Modular Offshore Grid 2 (MOG2)

Life Cycle Analysis (LCA)

Elia Asset NV

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Colophon

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Executive Summary

This Life Cycle Analysis (LCA) study is performed to support the Environmental Impact Report of the Modular Offshore Grid 2 (MOG2) project from Elia. This study covers for the full duration of the requested environmental permit (20 years) for all project phases of the MOG2 project (construction phase, production phase, operation phase, and decommissioning phase). Two time periods are investigated in the LCA: 20 year (permit duration), and 50 year (long term).

The following offshore structures are considered for this LCA, island (caisson and revetement alternative), platform alternative (set of three AC platforms (either with jacket or monopile foundation), and one HVDC platform with jacket foundation), and the associated export cables for each structure to the landfall zone Blankenberge-Zeebrugge (worst case for cable length). For caisson island, consideration is given to manufacturing and transportation of the caissons from Belgium or from Spain. Two cable installation techniques are also considered, cable scenario 1 (pre-trenching, backfilling, and pre-sweeping) and cable scenario 2 (ploughing and pre-sweeping).

Four pollutants are investigated: emissions during material production (CO_2), transport emissions (CO_2, NO_x, PM10 and SO_2), and emissions from seafloor disturbance (CO_2). Overall for all emissions, the highest total emissions are for the revetment island alternative, followed by caisson island and least for platform alternative (all including the export cables).

For the total CO2 balance, the highest part of emissions is the result of material production. The highest production values are for the revetement island, this is due to the large quantity of granite needed and the high CO_2 emissions from the production of granite. Following the revetement island, the caisson islands have high production emissions, this is again due to the granite emissions during production. Finally, the least emissions are from the platforms due to the limited loads and therefore ship time needed (scenario with AC monopiles results in less emissions compared to the scenario with AC platforms due to the difference in steel volume).

During construction, three main factors explain the main emission differences between all alternative scenario's. The highest emissions during the construction phase per structure are for the revetment island, this is due to the emissions from the installation of the wide grade, quarry run, armour rock and scour protection. For the caisson island, the emissions related to the scenario with caissons transported from Spain are higher due to the greater transportation distance (compared to caissons from Belgium). Cable scenario 1 (pre-trenching, backfilling, and pre-sweeping) has higher CO_2 emissions for all structures and locations compared to cable scenario 2 (ploughing and pre-sweeping).

Since the island is designed for a life duration of at least 50 – 100 years, also the long term of 50 years is evaluated. Due to their lifetime limitation the platforms and cables are expected to be decommissioned twice and constructed twice in the long-term period of 50 years. Overall, the same conclusions as 20 years hold for the 50 years scenario. With the platforms rebuild within the 50 year time span, the total emissions of the caisson island or platforms alternative become similar although the emissions of the caisson island remain the highest.

Transportation also results in additional emissions of NO_x, SO_2 and PM10. The differences between scenario's depend on transport distance (eg caissons from Belgium versus Spain), and dredging activities (eg cable installation with dredging and backfill, versus ploughing). The platform alternative requires less transport and dredging activities compared with the caisson island (about 50% less total emissions).

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1 Introduction

1.1 The assignment

Life Cycle Analysis (LCA) is a methodology that allows the calculation, evaluation, and interpretation of the generated emissions during the lifetime of an infrastructure, thereby showing the emissions produced during all the project phases (Figure 1-1). The LCA quantifies the emissions generated, produced directly and/or indirectly by an activity, or by the set of activities during the life cycle of a product and can be adaptable it to any project. The main gases that are assessed are PM10, SO_2, NO_x and CO_2.

Figure 1-1: LCA model .

1.2 MOG2 project

The MOG2 project covers the energy-island and export cables. In this LCA study, following alternatives and variations are analyzed:

- **Energy-island:**
  - **Caisson island** (Figure 1-2), at three alternative locations. The caisson island with the caisson ring and filling are assumed identical for each alternative location but because of the water depth differences at each alternative location the basis below the caissons differs. This is shown in Figure 1-2. At the deepest location West 1, the caissons will but placed on the gravel bed, while at the deeper locations West 2 and North a sand plateau is needed below. Consequently, there are differences in the construction of the caisson island at the three alternative locations. This is reflected in the LCA analysis (differences in material for the sand plateau and erosion protection layer). A crew transfer vessel (CTV) harbor is also foreseen in the island design with two breakwaters.
  - **Revetment island**, at location West 1. In this LCA study, the caisson island type is compared with the revetment island type.

- **Platform alternative**: A set of 4 platforms is analyzed as alternative for the energy-island. This alternative consists of three AC platforms (either with monopile foundation, or jacket foundation), and one HVDC platform (only feasible with jacket foundation).

- **Export cables:**
  - The energy-island is connected to land with 6 AC cables and 1 HVDC cable set. The HVDC cable set consist of 2 cables and one metallic return. The HVDC cable set can be installed in different configurations, in one or two tranches. In the analysis two trenches are considered as worst case (more installation works required).
  - Cable installation: two scenarios with full cable lengths pre-trenched (worst case for dredging volumes), or pre-ploughing.
  - For the export cables to island location option North, two route variations are analyzed. Route option 1 mostly through the Natura2000 zone and route option 2 mostly outside Natura2000 zone (Figure 1-3).
  - For the export cable route to land four alternative routes are considered to four alternative landfall zones. In the analysis the worst-case route (= longest route) to the landfall zone Blankenberge-Zeebrugge is analyzed.

Time horizon of the LCA for MOG2

The LCA study is performed for the full duration of the requested environmental permit (20 years). Because the island is intended to last for much longer (50-100 years), this LCA also provides an analysis of total emissions after 50 years. The expected lifespan of the platforms and cables are shorter than 50 years and hence it is assumed that they are decommissioned and rebuild again during the 50-year scenario.

