) for sand islands (lifetime 100 years).*

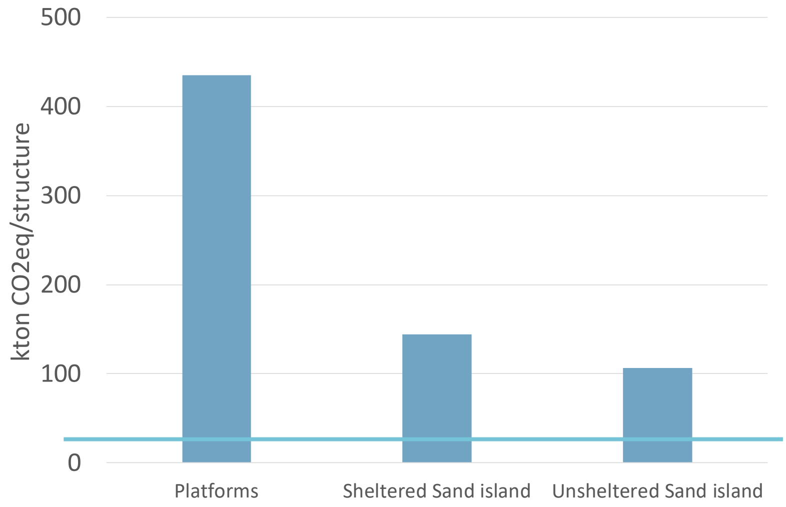


*Figure 3.2 Total carbon footprint of each structure over the entire life cycle. The blue lines indicates the carbon footprint of an oil and gas platform as reported by ecoinvent.*

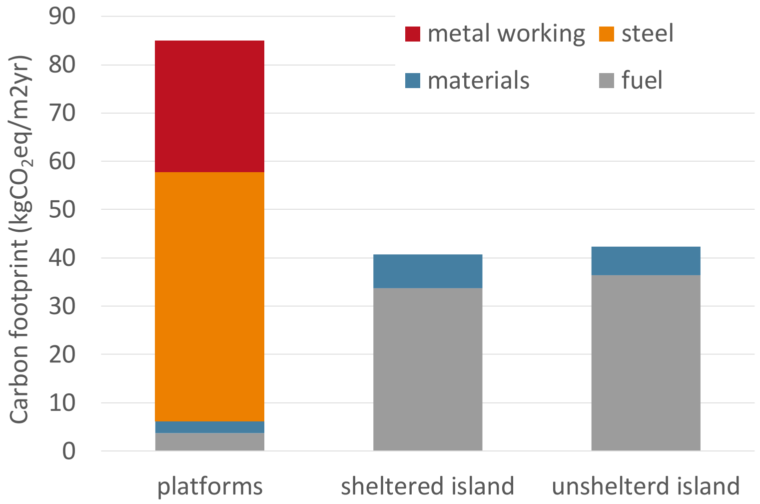


*Figure 3.3 Material contributions to carbon footprints of sand islands and platform per $m^2$ and year.*

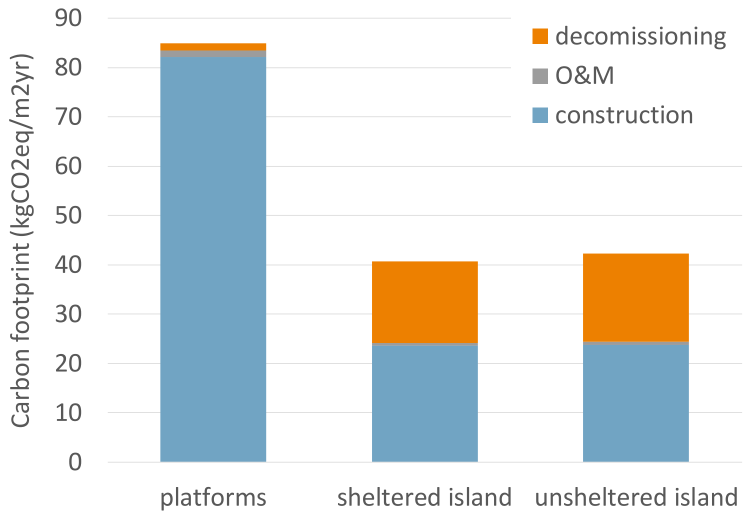


*Figure 3.4 Comparison of carbon footprints per life cycle stage.*

Figure 3.5 shows the carbon footprint of hybrid islands. The carbon footprint was about 90 $kgCO_2eq/m^2yr$ for an total effective area of 37 ha, steel for the floating part had a major contribution in the carbon footprint.

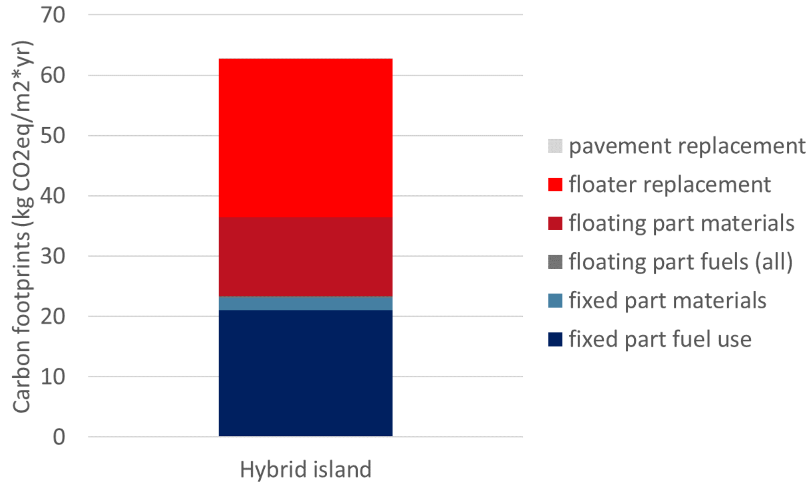


*Figure 3.5 Carbon footprint of hybrid island, red colours indicate contribution of the floater part (dark red for construction, light red for replacement, fuel use and decommissioning are included but had minor contributions), blue colours indicate contributions of the fixed part (dark blue for materials, light blue for fuel, including construction, replacement and decommissioning).*

## 3.2 Sensitivity analysis

### 3.2.1 Functional unit

Figure 3.6 shows the results if they were presented per GW installed capacity (for 100 years) instead of $m^2$year. Although carbon footprints are higher on a GW basis, they are also higher for platforms than for islands. The difference between platform and islands is, however, higher due to the shorter lifetime of the platforms.