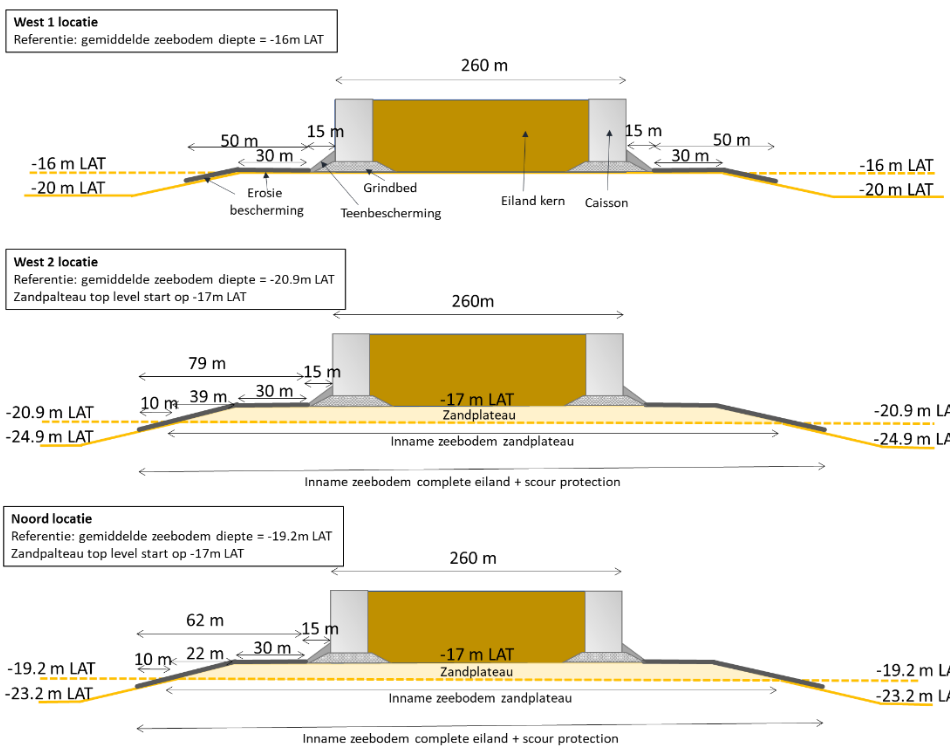

Figure 1-2: Caisson island physical dimensions for the different locations.

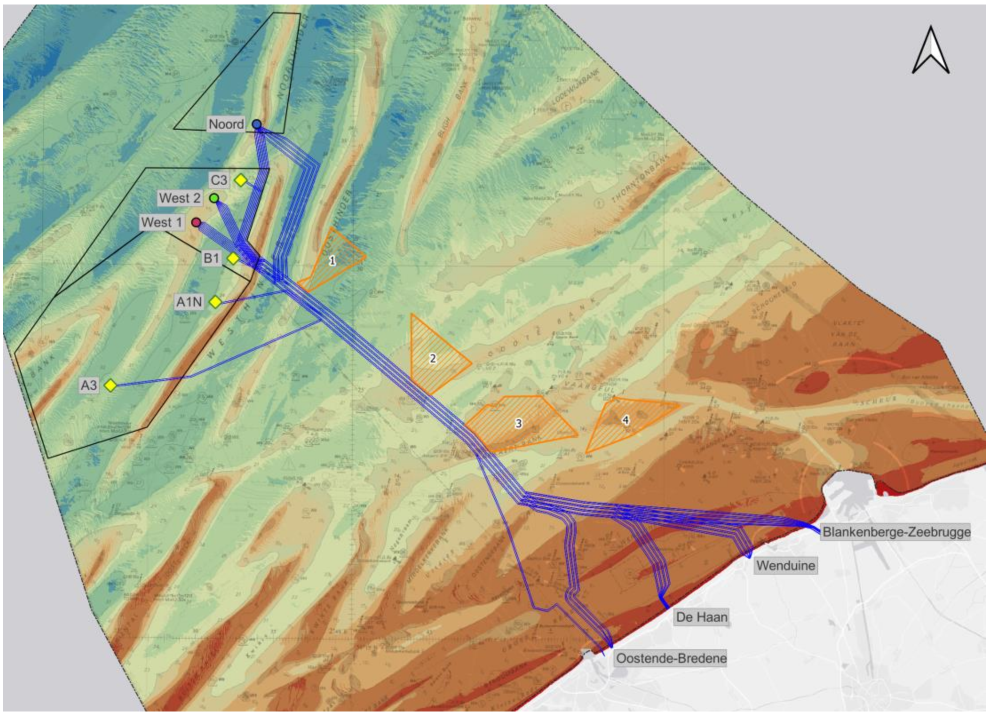

Figure 1-3: Map indicating the locations of the islands; Red dot: island location West 1 and alternative locations West 2 (green dot) and North (Noord; blue dot), platform alternative consisting of a set of four platforms (yellow diamonds), and export cables (to four alternative landfall zones: Blankenberge-Zeebrugge, Wenduine, De Haan, Oostende-Bredene).

1.3 Approach

The following offshore structures are considered for this LCA, islands (caisson and revetment alternative), platform alternative (three AC platforms (either with jacket or monopile foundation), and one HVDC platform with jacket foundation), and the associated export cables for each structure to the landfall zone Blankenberge-Zeebrugge. Only the foundation parts are considered (island, platforms). The transmission-infrastructure on top is not included in LCA calculations as this is assumed to be the same for both the island and platform alternative, and the focus of the study is to compare all alternatives. For the export cables, two installation techniques are analyzed: with pre-trenching or with pre-ploughing.

In the LCA a distinction is made between four phases:

- The production phase: extraction of raw materials (e.g., granite rocks and quartzite), artificial elements (interlocking concrete elements), production of materials (e.g., concrete, steel), production of offshore shore cables.
- The construction phase: the construction and installation (including transport of materials) of the island (caisson or revetment type), platforms, and export cables. The emissions and energy consumption associated with the transport of the components of the islands, platforms, and cables from the place of production to the destination fall under the construction phase. Once on site, the islands, platforms, and cables must be assembled, this happens during the construction phase. Here the type of foundation is important: with gravitational foundations, dredging works are first carried out, while with a jacket foundation pile must be inserted. Assembling the structures on site is also part of this phase.

- The operation phase: the use and maintenance of the island/platforms/cables over a period of 20 years and 50 years. The operation of the islands, platforms and associated cables during the operational phase includes repair work, control, and maintenance.
- The decommissioning phase: the dismantling of the island/platforms/cables. For the dismantling of the structures, cranes are again needed. The dismantled parts of a structures are brought back ashore where they can be recycled. Two scenarios are considered full demolishing and recycling of the construction materials after its lifetime; or no decommissioning (but minimal inspections).

In this report the air quality affected by the production and construction of the artificial islands (caisson and revetment), four platforms, the cable lying works and the related activity in different phases is evaluated.

In the production phase, the material produced are considered (e.g., rock, sand, concrete, steel, concrete elements like accropodes, and cable). Rock will be mined (e.g., explosion), produced (e.g., sieving) and prepared (e.g., packed) in a quarry. After that, they can be transported to the construction site or will be stored at a temporary stock yard near the project site. In other words, the air quality affected by the process to have rock material available at the project site should be calculated in the following two phases: the production phase and the construction phase (including transportation).

In contrary to rock, some materials are applied in their existing form (e.g., sand from marine extraction zone). For this type of material only the transportation and the construction phase are considered. The activities related to the application of sand material for the island construction are dredging and dumping. In other words, the air quality affected by the process to have sand available for the construction of the island should be calculated only in construction phase (including transportation).

1.4 Scope of the report

This report provides an overview of the emissions (PM10, SO_2, NO_x and CO_2) during the different phases (construction, operation, and decommissioning) of the life of the artificial structures (caisson island, revetment island, platforms) and the accompanying export cables (AC and DC). Note that only CO_2 is analyzed for the production phase.