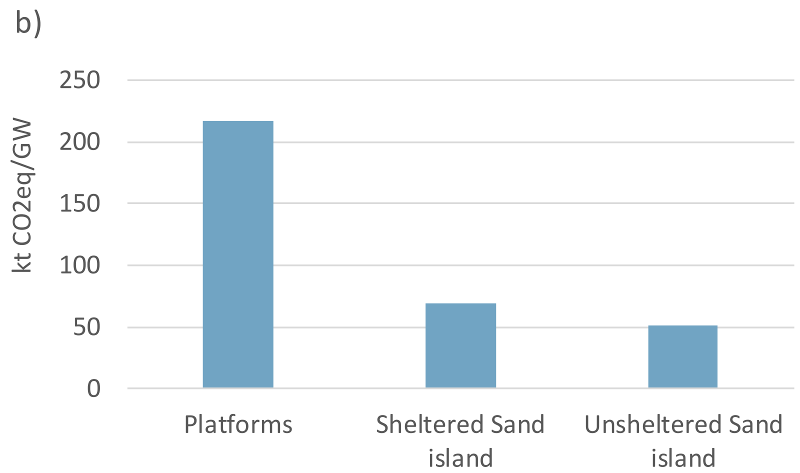


*Figure 3.6 Carbon footprints of platforms and sand islands in ktonCO$_2$eq per GW.*

### 3.2.2 Fuel use

Hydrogen as ship fuel is a promising solution to reduce the environmental impacts of marine transport due to reduced emissions associated with hydrogen combustion. Hydrogen can be used as ship fuel in multiple ways: it can be used in parallel to the diesel and be burnt in the diesel engines (dual-fuel motors) or it could be used in a mono-fuel engine (i.e. in a combustion engine) or it could be used in a fuel cell in an electrical engine. In the latter case, the ship engine should be substituted with an electrical engine and a battery should be added for peak demand management, as the fuel cell alone cannot respond to sudden increases in power demands. Based on consultations with internal TNO experts, the latter scenario was excluded as it is too unrealistic and uncertain at this stage: fuel cell technology is still too immature and expensive to provide a viable alternative to improve the environmental performance of the existing fleet in the next 10-30 years. The most realistic scenario is the use of hydrogen in combination with diesel in a dual-fuel engine, thus substituting 50% of the diesel. In this case, hydrogen has to be stored in the ship and compressed to about 350 - 700 bar. Energy use for this compression has been added to the provision of hydrogen. In accordance to the data reported in the latest WTT report (Prussi et al 2020)[5], it has been assumed that 0.09 $MJ_{electricity}/MJ_{H2}$ were necessary for compression.

Two hydrogen production pathways were considered; 1) hydrogen produced by electrolysis offshore in an alkaline electrolyser using wind electricity (green hydrogen) and 2) hydrogen produced by steam reforming (SMR) with carbon capture and storage (CCS) (blue hydrogen). In the case of the green hydrogen, the energy used for compression is renewable offshore wind energy (using the process card available in ecoinvent) while in the case of the blue energy pathway, the compression energy is supplied by the current grid electricity mix. The $CO_2$ emissions associated with these two hydrogen production pathways were those calculated in the previous NSE reports (Hauck, 2020). Use of alkaline offshore is not currently expected to be feasible, however, differences between carbon footprints using PEM or alkaline offshore were negligible. These two processes have been chosen as they represent the best case scenarios of the most viable hydrogen production processes i.e. hydrogen from electrolysis and from natural gas. SMR without CCS has been excluded a priori from this sensitivity analysis as it has a higher carbon footprint than marine diesel oil..

The substitution was based on the lower heating value of the hydrogen, assuming that the combustion efficiency of the engine would not change (Jochemsen-Verstraeten et al., 2016). The parameters necessary for the calculations are reported in Table A 1, the resulting fuel use is shown in the Appendix A.6. Results with substitute fuel are shown in Figure 3.7 for platforms and sand islands and in Figure 3.8 for a hybrid island.

Comparing the results of this sensitivity analysis (figure 3.7) with the results presented in Figure 3.3, it can be seen that the carbon footprint of the sand island decreases substantially (25%-40%) by replacing half of the diesel with hydrogen. The choice of green or blue hydrogen gives rise to a small difference. The impact of using hydrogen on the platforms is not remarkable as the carbon footprint is dominated by the steel and metal working contributions.

Another possibility to reduce the environmental impact of the fuels used in the construction of platforms in the North Sea, would be to replace the marine Diesel with Liquefied Natural Gas (LNG). Still, the GWP of the LNG is 4.91 kgCO2-eq/kg, considerably higher than the $CO_2$ emissions of MDO. This can be explained by two reasons. On one hand, inefficient combustion of the LNG leads to methane spillages, a gas with a high GWP. On the other hand, the LNG is likely to be burnt in a marine dual-fuel motor where MGO is used as a pilot fuel. Kruk and Bolech (2022) in their report assume a mixture of 80% LNG + 20% MGO. This is surely a worst case scenario as more modern dual-fuel engines already exist that would

[5] The data used in this report were taken from the Excel appendices of the report, JEC_WTTv5_ Appendix 1_Pathways 8_H2, for GPCHx. The file reports 0.09 $MJ_{electricity}/MJ_{H2}$ to compress hydrogen from 1.5 to 88 MPa. We assumed that this was equivalent to the compression of Hydrogen from 7 to 70MPa.

 

reduce the use of MGO considerably (Kruk and Bolech, 2022). Substituting MDO with LNG will lead to environmental benefits, due to reduced acidification potential, nitrogen emissions and impacts on human toxicity, but these are not reflected in the carbon footprint which is higher than for MDO. For this reason, this route was not investigated further in this sensitivity analysis.

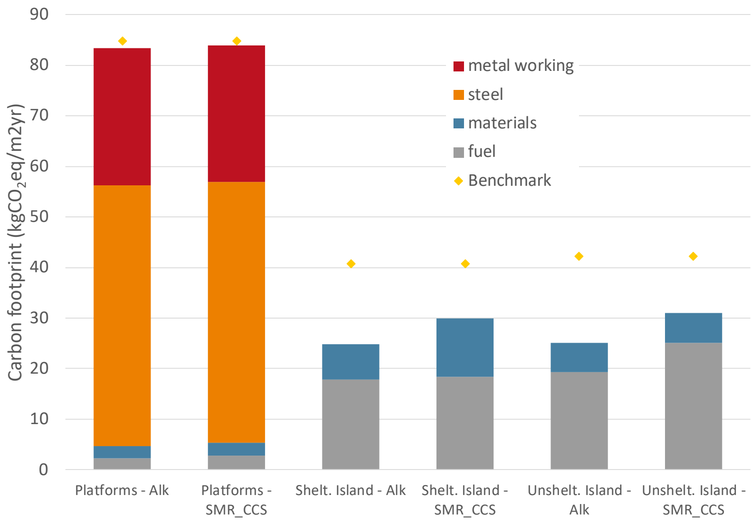


*Figure 3.7: Material contributions to carbon footprints of sand islands and platform per m$^2$ and year, using hydrogen produced from electrolysis offshore and SMR with CCS as partial substitution for MDO. Yellow dot represents the benchmark reference.*

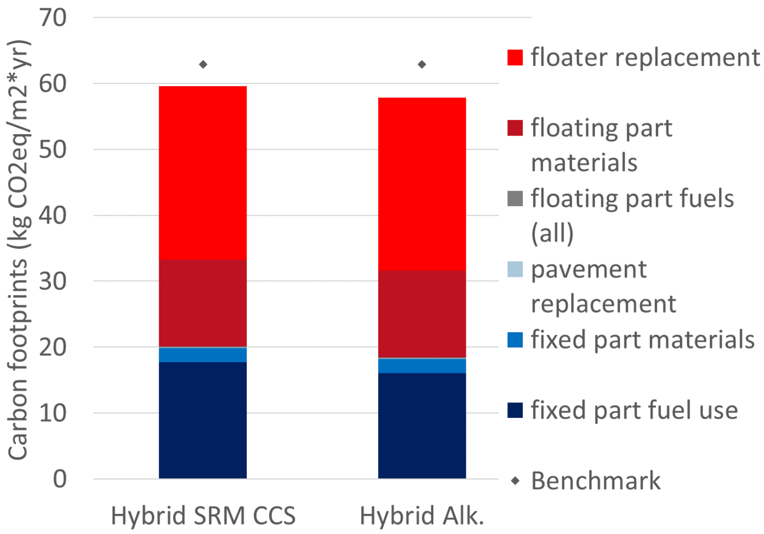


*Figure 3.8 Contributions to carbon footprint of Hybrid islands per m$^2$ and year, using hydrogen produced from electrolysis offshore and SMR with CCS as partial substitution for MDO. Grey dot represents the benchmark reference*

### 3.2.3 Recycled Materials

The possibilities to include secondary materials in concrete encompass the use of crushed concrete to replace the filling materials (sand and grind) and the replacement of part of the Portland cement by other secondary materials, such as fly ash or blast furnace slag. The latter option is expected to give a higher benefit as the largest contribution to the environmental impact of concrete is given by the cement. For most concrete applications, up to 20% of crushed concrete can be added without technical limitations (de Vos-Effting et al. 2017). For this sensitivity scenario's it was assumed that 20% of the gravel was replaced by crushed concrete and that the cement used in the concrete mixture contained 25% of Portland cement and 73% of blast furnace slag. Note, as the reinforced concrete used in the ring road and caissons already contains a cement partially made of secondary materials (CEM II\B), this assumption has been applied only to the concrete blocks.

It has been assumed that 95% of the steel used was electric arc furnace steel, the remaining 5% blast furnace. These amounts have been chosen due to the fact that construction steel can contain up to 95% or recycled steel (Levels 2022). This assumption has been applied in the jacket and topside of the platform, tubular piles of the hybrid island and floaters of the hybrid island.

It has been assumed that all the gravel used in the revetment could be substituted by crushed concrete. Results of using secondary materials are shown in Figure 3.8 and 3.9.

As it can be seen from Figures 3.8 and 3.9 also the application of secondary materials in the construction of the different islands and platforms leads to considerable reductions in the carbon footprint of the installations. This is particularly visible for the Jacket Platforms (moving from 85 kg $CO_2$-eq/$m^2$yr to 53 kg $CO_2$-eq/$m^2$yr) and for the hybrid island (moving from 62 kg $CO_2$-eq/$m^2$yr to 51 kg $CO_2$-eq/$m^2$yr). This is a consequence of the reduced impact of secondary steel, that in both cases is delivering an important contribution to the carbon footprint of the structures (steel is used in the floaters of the hybrid island and in the jacket and top of the platform). As expected, the benefits for the sand island are not as remarkable (moving from 41 and 42 kg $CO_2$-eq/$m^2$yr to 37 and 38 kg $CO_2$-eq/$m^2$yr for the sheltered and unsheltered island respectively) due to the fact that their largest impact comes from the fuel usage rather than the materials. A further detailed analysis on the impact of the secondary materials per structure can be seen in the appendix, figures A.5 to A.8.

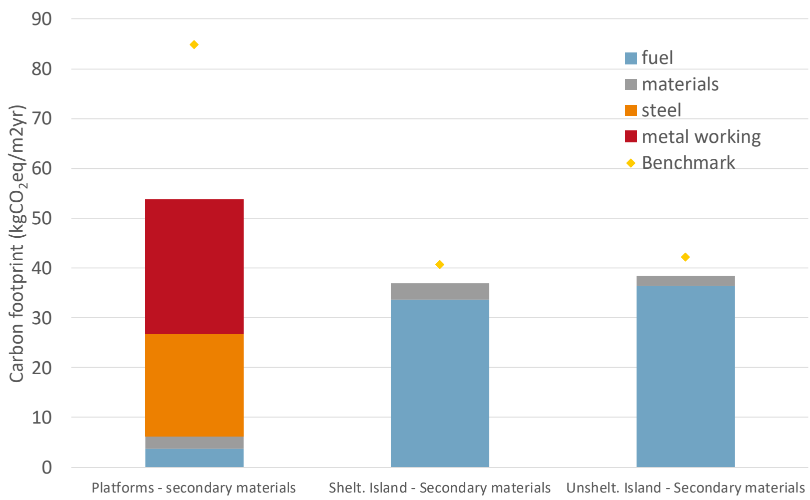


*Figure 3.8: Material contributions to carbon footprints of sand islands and platform per $m^2$ and year, when using secondary materials in steel, concrete and gravel.*

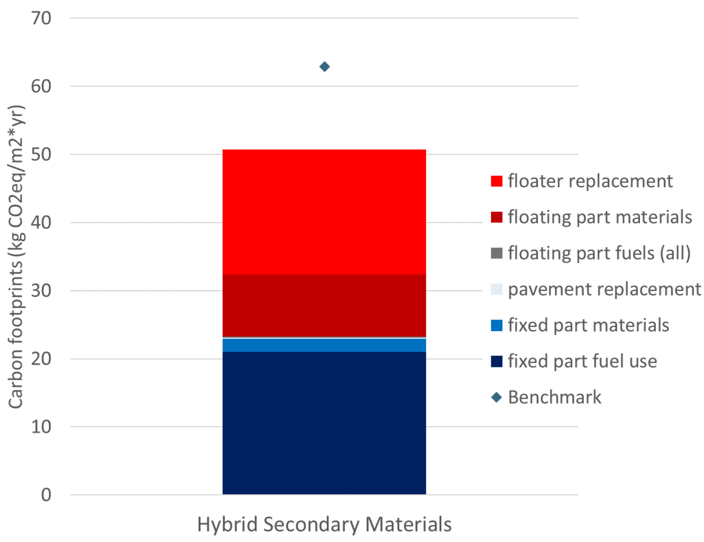


*Figure 3.9: Material contributions to carbon footprints of hybrid islands per $m^2$ and year, when using secondary materials in steel, concrete and gravel.*

### 3.2.4 Lifetime and end of life scenarios

A sensitivity analysis confirmed that the carbon footprint of platforms almost linearly decreases or increases with lifetime changes: it was 425 $kgCO_2eq/m^2yr$ for a lifetime of 10 years and 42 $kgCO_2eq/m^2yr$ for a lifetime of 100 years compared to 85 $kgCO_2eq/m^2yr$ in Figure 3.2 (50 years lifetime). The comparison for different lifetimes, (100 years, 50 years, 30 years and 10 years), is displayed in figure A.3 in appendix A.7.

Different end of life scenarios were considered for the different platforms as described in Table 2.3. The results of this analysis are reported in figures 3.10 for the "abandonment" scenario and in figures A.9-A.10 in the appendix for the other end of life options. As can be seen in the figures, all the benefits are only visible in the decommissioning life cycle stage. These are benefits that stem mostly from avoided fuel use during decommissioning and avoided preparations for steel recycling, thus they deliver an important reduction in carbon footprint for the islands (where fuel has an important contribution), but are nearly invisible for the platforms. In this sensitivity scenario, the choice of using the cut-off methodology for burden allocation (i.e. all the benefits and burdens of recycling are assigned to the second life cycle of the material) plays an important role. In the case of the platforms and hybrid islands, where a lot of steel is employed, recycling does not deliver any benefits. The benefits of recycling steel can be seen in Figure 3.8, where the use of secondary steel reduces significantly the carbon footprint of these two constructions.