1.5 Reading guidance

Chapter 2 details the gas emissions to produce all materials used for the islands (caisson and revetement), the materials for the cables and the platforms. Chapter 3 evaluates the air quality affected by the construction phase. The construction phase includes the construction of the artificial islands (caisson and revetement), the cable lying works and the platforms. For different activities the relevant transportations are also considered (to transport the material to the project location, dredge sand, and installing everything at the project location). Chapter 4 details the maintenance work during the lifetime of the project and chapter 5 assesses the gas emissions due to the demolishing of the construction materials of the islands with cables (caisson and revetment) and platforms with cables after their lifetime (20 years) is evaluated. Chapter 6 gives the overall conclusions of emissions during the 20 years and 50 years period.

2 The Production Phase

2.1 Islands

2.1.1 Caisson

Three material types are produced for the caisson island: concrete, granite rocks, and quartzite.

2.1.1.1 Production of Concrete

The caisson island requires concrete in four specific areas. Concrete will be required to build the caissons themselves, the seawall, the top slab and second wall and concrete is required for the interlocking elements in the breakwater (CTV). The concrete used for the different areas is different, for the caissons, seawall and second wall steel reinforced concrete is required but for the interlocking elements high strength concrete (40-50 MPa compressive strength) is needed. Steel reinforced concrete is reinforced with 100 kg of rebar per m^3 of concrete, assuming world average steel rebar values (Hammond and Jones, 2019). The value of emissions per kg for the high strength concrete, was taken as CEM 1 concrete (contains 100% mixed cement), with a strength of 40/50 MPa with 420 kg cementitious content per m^3 concrete assumed (Hammond and Jones, 2019). For producing of 1 kg of steel reinforced concrete 0.249 kg CO_2 is emitted, whilst for high strength concrete 0.172 kg CO_2 is emitted (Hammond and Jones, 2019). Therefore, the CO_2 emission to produce concrete to construct the caissons and interlocking elements would be **0.16 Mt CO_2**.

Table 2-1: Showing the different concrete volumes and the CO_2 equivalent emissions emitted.

Island Section	Part	Losses (%)	Volume (m^3)	Volume (kg)*	CO2 emissions 1 kg of concrete (kg/kg)	Total CO2 emissions (kg)
Structure	Caissons	15	155 000	403 904 813	0.249	97 259 400
Structure	Seawall	15	28 000	79 912 350	0.249	19 242 720
Structure	Top slab and second wall	15	50 000	142 700 625	0.249	34 362 000
Breakwater	Interlocking elements	15	18 000	49 680 000	0.172	8 544 960
TOTAL concrete			**251 000**	**676 197 788**		**159 409 080**

* The conversion of m^3 concrete to kg is 2400 (Anupoju, 2016). The volume in kg also includes the estimated losses (15%)

2.1.1.2 Production of Granite rocks

Rock will be used as the base protective material, for protection against scour. It is assumed that the rock materials are brought from Norway. To be conservative it is assumed that the rock type is granite (as can be found in several quarries in Norway). The CO_2 emissions during the production of the blocks from granite, in comparison to other types of rock (e.g. limestone and sandstone), are the highest rate (Hammond and Jones, 2019).

The broken rock (breuksteen) will be used in several places in the structure: filter bed, filter protection, filter rear side, toe protection (structure and breakwater) and scour protection (two different sizes). The different locations of the caissons require different volumes of broken rock (Table 2-2).

For the three alternative locations the required volume ranges between 452 Mm^3 and 592 Mm^3. The difference is due to the different depth of the three location options that require a different sand plateau and hence different surface of scour protection.

For producing of 1 kg broken rock from granite 0.7 kg CO_2 is emitted (Hammond and Jones, 2019), the CO_2 emission for **West 1 is 0.98 Mt CO_2,** for **West 2 1.29 Mt CO_2,** and for **North 1 is 1.16 Mt CO_2.** The difference between the three location options is due to the different required scour protection surface because they are located in different water depths (Figure 1-2).

Table 2-2: Showing the different granite volumes and the CO_2 equivalent emissions emitted for the different island sections

Island Section	Part	Location	Losses (%)	Volume (m^3)	Volume (kg)*	CO_2 emissions 1 kg of granite (kg/kg)	Total CO_2 emissions (kg)
Structure	Filter bed (1-150 kg)	NA	15	175 000	543 375 000	0.7	380 362 500
Structure	Filter protection (60-300 kg)	NA	15	27 000	83 835 000	0.7	58 684 500
Structure	Filter-rear side (gravel)	NA	15	5 500	17 077 500	0.7	11 954 250
Structure	Toe protection (3-6 tonnes)	NA	15	55 000	17 077 5000	0.7	119 542 500
Breakwater	Toe protection (1-5 tonnes)	NA	15	60 000	186 300 000	0.7	130 410 000
Structure	Scour protection (60-1000 kg)	West 1	15	75 000	232 875 000	0.7	163 012 500
		West 2	15	160 000	496 800 000	0.7	347 760 000
		North	15	125 000	388 125 000	0.7	271 687 500
Structure	Scour protection (45-180 mm)	West 1	15	55 000	170 775 000	0.7	119 542 500
		West 2	15	110 000	341 550 000	0.7	239 085 000
		North	15	85 000	263 925 000	0.7	184 747 500
TOTAL granite rock		**West 1**		**452 500**	**1 405 012 500**		**983 508 750**
		West 2		**592 500**	**1 839 712 500**		**1 287 798 750**
		North		**532 500**	**1 653 412 500**		**1 157 388 750**

*The conversion of m^3 rock to kg is 2700 (Anupoju, 2016). The volume in kg in the table also includes the estimated losses (15%).

2.1.1.3 Production of Quartzite

Two different sizes of quartzite will be used in the core of the CTV breakwater. For producing of 1 kg gravel from quartzite we assume the same emission as for sandstone: 0.06 kg CO_2 (Hammond and Jones, 2019). The CO_2 emission to produce the required **0.5 million ton** of quartzite rock would be **0.03 Mt CO_2.**

Table 2-3: Showing the different quartzite volumes and the CO_2 equivalent emissions emitted.

Island Section	Part	Location	Losses (%)	Volume (m^3)	Volume (kg)*	CO_2 emissions 1 kg of granite (kg/kg)	Total CO_2 emissions (kg)
CTV Breakwater	Core (0-200 mm)	NA	15	102 500	306 475 000	0.06	18 388 500
	Core (0-1000 kg)	NA	15	90 000	269 100 000	0.06	16 146 000
TOTAL quartzite				**192 500**	**575 575 000**		**34 534 500**

* The conversion of m^3 Quartzite to kg is 2600 (Anupoju, 2016). The volume in kg also includes the estimated losses (15%)

2.1.2 Revetment

Two material types are produced for the revetment island: granite rock and concrete.

2.1.2.1 Production of granite Rock

To be conservative it is assumed that the rock type is granite (as can be found in several quarries in Norway).

Rock will be used for different purposes and in different sizes, e.g., as filter material between the armor layer and the fine core of the sea defense (two different sizes), for the armor rock, the scour protection and covering the plateau (Table 2-4). It is assumed that the rock materials are brought from Norway. A volume of **1 995 000 m^3** broken rock is needed which is equal to **6 million ton** (conversion factor 2700 and including 15% losses).