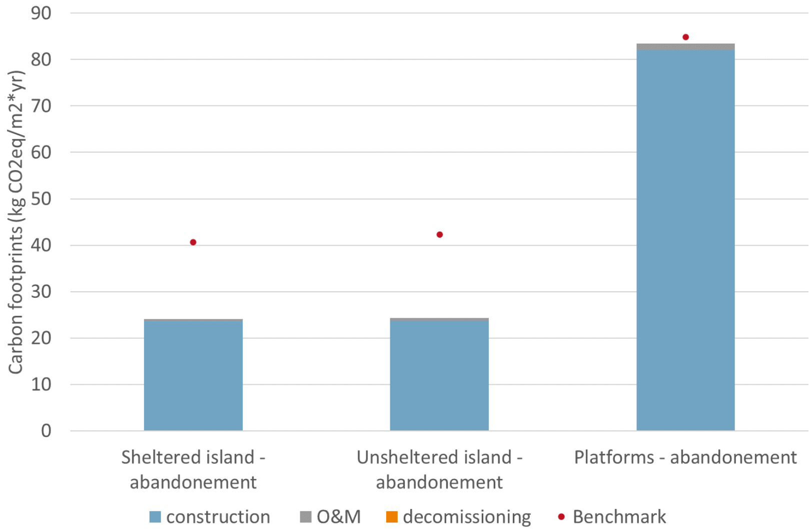


*Figure 3.10: Carbon footprint for the platforms and sand islands when choosing abandonment as EOL scenario in comparison with the benchmark.*

### 3.2.5 Production and transport of floaters

In this project it was assumed that the floaters would be produced in China and transported from the port of Shanghai. As the transport from China represents ~1% of the impact of the floater (the main contributions coming from the steel and the metal working), no sensitivity analysis has been carried out on the transport distance.

Still, another possibility would be the local production of concrete floaters. The results of a sensitivity scenario where the production of concrete floaters taking place in Rotterdam was modelled are shown Figure 3.11.

The carbon footprint of the hybrid island in this case would decrease by more than half, to ~26 kg $CO_2$-eq/$m^2$yr (where as the benchmark case was ~63 $CO_2$-eq/$m^2$yr). As it was to be expected, the reduction is to be attributed to the complete elimination of the steel in the floaters. This is the most effective strategy to reduce the carbon footprint of the hybrid island.

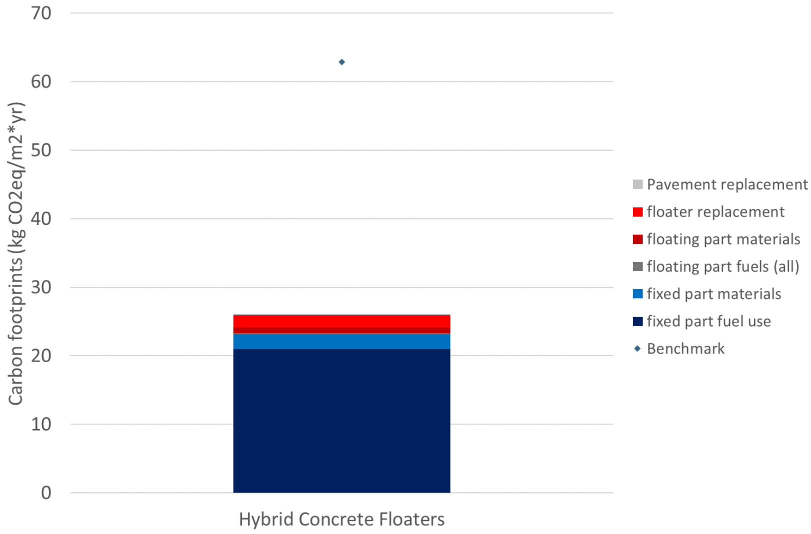


*Figure 3.11: Material contributions to carbon footprint of hybrid islands per m$^2$ and year, when using concrete floaters locally manufactured instead of steel floaters produced in China.*

## 3.3 Discussion

*Decarbonisation of steel manufacturing*

Primary steel manufacturing (i.e. steel production by Blast Furnace and Basic oxygen furnace BF-BOF) is a carbon intense process as it requires coal (for the production of coke) and a lot of energy (for the operation of the blast furnace and production of coke). The $CO_2$-eq emissions associated with BF-BOF steel amount to 2.3 tons $CO_2$-eq/ton of steel (global average) (Material Economics 2018) and a recent report of PBL reports approximately 1.85 tons $CO_2$-eq/tons steel (Hot Rolled Coil) for the Tata steel plant in IJmuiden (NL) (Keys, M. van, and Daniëls 2021). In order to achieve the international carbon reduction goals set for 2050, the steel industry has to implement important changes to the steel manufacturing process. Some alternative manufacturing processes are already being implemented at a smaller scale, showing promising results for the reduction of $CO_2$ emissions associated to primary steel manufacturing. One such alternative is the direct reduction of the iron by means of hydrogen. According to Material Economics (2018), this could reduce the carbon emissions associated with primary steel to 1.1 ton $CO_2$/ton steel (i.e. 53% reduction). Similarly others (Keys, M. van, and Daniëls 2021) report $CO_2$ emission values ranging from 0.65-0.20 ton $CO_2$/ton HRC (i.e. more than 65% reduction from the Tata steel IJmuiden baseline). Still, both reports agree that the most convenient process to reduce carbon emissions would be steel recycling: Material Economics (2018) reports $CO_2$ emissions as low as 0.4 ton $CO_2$/ton steel for Electric Arc furnace steel and ~0.20 ton $CO_2$/ton HRC. For this reason, and considering that the types of steel used in the platform can realistically contain up to 95% of recycled steel, in this project it was chosen to focus on the steel recycling scenario and exclude the decarbonisation of steel from the sensitivity analysis.

*End of life*

Different routes can be taken to model end of life and in particular recycling in LCA. Here, the cut-off approach has been chosen, as is standard in many guidelines. This implies that benefits (from preventing the use of virgin material) and burdens (from recycling processes) arising after the first life cycle are not allocated to the fist life cycle, but are cut-off at the point of lowest value. As a result, end of life decommissiong re-use of materials did not affect the carbon footprint positively or negatively. Decommissioning to shore is not beneficial in terms of carbon footprint because transport is included, but benefits from re-use of materials are not. Recycling potentials and benefits differ between the materials used in this analysis. To be able to show these differences, a sensitivity analysis has been performed where it is assumed that maximal effort is put in applying as much as possible secondary material in the construction phase. This is also more consistent with the span of control in our analysis, where it is more likely to influence purchase of material than to influence end of life treatment.

*Carbon footprint*
Recent publications (Cooper et al 2022, Derwent 2018) have underlined the fact that hydrogen is an indirect greenhouse gas and should have an associated Global Warming Potential. In this report leakages of hydrogen during production phases and use phases (slip) have not been considered. Still, it is recommended that this is explored further in future work. Likewise, hydrogen combustion might still contribute to the emissions of nitrous oxides, these have not been assessed in this study. This study focussed solely on assessing the carbon footprint of structures. However, other environmental and ecological considerations might affect the choice of a specific structure, such as the release of toxicants or nitrous oxides. Effects on biodiversity might be affected by choices of way of installation and location (see also Deliverable 4.1).

# 4 Conclusions and recommendations

Our results showed relative small differences between carbon footprint of the different types of constructions (compared to remaining uncertainties). Other considerations might be more decisive when regarding the type of construction. However, this analysis allows to identify for each construction where the focus should be when striving to reduce carbon footprints. This is based on the fact that the major contributors are steel, fuels and other materials (to a lesser extent).

Therefore our recommendations are:

- Focus for platforms is to source low carbon steel (likely via higher recycled content)
- Focus for islands is to secure low emission fuelled vessels (for installation and decommissioning).

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# Appendices

## A.1 Relation with other WP

Work package 4 consists of 2 parts: In WP 4 Ecology an Ecological assessment is conducted, which focuses on the integration of ecological layers into the existing North Sea Atlas and on an exploration of methods to determine the ecological value of existing offshore structures. This work is included in another deliverable. Thus work package part WP4 Environment focusses on the LCA.
North Sea Energy Hubs are one of the central elements in the North Sea Energy 4 project. Energy Hubs are defined throughout the project as search areas for offshore system integration opportunities. More details on the hub location and storyline selected within NSE 4 can be found in the deliverable of WP1. Although differences in the functions for each hub are expected, they are explicitly 'multi-carrier' (electrons and different molecules) and including production, conversion and/or storage. Although the LCA is not intended as a location specific analysis describing or distinguishing any of these hubs, results should be valid for any of them. As such the hub selection sets the boundaries for defining the functional unit as well as the scenarios included in the LCA. Figure 1.1 shows the parameters considered important to define the LCA methodology that depend on the hub definition. More details are given in the methodology chapter. Next to WP 1, there is also a close alignment with WP 5 on logistics: whereas WP 4 needs to learn from WP 5 the fuel type and consumption of divers vessel activity over the structure life cycle, WP4 can deliver to WP 5 factors of direct carbon dioxide and $NO_x$ emissions for fuel-vessel combinations.

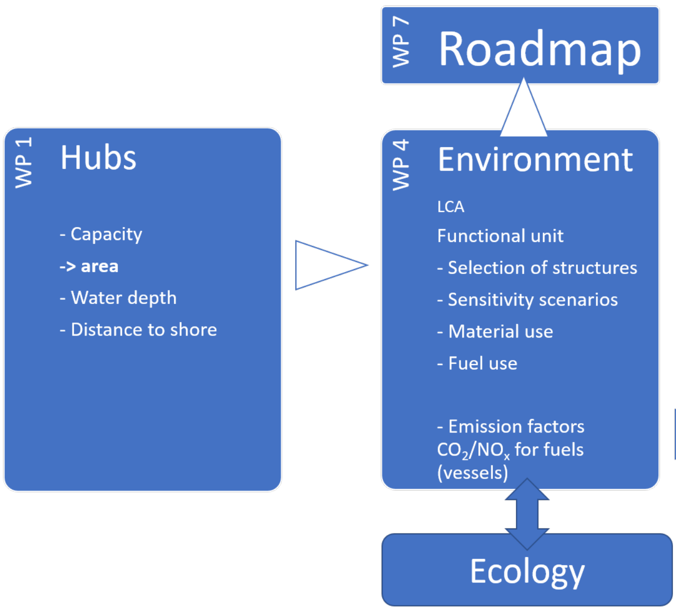


*Figure A.1 Interaction between WP 4 Environment and other work packages within the NSE 4 programme.*

## A.2 Values for parameter conversion

*Table A 1 Ancillary assumption for parameter conversion*

| Parameter | Value | Reference |
|---|---|---|
| Energy density of Diesel | 42.7 MJ/kg | Wernet et al., 2016. (ecoinvent) |
| Sand Density | 1900 kg/m$^3$ | Densities of Materials (engineeringtoolbox.com) |
| Density of Marine Diesel Oil | 0.885 kg/liter | Shell Sirius X30 technical datasheet |
| Density of concrete | 2200 kg/m$^3$ | Materiaaleigenschappen betonelementen \| Bodemrichtlijn |
| Density of Epoxy resin | 1100 kg/m$^3$ | Hexion EK8530 W- 75 resin datasheet and formulation guide + floating |
| Thickness of epoxy coating | 2mm | Educated guess |
| Gravel bulk density | 1400 kg/m3 | HybridEnergSeaHub |
| Filter layer rocks (0.3-1 ton) bulk density | 1.590 kg/m3 | 2650 kg/m3; 40% porosity |
| Upper layer - Big rocks (3t-10t) | 1458 kg/m3 | 2650 kg/m3; 45% porosity |
| Crude oil density | 1199 Mt/litre | http://www.eurocbc.org/Standard%20Conversion%20Factors%20dti_converfactors.pdf |
| Energy density of Hydrogen | 120 MJ/kg | Fuels - Higher and Lower Calorific Values (engineeringtoolbox.com) |
| Energy density of LNG | 48.6 MJ/kg | Fuels - Higher and Lower Calorific Values (engineeringtoolbox.com) |

## A.3 Activities in maintenance voyage

*Table A 2 Activity characteristics for example maintenance voyage*

| Activity | time (hours) | average distance (nm) | average fuel (litre per s or per NM (for passing)) |
|---|---|---|---|
| Loading in port | 0.98 | | 0.007 |
| Loading fresh water in port | 2.27 | | 0.001 |
| Waiting on Departure | 4.06 | | 0.047 |
| passing | | 81.00 | 49.893 |
| waiting on handling offshore | 26.48 | | 0.037 |
| DP Set up | 0.65 | | 0.094 |
| Moving In | 0.83 | | 0.093 |
| Handling offshore | 2.37 | | 0.089 |
| Moving out | 0.46 | | 0.101 |
| Waiting on handling in port | 7.85 | | 0.011 |
| Discharge in port | 1.41 | | 0.034 |
| clean | 5.89 | | 0.001 |

## A.4 Comparison of areas for island scenarios

*Table A 3 Comparison of areas for different functions for platform, complete sand island and island similar to platform, hybrid island for 2GW and for 4 GW.*

| | | platform (500MW) | 4GW - like for like island (unsheltered) | 4GW full option island (sheltered) | Hybrid island (2 GW) | Hybrid Island (4 GW) |
|---|---|---|---|---|---|---|
| Electrical | [m²] | 7.200 | 56.000 | 56.000 | | |
| Desalination | [m²] | 1.600 | 24.000 | 24.000 | 102.400 | 154.600 |
| Electrolysis | [m²] | 6.400 | 120.000 | 120.000 | | |
| cooling | [m²] | 1.800 | - | - | | |
| Control on/off | [m²] | 800 | 5.000 | 5.000 | | |
| Harbour | [m²] | | - | 40.000 | | |
| Fixed part including electric and harbour | [m²] | | | | 154.500 | 154.500 |
| Helipad | [m²] | 800 | 4.000 | 4.000 | 9.600 | 4.000 |
| Living accomodation | [m²] | 800 | 6.400 | 10.000 | 16.900 | 10.000 |
| FBW | [m²] | | | 15.000 | 48.300 | 48.300 |
| Laydown area | [m²] | | | 10.000 | | |
| Warehouse | [m²] | 800 | 6.400 | 30.000 | | |
| Coastguard | | | | | 5.500 | 5.500 |
| 10% roads | [m²] | | 16.580 | 25.800 | | |
| Aquaculture | | | | | 19.100 | 0 |
| Data center | | | | | 11.400 | 0 |
| Visitor center | | | | | 9.200 | 0 |
| | | | | | | |
| Total plot dimension | | 80 x 40 m | 500 x 480 m | 600 x 575 m | | |
| Total floater area | | | | | 222.400 | 222.400 |
| **Total area** | [m²] | 20.200 | **238.380** | **339.800** | 376.900 | 376.900 |
| | [ha] | **2** | **24** | **34** | **38** [A] | **38** |

A: this is the covered area, including water between the floaters, In Table X the effective area is given, because this is included in the carbon footprint calculations

## A.5 Ecoinvent processes

For simplicity, concrete blocks have been modelled based on the available ecoinvent process for concrete blocks using the major type of concrete available in there. This process is built upon the "Concrete, normal, {RoW} market for" process, including extra transport machinery and electricity use. The "Concrete, normal, {RoW} market for" is a mix of 6 different generic concretes for the market, with normal strength ranging from 20 to 35 MPa. In turn, each of these 6 concretes are mixes of different concrete types. This process is constructed in this way to represent an "average", generic type of concrete. Unfortunately, such complex process construction makes it impossible to perform a sensitivity analysis on the use of secondary material in concrete. To overcome this issue, the process "Concrete block {DE}| market for concrete block | Cut-off, U" was modified substituting the "Concrete, normal, {RoW} market for" with the process "Concrete, 25-30MPa {RoW}| market for concrete, 25-30MPa | Cut-off, U". This type of concrete was chosen out of the 6 as it corresponds to the largest share of the mix. Furthermore, this process card contains directly all the basic "ingredients" of a generic concrete (Portland cement, gravel and sand). In this way, it will be easier to introduce secondary materials in the concrete. The modified process is called "NSE_basic_concrete block_for market".