For producing of 1 kg broken rock from granite 0.7 kg CO_2 is emitted (Hammond and Jones, 2019). Therefore, the CO_2 emission to produce **6 million ton** of broken granite rock would be **4.34 Mt CO_2**. Mentioned amount of CO_2 emission is applied to produce the needed broken rock material for construction works.

Table 2-4: Showing the different broken rock volumes and the CO_2 equivalent emissions emitted.

Island Section	Part	Losses (%)	Volume (m³)	Volume (kg)*	CO_2 emissions 1 kg of rock (kg/kg)	Total CO_2 emissions (kg)
Structure	Filter material (0~200mm)	15	1 300 000	4 036 500 000	0.7	2 825 550 000
Structure	Filter material (1-1000kg)	15	30 0000	931 500 000	0.7	652 050 000
Structure	Armor Rock (1-3t & 3-6t)	15	190 000	58 9950 000	0.7	412 965 000
Structure	Scour protection (60-300 kg)	15	80 000	248 400 000	0.7	173 880 000
Plateau	Cover layer (1m thick) gravel	15	125 000	38 8125 000	0.7	271 687 500
TOTAL granite			1 995 000	6 194 475 000		4 336 132 500

*The conversion of m³ rock to kg is 2700 (Anupoju, 2016). The volume in kg in the table also includes the estimated losses (15%).

2.1.2.2 Production of concrete

The revetment island requires concrete in two specific areas. Concrete will be required for the seawall and the second wall, as well as for the interlocking elements in the breakwater (CTV). The concrete used for the different areas is different, for the seawall steel reinforced concrete is required but for the interlocking elements high strength concrete (40-50 MPa compressive strength) is needed. For producing of 1 kg of reinforced concrete 0.249 kg CO_2 is emitted, whilst for high strength concrete 0.172 kg CO_2 is emitted (Hammond and Jones, 2019). Therefore, the CO_2 emission to produce concrete to construct the seawall and interlocking elements would be **0.064 Mt CO_2**.

Table 2-5: Showing the different concrete volumes and the CO_2 equivalent emissions emitted.

Island Section	Part	Losses (%)	Volume (m³)	Volume (kg)*	CO_2 emissions 1 kg of concrete (kg/kg)	Total CO_2 emissions (kg)
Structure	Seawall	15	23 500	281 520 000	0.249	48 421 440
Breakwater	Interlocking elements	15	102 000	67 069 294	0.172	16 150 140
TOTAL concrete			**125 500**	**348 589 293**		**64 571 580**

* The conversion of m³ concrete to kg is 2400 (Anupoju, 2016). The volume in kg also includes the estimated losses (15%)

2.2 Platforms

2.2.1 Production of Steel

A set of four platforms is considered (3 AC platforms and 1 GW HVDC platform). As a substructure for the platforms, a jacket or monopile can be used for the AC, but only a jacket structure is possible for the HVDC platform (because of its size). The two scenarios are 3 AC monopiles with one DC, or 3 AC jackets with 1 HVDDC. The topside is not included in LCA calculations as this will be the same for both the platforms and the islands. The volumes of steel required for the platforms are indicated in Table 2-6.

Table 2-6: Overview steel volume (kg) for AC and DC platforms, and with jacket and monopile alternatives for the AC platform, according to the assumptions in the EIR study of the MOG2 project, (IMDC, 2022).

Application in MOG2	AC platform - monopile	AC platform - jacket	DC platform - jacket
Foundation		3 000 000	7 000 000
Foundation poles (volume of 6 per platform)		2 000 000	3 000 000
TOTAL steel volume ton (not transmission infrastructure on top)	**4 000 000**	**5 000 000**	**10 000 000**

The steel used for building platforms are SS 316L. This steel augments strength at high temperatures and defends the structures against severe acidic environments. For producing of 1 kg for 316 steel 2.28 kg CO_2 is emitted (Hammond and Jones, 2019). Therefore, the CO_2 emission to produce the jacket for the AC platform (jacket) would be **0.011 Mt CO_2**, for the DC platform it would be roughly double this amount (**0.023 Mt CO_2**) and for the AC platform-monopile it would be equivalent to **0.009 Mt CO_2.** For the two scenario's it gives a total of **0.05 Mt CO_2** or **0.057 Mt CO_2** (Table 2-7).

Table 2-7: the CO_2 equivalent emissions emitted for the platforms (with jacket or monopile AC platforms)

Scenario	Volume (kg)	Kg CO_2 emissions for 1 kg of steel (kg/kg)	Total CO_2 emissions (kg)
Platforms (3 AC & 1 DC) - with AC monopiles	22 000 000	2.28	50 160 000
Platforms (3 AC & 1 DC) - with AC jacket	25 000 000	2.28	57 000 000

2.3 Cables

The type of the export cables applied in this project is considered as 6 AC (170kv) and 1 HVDC (525kv) cable system (consisting of three parts). An illustrative summary of the AC and DC cable cross section and technical information applied in the life cycle analysis are presented in Annex 7A.1 and 7A.2 respectively.

The weight of the cable and the CO_2 emission for the cable production are calculated in detail. The weight of the 170 kv AC cable is 8.800 kg/km and to produce each kilometer of cable, **629 ton CO_2** is emitted Annex 7A.1. In other words, for producing of 1 kg 170 kv cable, **7.15 kg CO_2** is emitted. The relevant data, information and explanations are presented in Annex 7A.1.

The weight of the 525 kv DC cable is 24.9 kg/m (per core); therefore, we approximate the entire DC cable is 7.500 kg/km and to produce each kilometer of cable, **1 144 ton CO_2** is emitted (Annex 7A.1). In other words, for producing of 1 kg 525kv DC cable, **15.26 kg CO_2** is emitted. The relevant data, information and explanations are presented in Annex 7A.2.

There is a variation in the AC and DC cable lengths and weights due to the different positions of cables for the island (North route 1, North route 2, West 1, West 2) and the platforms which has consequences on the carbon dioxide emissions (Table 2-9, Table 2-8). The relevant data, information and explanations are presented in Annex 7A.1 and 7A.2.

Table 2-8: Showing the different locations of the islands and the corresponding cables lengths (km), to landfall zone Blankenberge-Zeebrugge (worst case: longest route).

Cable	Island West 1	Island West 2	Island North, route option 1	Island North, route option 2	Platforms (4)
AC1	53	53	58	60	55
AC2	53	53	58	60	55
AC3	53	53	58	60	50
AC4	53	54	59	60	50
AC5	53	54	59	60	50
AC6	53	54	59	60	50
HVDC 1/1	53	54	59	60	58
HVDC 2/1	53	54	59	60	58
Total AC	**319**	**321**	**351**	**357**	**309**
Total HVDC	**106**	**107**	**118**	**119**	**116**

Table 2-9: Showing the different cable weights, and carbon emissions for the variations in the caisson and revetement island and platforms positions.