Ship operations have been modelled using the ecoinvent process "Diesel, burned in fishing vessel {GLO}| diesel, burned in fishing vessel | Cut-off, U". This choice is determined by the limited availability of ship operation process cards the ecoinvent database. Still, this is a reasonable proxy as for this project only the carbon emissions of the ship transport are of interest and not other types of emissions. Carbon emissions from ship transport and operations are determined by the type of fuel used and the amount of fuel consumed, the type of engine used or the intensity at which the engine is used has little impact on the $CO_2$ emissions.
The $CO_2$ emissions per kg of different marine fuels and different ship types are listed in Table A4. The LHV of the diesel assumed in the ecoinvent process card is 42.8 MJ/kg. The diesel density used in the calculations is 0,885 kg/l, based on the material safety datasheets of Shell marine fuels.

*Table A 4 $CO_2$ emissions per kg diesel in different databases.*

| Emission factor | Referecnce | Comments |
|---|---|---|
| 3.75 kg$CO_2$/kg Diesel | NMD process card "Scheepsbrandstoffen, Marine Diesel Oil, c2" | 3.75 kg $CO_2$-eq emissions to air listed in the process card per 1 kg of MDO |
| 3.65 kg$CO_2$/kg Diesel | Ecoinvent process card "Diesel, burned in fishing vessel {GLO}\| diesel, burned in fishing vessel \| Cut-off, U". Wernet et al., 2016. | $CO_2$ emissions calculated with IPCC GWP 100a method. Heating value obtained using fuel input in kg per MJ. |
| 3.83 kg$CO_2$/kg Diesel | NMD process card "Scheepsbrandstoffen, Heavy Fuel Oil, c2" | 3.83 kg $CO_2$-eq emissions to air listed in the process card per 1 kg of HFO. (HFO is used in the ecoinvent process cards for transport via container ships. For the operations considered in this project Diesel was preferred) |

# A.6 Hydrogen use as fuel

*Table A 5 Fuel and Hydrogen use for Sheltered and Unsheltered sand islands*

| Material | Unit | Quantity | | Database process |
|---|---|---|---|---|
| **Fuel use for transport and installation** | liters | 66,500,000 | 87,500,000 | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U |
| **Hydrogen use for transport and installation** | ton | 20942 | 27555 | Hydrogen fuel ready to use in a ship |
| **Fuel use for maintenance** | liters | 2,142,226 | 2,142,226 | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U |
| **Hydrogen use for maintenance** | ton | 675 | 675 | Hydrogen fuel ready to use in a ship |
| **Fuel use for decommission in default scenario** | liters | 66,500,000 | 87,500,000 | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U |
| **Hydrogen use for decommission in default scenario** | ton | 20942 | 27555 | Hydrogen fuel ready to use in a ship |

*Table A 6 Fuel and Hydrogen used for Platform construction*

| Material | unit | Quantity | comment | Database process |
|---|---|---|---|---|
| **Topside** | | | | |
| Fuel use | litres | 43447 | One day of Thialf (48.4tonnes)+ one day of Aegir (28.5tonnes) | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U |
| Hydrogen use for Topside installation | ton | 13.7 | | Hydrogen fuel ready to use in a ship |
| **Jacket** | | | | |
| Fuel use for installation | litres | 43447 | One day of Thialf (48.4tonnes)+ one day of Aegir (28.5tonnes) | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U |
| Hydrogen use for Jacket installation | ton | 13.7 | | Hydrogen fuel ready to use in a ship |
| **Energy** | | | | |
| Fuel use for maintenance | tonne | 1071113 | As in the case of the sand islands, this is modelled based on the data delivered by the project partner Peterson. | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U |
| Hydrogen use for maintenance | ton | 337.3 | | Hydrogen fuel ready to use in a ship |
| Energy use for EoL (ships) in default scenario | litre | 86893 | Two days of work on the Thialf and the aegir | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U |
| Hydrogen use for EoL (ships) in default scenario | ton | 27.4 | | Hydrogen fuel ready to use in a ship |

*Table A 7 Fuel and Hydrogen use for hybrid island*

| Material | unit | Quantity | comment | Database process |
|---|---|---|---|---|
| **Fixed part** | | | | |
| Fuel use for building | litres | 59673694 | | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U[6] |
| Hydrogen use for building | ton | 18792 | | Hydrogen fuel ready to use in a ship |
| Fuel use for decommissioning | litres | 59673694 | | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U[3] |
| Hydrogen use for decommissioning | ton | 18792 | | Hydrogen fuel ready to use in a ship |
| Fuel use for Pavement replacement | litres | 630 | | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U[3] |
| Hydrogen use for Pavement replacement | ton | 0.2 | | Hydrogen fuel ready to use in a ship |
| **Large floater** | | | of which 11 + 22 | |
| fuel use for transport of floaters (installation) | litres | 15140 | 2 days for installation, decommissioning each, 15.140 litres per day; | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U[3] |
| hydrogen use for transport of floaters (installation) | ton | 4.8 | | Hydrogen fuel ready to use in a ship |
| fuel use for transport of floaters ( replacement ) | litres | 30.280 | Two replacements in the lifetime, (2 days of work each time). | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U[3] |
| hydrogen use for transport of floaters ( replacement ) | ton | 9.6 | | Hydrogen fuel ready to use in a ship |
| fuel use for transport of floaters (decommissioning) | litres | 15140 | | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U[3] |
| hydrogen use for transport of floaters (decommissioning) | ton | 4.8 | | Hydrogen fuel ready to use in a ship |

[6] See Appendix A.5

| | | | | |
|---|---|---|---|---|
| Transport floaters from China[D] | ktkm | 265732 | Calculated multiplying the average distance by sea between Port of Rotterdam and port of Shanghai (22224 km) by the total weight of 1 floater. | Transport, freight, sea, container ship {GLO}\| transport, freight, sea, container ship \| Cut-off, U |
| **Small floater** | | | of which 4 + 8 | |
| fuel use for transport of floaters (installation) | litres | 15140 | 2 days for installation, 1 replacement, decomissioning each, 3 replacements over lifetime, 15.140 liters per day; total days of tug: 10 | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U[3] |
| hydrogen use for transport of floaters (installation) | ton | 4.8 | | Hydrogen fuel ready to use in a ship |
| fuel use for transport of floaters ( replacement ) | litres | 30.280 | | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U[3] |
| hydrogen use for transport of floaters ( replacement ) | ton | 9.6 | | Hydrogen fuel ready to use in a ship |
| fuel use for transport of floaters (decommissioning) | litres | 15140 | | Diesel, burned in fishing vessel {GLO}\| market for diesel, burned in fishing vessel \| Cut-off, U[3] |
| hydrogen use for transport of floaters (decommissioning) | ton | 4.8 | | Hydrogen fuel ready to use in a ship |
| Transport floaters from China[B] | ktkm | 177236 | Calculated multiplying the average distance by sea between Port of Rotterdam and port of Shanghai (22224 km) by the total weight of 1 floater. | Transport, freight, sea, container ship {GLO}\| transport, freight, sea, container ship \| Cut-off, U |