Structure	Location	Cable	Weight (kg)	CO_2 emission (kg/kg)	CO_2 emissions (kg)
Caisson island/revetement	West 1	total AC	31 888 800	7.15	228 004 920
		total HVDC	7 981 875	15.26	121 803 413
		TOTAL	**39 870 675**		**349 808 333**
Caisson island	West 2	total AC	32 109 500	7.15	229 582 925
		total HVDC	8 053 350	15.26	122 894 121
		TOTAL	**40 162 850**		**352 477 046**
Caisson island	North, route 1	total AC	35 124 500	7.15	251 140 175
		total HVDC	8 852 700	15.26	135 092 202
		TOTAL	**43 977 200**		**386 232 377**
Caisson island	North, route 2	total AC	35 732 700	7.15	255 488 805
		total HVDC	8 946 750	15.26	136 527 405
		TOTAL	**44 679 450**		**392 016 210**
Platforms		total AC	35 732 700	7.15	274 862 768
		total HVDC	8 946 750	15.26	78 405 470
		TOTAL	**44 679 450**		**353 268 238**

2.4 Overview of Findings for the production phase

The CO_2 emissions during the production phase are summarized in this paragraph. For each item in production phase the total CO_2 emissions are presented in Table 2-10.

The highest production values are for the revetment island, this is due to the large quantity of granite needed and the high CO_2 emissions from the production of granite. Following the revetment island, the caisson islands have higher production emissions, this is again due to the granite emissions during production, however as less granite is needed for the caisson islands compared to the revetment island the overall emissions are less. Emissions from concrete are small compared to the total emissions, for caisson islands concrete is 11-14% of total emissions and for the revetment island it is 1.5% of total emissions. Finally, the least emissions are from the platforms, where AC monopiles are 2% less than the production emissions from AC and DC jackets.

Table 2-10: CO_2 emissions due to the production phase for the caisson island, revetment island and platforms (including export cables).

Item	Location	Total CO_2 emissions (kg)
Caisson Island + cables	West 1	1 527 260 663
	West 2	1 834 219 376
	North, cable route 1	1 737 564 707
	North, cable route 2	1 743 348 540
Revetment Island + cables	West 1	4 750 512 413
Platforms + cables (AC monopile + DC jacket)	NA	403 428 238
Platforms + cables (AC and DC jacket)	NA	410 268 238

* kg/kg is the gas (CO_2) emission in kg per kg of the produced item.

3 The Construction Phase

In this paragraph the air quality affected by the construction phase is evaluated. The construction phase includes the construction of the artificial islands and/or platforms and the cable lying works. It should be reminded that for different activities the relevant transport is also considered, but not the construction of the transmission infrastructure. These activities cause gas (CO_2, SO_2, PM10 and NO_x) emissions. The emissions of the gases CO_2, NOx, PM10 and SO_2 depends on several factors. The applied vessel characteristics (speed, load capacity and fuel consumption), the sailing distances and time of dredging and dumping.

The emissions of the vessel movements are included in this section. The calculations of the vessel movements and its emissions are explained in the MOG2 EIR chapter 2 Project description and chapter 5.3 Climate and atmosphere (IMDC, 2022).

3.1 Islands

3.1.1 Caisson

For the construction of the caisson island several different types of materials are required to be transported and the installation. Due to the different materials, different vessels are needed, such as a trailing suction hopper dredger for the sand. A fall pipe vessel for the filter bed, filter protection, filter rear side, toe protection and scour protection. A jack-up vessel is needed for moving and placing the caissons, concrete wall and both pontoon and barges are needed for the interlocking elements.

The calculated gas emissions from those vessel activities for transporting and installing the materials are presented in Table 3-1.

Table 3-1: Gas emissions (kg) due to the construction of the caisson island.

Structure	Step		West 1				West 2				North			
	In kg		CO_2	NOx	PM10	SO_2	CO_2	NOx	PM10	SO_2	CO_2	NOx	PM10	SO_2
1 – Preparation works / sand plateau	Leveling seabed (dredging) and temporal disposal of dredged material		142 740	2 250	103	935								
	Constructing sand plateau						1 215 467	1 9160	878	7 963	607 733	9 580	439	3 982
2 - Installation of rocks - phase 1	Transport of rocks (from Norway)		5 628 784	88 730	4 067	36 878	5 628 784	88 730	4 067	36 878	5 628 784	88 730	4 067	36 878
	Installation of rocks: filterbed		16 451 770	259 338	11 886	107 787	16 451 770	259 338	11 886	107 787	16 451 770	259 338	11 886	107 787
3 - Transport and installation of caissons (# = 24)	Scenario 1: Caissons from Belgium	Transport to island location	5 261 760	82 944	3 802	344 734	5 261 760	82 944	3 802	3 4474	5261 760	8 2944	3 802	3 4474
		Installation (sinking)	2 046 240	32 256	1 478	13 406	2 046 240	3 2256	1 478	13 406	204 6240	32 256	1 478	1 3406
	Scenario 2: Vanuit Spanje	Transport to Zeebrugge	22 444 873	353 811	1 6216	147 053	22 444 873	353 811	1 6216	147 053	22 444 873	353 811	16 216	14 7053
		Transport from ZB to island location	5 261 760	82 944	3 802	34 474	5 261 760	82 944	3 802	34 474	5 261 760	82944	3802	3 4474
		Installation (sinking)	2 046 240	32 256	1 478	13 406	2 046 240	32 256	1 478	13 406	2 046 240	32 256	1 478	1 3406
4 – Filling of the island with sand	Filling of the caissons and island core with sand		5 138 635	81 003	3 713	33 667	5 138 635	81 003	3 713	33 667	5 138 635	81 003	3 713	33 667
5 – Installation of rocks - phase 2	Transport of rocks (from Norway)		6 566 915	10 3518	4 745	43 025	10 944 858	172 530	7 908	71 708	938 1307	147 883	6 778	61 464
	Installation of rocks: filterbed, toe and scour protection		1 6255 915	25 6251	11 745	106 504	16 255 915	256 251	11 745	106 504	16 255 915	256 251	11 745	10 6504
6- Concrete seawall and cover plate on the island	Transport of material, and installation		15 390 648	242 611	11 120	100 835	15 390 648	242 611	11 120	100 835	15 390 648	242 611	11 120	100 835
7 - Construction breakwater + CTV	Constructing sand plateau		51 648	814	37	338	51 648	51 648	37	338	56 344	888	41	369
	Installing filterbed		312 710	4 929	226	2 049	312 710	312 710	226	2049	312 710	4 929	226	2 049
	Installing wide grade + quarry run + toe protection		21 723 418	342 438	15 695	142 326	21 097 998	332 579	15 243	138228	21 097 998	332 579	15 243	138 228
	Placing interlocking elements (10 m³ accropodes)		1 263 419	19 916	913	8 278	1 263 419	19 916	913	8278	1 268 917	20 003	917	8 314
Total – with transport caissons from Belgium			**96 234 603**	**1 516 999**	**69 529**	**630 503**	**101 059 852**	**1 951 677**	**73 015**	**662 116**	**98 898 761**	**1 558 995**	**71 454**	**647 957**
Total - with transport caissons from Spain			**118 679 475**	**1 870 809**	**85 745**	**777 555**	**123 504 725**	**2 305 488**	**89 232**	**809 169**	**121 343 634**	**1 912 806**	**87 670**	**795 010**

For the required island infill, sand will be dredged from the pre-scour dredging areas around the caisson island. For the West 1 location option first, the seabed is leveled, and this material is stored at another location. The emissions for the plateau are assumed to be the same for each island location and are based on emissions from location West. The emissions for the sand are different in the different locations due to physical constraints and therefore different depths are required and seabed preparation needs.

The broken rock (breuksteen) will be used in several places in the structure: filter bed, filter protection, filter rear side, toe protection (structure and breakwater) and scour protection. The broken rock materials are assumed to be sailed to the project area from Norway. It should be mentioned that the broken rock from the Norwegian quarry, in the first step is brought to Zeebrugge and then the island, and in the second step it is installed. The boat types used for the transportation and the installation of the broken rock is a fall pipe vessel.

For the caisson island, the caissons are constructed and then transported to the site. There are two options for the construction and transportation of the caissons, the first is that the caissons are constructed in Spain and transported from Spain (assumed Algeciras port, 3.000 km distance). The second option is that the caissons are built and transported from a Belgian port.

The range of emissions are as follows, in the scenario with caisson transported from **Belgium 0.096 – 0.1 Mt CO_2** emissions (rounded positively) and scenario with caissons transportef from **Spain 0.11 - 0.12 Mt CO_2** emissions (rounded positively). The West 2 location has the highest emissions, Nord has the next highest emissions then West 1 location has the lowest emissions for both Belgium and Spain. For Spain and Belgium, the difference between the highest and lowest location is ca. 8 000 000 kg emissions from CO_2. A large aspect of the emissions are construction of the toe/scour protection, the concrete seawall and the transport of the caissons (both large emissions for Belgium and Spain).

3.1.2 Revetment

For the construction of the revetement island several different types of materials are required to be transported and the installation. Due to the different materials, different vessels are needed, such as a trailing suction hopper dredger for the sand plateau and sand core. A fall pipe vessel for the gravel filter placement, armor rock, wide grade quarry run and scour protection. A jack-up vessel is needed for moving and placing the concrete wall and both pontoon and barges are needed for the interlocking elements. The calculated gas emissions from those vessel activities for transporting and installing the materials are presented in Table 3-2. The Installation of the wide grade rock, quarry run rock, armour rock and scour protection provides the most emissions in the construction of the revetment island.

Table 3-2: Gas emissions due to the construction of the revetement island (West 1 location).

Part	Step	CO_2 (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)
Foundation: Sand Plateau	Constructing a sand plateau	417 161	6 576	301	2 733
	Gravel filter placement	3 439 813	54 224	2 485	22 537
Structure	Installation wide grade + quarry run + armour rock + scour protection	105 157 393	1 657 653	75 976	688 962
	Installation interlocking elements	5 044 637	79 521	3 645	33 051
	Construction of concrete wall	7 695 324	1 21 306	5 560	50 418
	Construction of sand core	5 679 778	89 533	4 104	37 212
Total		**127 434 104**	**2 008 813**	**92 071**	**834 913**

3.2 Platforms

For the construction of the 3xAC and 1xDC platforms steel is required to be transported and the installation. A jack-up vessel is needed for moving and placing the steel in the correct locations. The calculated gas emissions are presented in Table 3-3. The range of the CO_2 emissions (the highest gas emissions) are from 0.0023-0.0028 Mt CO_2. The highest gas emissions are CO_2, the 3 monopiles with 1 DC jacket that emit more than ca. 500 000 kg CO_2 compared to the platform with 3 AC jackets and 1 DC jacket.

Table 3-3: Gas emissions due to construction of the steel elements of the platforms (2 scenario's: AC platforms with monopile or jacket).

Installation works	Scenario 1: 3 AC monopiles and 1 DC jacket				Scenario 2: 3 AC jackets and 1 DC jacket			
	CO_2 (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)	CO_2 (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)
Preparatory works: Levelling seafloor bottom	391 709	6 175	283	2 566	391 709	6 175	283	2 566
AC Jackets (3x)								
Jacket + 6 foundation piles loading (AC)					23 086	364	17	151
Jacket + 6 foundation piles transport (AC)					121 686	1918	88	797
DC Jackets (1x)								
Jacket + 6 foundation piles loading (DC)	7 695	121	6	50	7 695	121	6	50
Jacket + 6 foundation piles transport (DC)	40 562	639	29	266	40 562	639	29	266
Post-piling jackets	750 294	11 827	542	4 916	1 462 112	23 048	1 056	9 579
Erosion protection (jacket)	195 854	3 087	142	1 283	783 418	12 349	566	5 133
Monopile (AC) (3x)								
Loading	25 010	394	18	164				
Transportation	141 967	2 238	103	930				
Installation	384 766	6 065	278	2 521				
Grouten	230 860	3 639	167	1 513				
Erosion protection	97 927	1544	71	642				
Total	**2 266 645**	**35 730**	**1 638**	**14 850**	**2 830 268**	**44 615**	**2 045**	**18 543**

3.3 Cables

For cable laying there are two scenarios considered for the emission calculation.

1. 100% of the cable length (*) will be pre-trenched and backfilled. Prior to pre-trenching, pre-sweeping will be performed where required.
2. 100% of the cable length (*) will be buried by ploughing or jetting. Prior to cable burial, pre-sweeping will be performed where required.

(*) the cable length is the length of the cable, cut off at the low water line (0 m LAT (2018)), thus only the offshore part is considered

Each cable is in a separate trench. To each island, 8 cable trenches are provided (6 AC, 2 HVDC). As there are 4 platform locations, there are also 8 cable trenches (6 AC, 2 HVDC).

3.3.1 Pre-Installation, loading and laying cables

For both scenarios of pre-trenching/backfilling and ploughing/jetting the pre-installation (clearing the seabed, pre-sweeping, and provisions at crossings of existing cables), loading, transporting, and laying cables follow the same procedures. For the clearing and pre-sweeping of the seabed a trailing suction hopper dredger and offshore support vessel are required. The installation and transporting of protection mats need a fall pipe vessel. For cable loading, transportation and laying a cable laying vessel is required. For sailing distance, 50% of the cables were assumed to come from the port of Vlissingen (40 km from Zeebrugge), and 50% from the port of Shanghai (20,000 km distance). Transportation of staff will be completed with a jack-up vessel (assumption in the vessel calculations). The emissions (CO_2, NOx, PM10 and SO_2) and steps for each island and the platforms are detailed in Table 3-4.

Table 3-4: Gas emissions (kg) due to construction required for the cables.