# A.7 Additional results

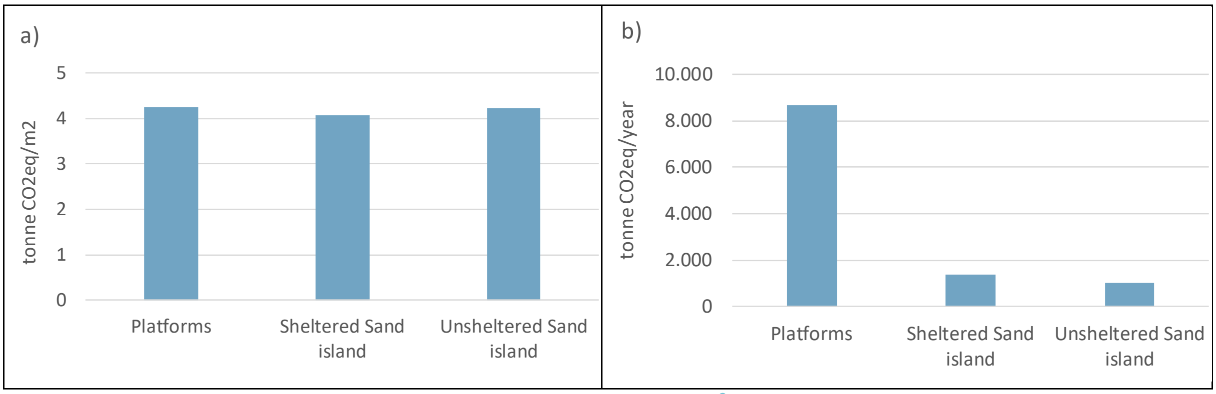


*Figure A 2. Carbon footprint comparison in tonne $CO_2$ equivalent a) per $m^2$ for the whole lifetime of each structure; b) per year for each complete structure.*

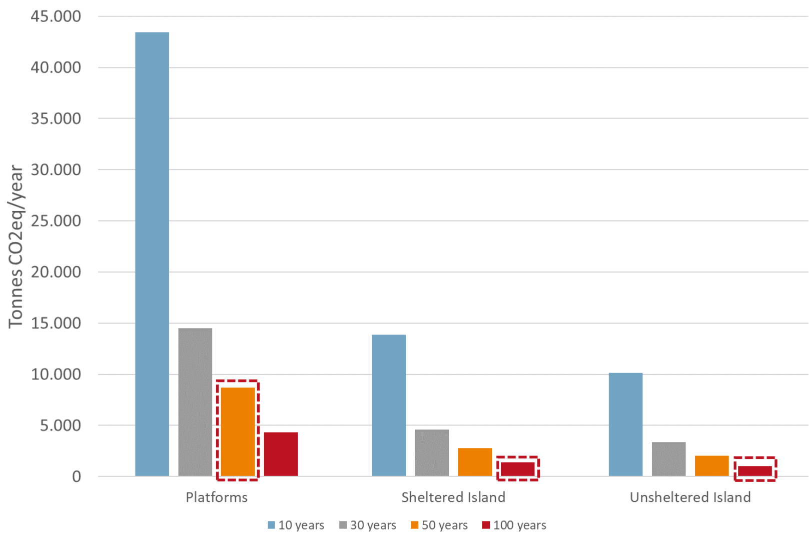


*Figure A.3: Carbon footprint comparison in tonne $CO_2$ equivalent per year for each complete structure, for different lifetimes. The red dashed boxes show the values for the benchmark lifetime.*

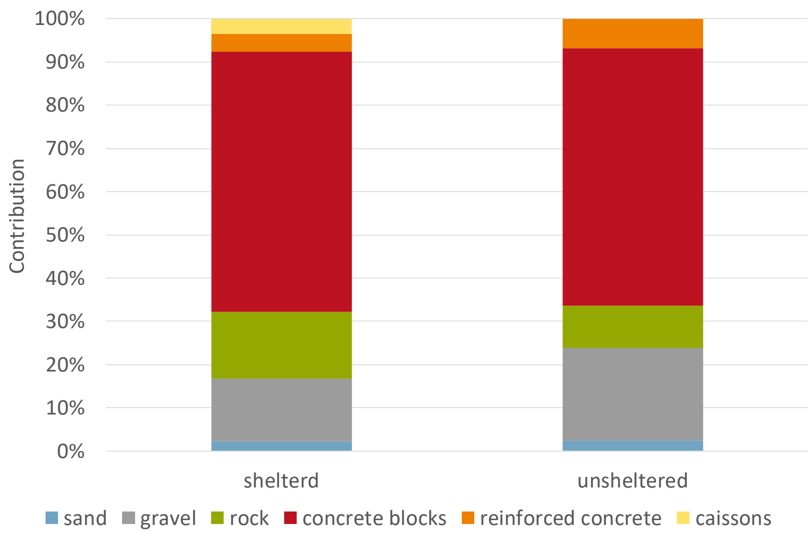


*Figure A4. Contribution of different materials to carbon footprint of sand island construction.*

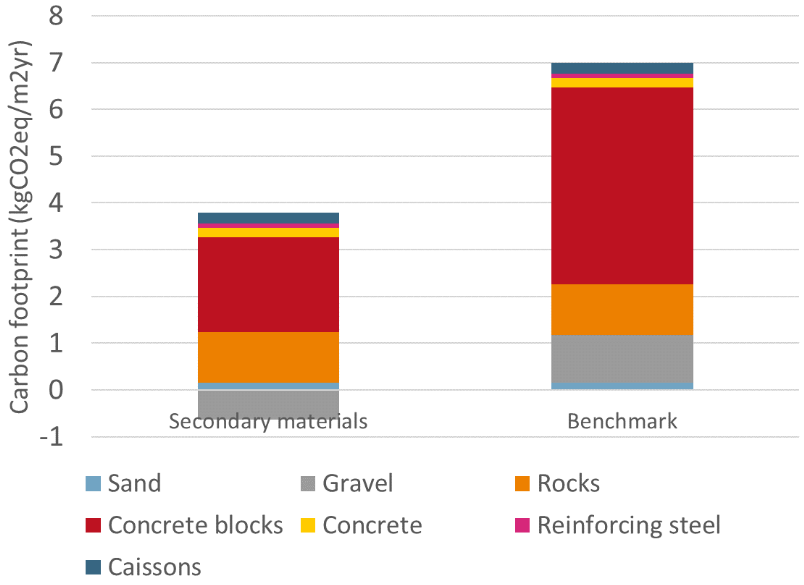


*Figure A.5: Contribution of the secondary materials to the carbon footprint of the sheltered sand island in the benchmark and recycled materials scenario. Note, in this figure only the material contribution is shown, leaving out fuel use and other processes*