Installation step	Project	CO_2 (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)
Clearing the seabed	West 1	3 104 146	48 932	2 243	20 338
	West 2	3 104 146	48 932	2 243	20 338
	North route 1	3 104 146	48 932	2 243	20 338
	North route 2	3 104 146	48 932	2 243	20 338
	Platforms	3 104 146	48 932	2 243	20 338
Pre-sweeping/ levelling of the routes	West 1	1 873 461	29 532	1 354	12 274
	West 2	1 887 225	29 749	1 364	1 2365
	North route 1	2 067 220	32 587	1 494	13 544
	North route 2	2 099 349	33 093	1 517	13 754
	Platforms	1 869 607	29 472	1 351	12 249
Transport protection mats or stone paving	West 1	312 710	4 929	226	2 049
	West 2	312 710	4 929	226	2 049
	North route 1	312 710	4 929	226	2 049
	North route 2	312 710	4 929	226	2 049

	Platforms	312 710	4 929	226	2 049
Installing protective mats or stone paving	West 1	3 917 088	61 747	2 830	25 664
	West 2	3 917 088	61 747	2 830	25 664
	North route 1	3 917 088	61 747	2 830	25 664
	North route 2	3 917 088	61 747	2 830	25 664
	Platforms	3 917 088	61 747	2 830	25 664
Loading cables	West 1	284 917	4 491	206	1 867
	West 2	287 034	4 525	207	1 881
	North route 1	314 371	4 956	227	2 060
	North route 2	319 286	5 033	231	2 092
	Platforms	284 344	4 482	205	1 863
Transporting cables - 50% *from Vlissingen*	West 1	25 914	408	19	170
	West 2	25 914	408	19	170
	North route 1	25 914	408	19	170
	North route 2	25 914	408	19	170
	Platforms	25 914	408	19	170
Transporting cables - 50% *from Shanghai*	West 1	12 957 029	204 249	9 361	84 891
	West 2	12 957 029	204 249	9 361	84 891
	North route 1	12 957 029	204 249	9 361	84 891
	North route 2	12 957 029	204 249	9 361	84 891
	Platforms	12 957 029	204 249	9 361	84 891
Laying cables	West 1	16 411 229	2 58 699	11 857	107 522
	West 2	16 533 162	260 621	11 945	108 321
	North route 1	18 107 789	285 443	13 083	118 637
	North route 2	18 390 858	289 905	13 287	120 492
	Platforms	16 378 238	258 179	11 833	107 306
Staff transportation	West 1	30 009	473	22	197
	West 2	30 009	473	22	197
	North route 1	30 586	482	22	200
	North route 2	30 586	482	22	200
	Platforms	28 855	455	21	189
Total	**West 1**	**38 916 504**	**613 462**	**2 8117**	**254 970**
	West 2	**39 054 318**	**615 635**	**2 8217**	**255 873**
	North route 1	**40 836 854**	**643 734**	**29 504**	**267 552**
	North route 2	**41 156 967**	**648 780**	**29 736**	**269 649**
	Platforms	**38 877 932**	**612 854**	**28 089**	**25 4717**

3.3.2 Scenario 1 pre-trenched and backfilled method

The trench profile for pre-trenching is as follows: Depth : 2m; Bottom Width : 5m; Trench slope : 1 :3.5.

The emissions (CO_2, NOx, PM10 and SO_2) for each island and the platforms are detailed in Table 3-5.

Table 3-5: Gas emissions due to pre-trenching and backfilling for cables.

Installation step	Project	CO_2 (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)
Pre-trenching	West 1	12 489 737	196 883	9 024	8 1829
	West 2	12 581 502	198 329	9 090	8 2431
	North route 1	13 781 466	217 245	9 957	90 292
	North route 2	13 995 661	220 621	10 112	91 696
	Platforms	12 464 043	196 478	9 005	81 661
Backfilling	West 1	17 840 525	281 230	12 890	116 886
	West 2	17 971 617	283 296	12 984	117 745
	North route 1	19 685 852	310 319	14 223	128 976
	North route 2	19 996 737	315 220	14 448	131 013
	Platforms	17 798 928	280 574	12 860	116 614
Total	**West 1**	**30 330 262**	**478 113**	**21 913**	**198 716**
	West 2	**30 553 119**	**481 626**	**22 075**	**200 176**
	North route 1	**33 467 317**	**527 564**	**24 180**	**219 269**
	North route 2	**33 992 399**	**535 841**	**24 559**	**222 709**
	Platforms	**30 262 971**	**477 052**	**21 865**	**198 275**

3.3.3 Scenario 2 Pre-ploughing method

The trench profile for pre-sweeping is as follows:

- Depth: Variable pre-sweeping depth.
- Bottom Width: 12m (same as top width of pre-dredged trench).
- Trench slope : 1 :3.5.

The emissions (CO_2, NOx, PM10 and SO_2) for each island and the platforms are detailed in Table 3-6.

Table 3-6: Gas emissions (kg) due to ploughing for cables.

Installation step	Project	CO_2 (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)
Advanced ploughing	West 1	38 651	609	28	253
	West 2	38 939	614	28	255
	North route 1	42 647	672	31	279
	North route 2	43 314	683	31	284
	Platforms	38 574	608	28	253

3.3.4 Cable overview

The emissions for each installation scenario during the construction phase for cables are presented in Table 3-7. CO_2 is the greatest quantity of gas emitted. Across all structures and locations, the ranges within scenarios are small. Scenario 1 ranges from **0.069 - 0.074 Mt CO_2**, whilst scenario 2 ranges from **0.038 - 0.041 Mt CO_2.** Scenario 1 has higher emissions than scenario 2, the difference is approximately double emissions of scenario 2 compared to scenario 1. This is because scenario 1 requires a greater amount of boat time, fuel, and distance in comparison to scenario 2 (pre-trenching versus pre-ploughing).

Table 3-7: Emissions for both scenarios due to the construction phase for the caisson island, revetment island and platforms.

Total cable emissions	Project	CO_2 (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)
Scenario 1: pre-trenching and backfilling (+ pre-sweeping)	West 1	69 246 766	1 091 575	50 031	453 686
	West 2	69 607 437	1 097 260	50 291	456 049
	North route 1	74 304 172	1 171 297	53 684	486 820
	North route 2	75 149 365	1 184 621	54 295	492 358
	Platforms	69 140 903	1 089 906	49 954	452 992
Scenario 2: ploughing (+pre-sweeping)	West 1	38 955 156	614 071	28 145	255 223
	West 2	39 093 257	616 248	28 245	256 128
	North route 1	40 879 502	644 406	29 535	267 831
	North route 2	41 200 281	649 463	29 767	269 933
	Platforms	38 916 506	613 462	28 117	254 970

3.4 Emissions from Seafloor

For the construction of the islands (caisson and revetement), platforms and cables, seafloor areas will need to be dredged. Areas which have been pre-dredged will have less CO_2 emissions than pristine seafloor. For this calculation we assume the worst-case scenario-that all seafloor areas are pristine and would emit the maximum of 3 kg CO_2 per m^2 seafloor area (Sala *et al.*, 2021). The calculated gas emissions are presented in

Table 3-8. The CO_2 emissions from the sediment are similar for both the caissons and revetement islands in all locations this is because the footprint and the cable lengths are similar. Platforms has a slightly smaller quantity of emissions from the seafloor, due to their smaller footprint although they have similar cable lengths to the caisson islands.