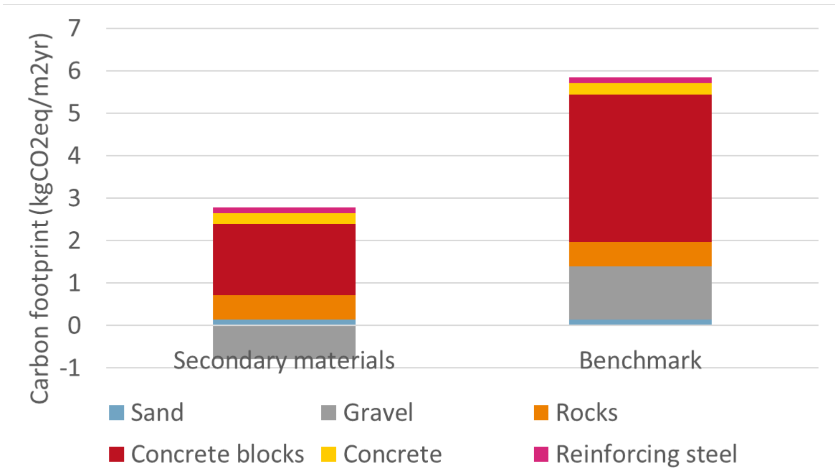


*Figure A.6: Contribution of the secondary materials to the carbon footprint of the unsheltered sand island in the benchmark and recycled materials scenario. Note, in this figure only the material contribution is shown, leaving out fuel use and other processes*

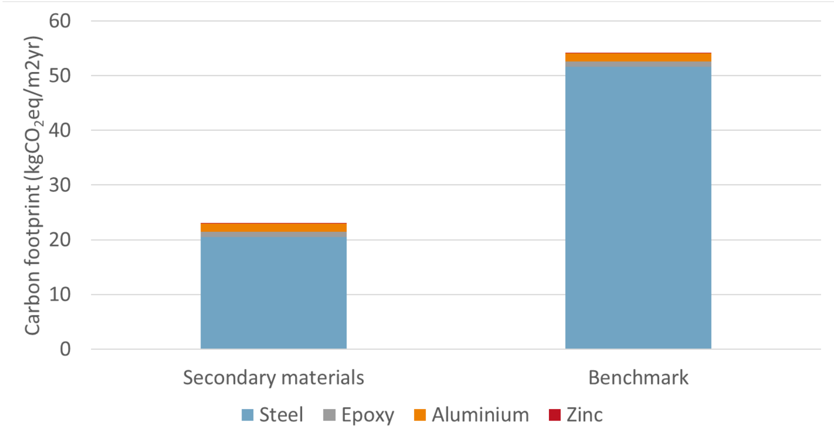


*Figure A.7: Contribution of the secondary materials to the carbon footprint of the Platforms (topside and jacket) in the benchmark and recycled materials scenario. Note, in this figure only the material contribution is shown, leaving out fuel use and other processes*

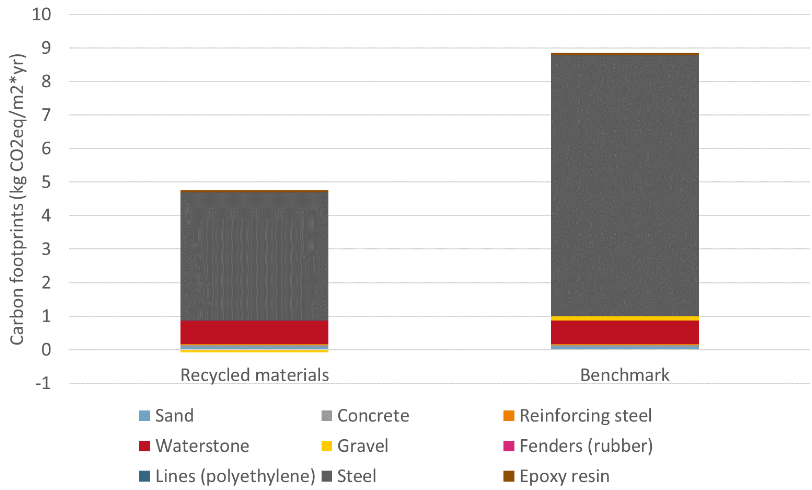


*Figure A.8: Contribution of the secondary materials to the carbon footprint of the hybrid island in the benchmark and recycled materials scenario. Note, in this figure only the material contribution is shown, leaving out fuel use and other processes.*

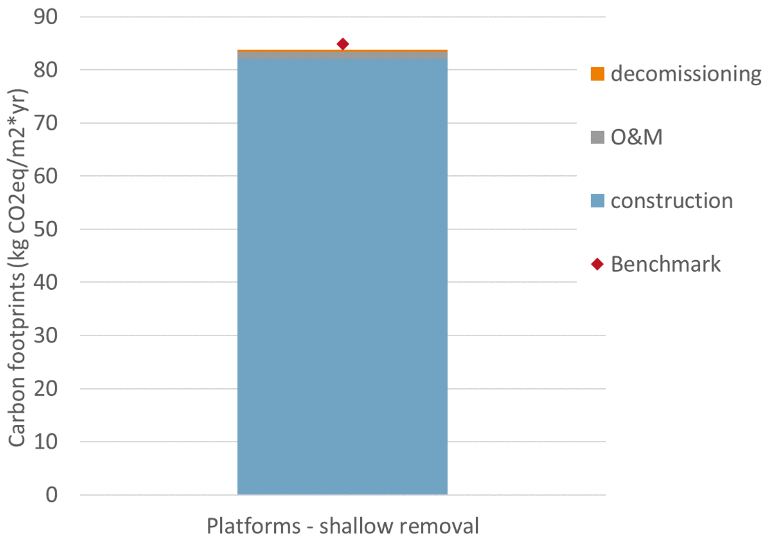


*Figure A.9: Carbon footprint for the platforms when considering shallow removal as EOL scenario, in comparison with the benchmark.*

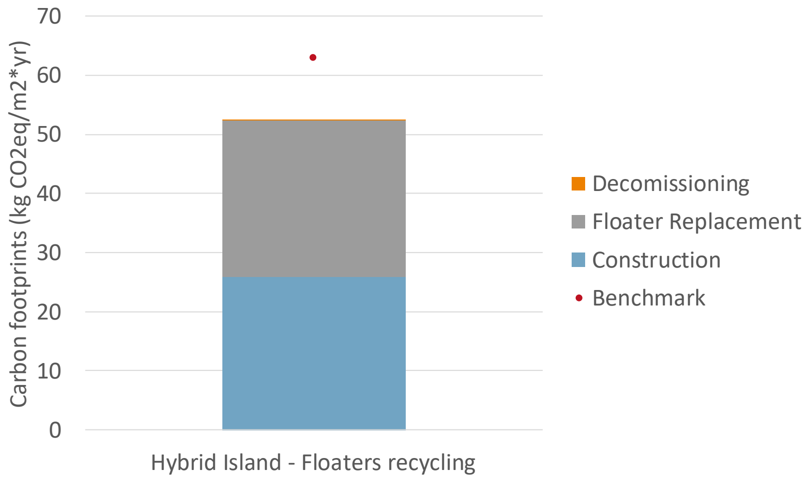


*Figure A.10: Carbon footprint for the hybrid island when considering different EOL scenario's, in comparison with the benchmark.*

In collaboration and appreciation to

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Royal HaskoningDHV
NEN
Energieke Communicatie
MSG
TKI Nieuw Gas
Total Energies
Shell
NAM
EBN
Gasterra
Gasunie
ONE-Dyas
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