Table 3-8: CO_2 emissions from the seafloor due to dredging for island/platform structures and cables.

Project structure alternatives	Location alternatives	Emission disturbed seafloor (kg per m²)	Volume of dredged seafloor (m2)		Total emissions (kg)
			Structure	Cables	
Islands (Caisson)	West 1	0.3	569 000	8 506 000	2 722 500
	West 2	0.3	573 000	8 569 000	2 742 600
	North route 1	0.3	547 000	9 385 000	2 979 600
	North route 2	0.3	547 000	9 532 000	3 023 700
Islands (Revetement)	West 1	0.3	549 000	8 506 000	2 716 500
Platforms	4 platforms	0.3	20 000	8 489 000	2 552 700

3.5 Overview of Findings

For each item in construction phase the total (CO_2, SO_2, PM10 and NO_x) emissions are presented in Table 3-9. CO_2 emissions from the seafloor due to dredging are also included in the CO_2 columns.

The highest emissions per structure are the revetment island, this is due to the emissions from the installation of the wide grade, quarry run, armour rock and scour protection. For the caisson island, the emissions for the scenario with caissons transported from Spain are higher due to the greater transportation distance, compared to caisson transport from Belgium (14% less emissions). The cable installation technique has a large impact on the emissions due to the large difference in dredging activities. Cable scenario 1 (pre-trenching, backfilling, and pre-sweeping) has higher CO_2 emissions compared to cable scenario 2 is (ploughing and pre-sweeping). The ploughing scenario results in around 10% less total emissions for the various project alternatives. The platforms release the least emissions for production, due to the limited loads and therefore ship time needed.

Table 3-9: Emissions due to the construction phase for the caisson island, revetment island and platforms (including cables, for the two-installation scenario's: (1) pre-dredging and (2) ploughing).

Project, including cables		Project location	CO_2 (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)
Scenario 1 cable installation with pre-dredging						
Caisson island + cables	Caissons from Spain	West 1	190 648 741	2 962 384	135 776	1 231 241
		West 2	195 854 762	3 402 748	139 523	1 265 218
		North (route 1)	198 627 406	3 084 103	141 355	1 281 830
		North (route 2)	199 516 699	3 097 427	141 965	1 287 368
	Caissons from Belgium	West 1	168 203 869	2 608 573	119 560	1 084 188
		West 2	173 409 889	3 048 937	123 306	1 118 165
		North (route 1)	176 182 533	2 730 293	125 138	1 134 778
		North (route 2)	177 071 827	2 743 616	125 749	1 140 315
Revetment island + cables		West 1	199 403 370	3 100 388	142 101	1 288 599

Platforms (3 AC & 1 HVDC) + cables	with AC monopiles	4 platforms	73 960 248	1 125 636	51 592	467 843
	with AC jacket	4 platforms	74 523 871	1 134 521	51 999	471 535
Scenario 2 cable installation with ploughing						
Caisson island + cables	Caissons from Spain	West 1	160 357 131	2 484 881	113 890	1 032 779
		West 2	165 340 582	2 921 736	117 476	1 065 297
		North (route 1)	165 202 736	2 557 212	117 206	1 062 841
		North (route 2)	165 567 615	2 562 269	117 437	1 064 943
	Caissons from Belgium	West 1	137 912 258	2 131 070	97 674	885 726
		West 2	142 895 709	2 567 925	101 260	918 245
		North (route 2)	142 801 963	2 203 401	100 989	915 789
		North (route 2)	143 122 742	2 208 458	101 221	917 890
Revetment Island + cables		West 1	169 111 760	2 622 885	120 216	1 090 137
Platforms (3 AC & 1 HVDC) + cables	with AC monopiles	NA	43 735 851	649 193	29 755	269 821
	with AC jacket	NA	44 299 473	658 077	30 162	273 513

*Cable scenario 1 is pre-trenching and backfilling (+ pre-sweeping), cable scenario 2 is ploughing (+pre-sweeping).

4 The Operational Phase

The emissions during the operational phase for all structures and cables are calculated as average per operational year. It includes transport for inspections, and maintenance works (material and transport).

4.1 Islands

4.1.1 Caisson

The operation phase includes inspections of the above and below structures as well replacement of parts of the structure. The assumptions on inspections needed are explained in the vessel calculations (EIR chapter 2 Project description, (IMDC, 2022)). In the caisson island it is expected that the only areas which will need replacement are the granite used for scour protection and the concrete interlocking elements. It is estimated that each year's 2% of the scour protection and 0.2% of the interlocking elements will need to be replaced per year. The emissions for the maintenance of the caisson island are detailed in Table 4-1. The maintenance is detailed per year and then multiplied by 20 and by 50 to provide the emissions for the entire project lifetime (20y being the environmental permit duration, and 50y long term duration). The greatest emissions are the replacement of quarry stones for spare parts and the monitoring using smaller ships.

4.1.2 Revetment

The operation phase includes inspections of the above and below structures as well replacement of parts of the structure. In the revetment island it is expected that the only areas which will need replacement are the granite used for scour protection and the concrete interlocking elements. It is estimated that each year's 2% of the scour protection and 0.2% of the interlocking elements will need to be replaced per year. The emissions for the maintenance of the revetment island are detailed in Table 4-1. The revetement are expected to need maintenance at 20 and 50 years, therefore the maintenance is detailed per year and then multiplied by 20 and 50 to provide the emissions for the entire project lifetime. The greatest emissions are the replacement of quarry stones for spare parts and the monitoring using smaller ships.

4.2 Platforms

The operation phase includes inspections of the below structures as well as the above structures. The monitoring, inspections and replacements for the platforms are the same for both designs of the platforms (i.e., monopile and jacket and no difference made between AC jackets and HVDC jacket). The emissions for the maintenance of the platforms are detailed in Table 4-3. The maintenance is detailed per year and then multiplied by 20 and 50 to provide the emissions for two-time scales considered in this LCA. The above water monitoring produces has the greatest impact on emissions.

4.3 Cables

The operation phase includes inspections of the below structures as well replacement of the cables. For each structure (caissons, revetment and platforms) the operation costs will be the same. It is assumed that for each year in the lifetime of the project 0.1% of the cable length will be replaced. The emissions for the maintenance of the cables are detailed in Table 4-3. The maintenance is detailed per year and then multiplied by 20 and 50 to provide the emissions for two-time scales considered in this LCA. The replacement of the cables produces the greatest impact on total emissions.

Table 4-1: Emissions for the lifetime maintenance of the Island, both types, in kg.

		Caisson Island (all location options)				Revetement island			
Operational Phase	Activities	CO_2 (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)	CO_2 (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)
Monitoring/ Inspections	Above water	384 693	6 064	278	2 520	384 693	6 064	278	2 520
	Underwater – large ship	96 173	1 516	69	630	96 173	1 516	69	630
	Underwater – smaller ships	155 514	2451	112	1 019	155 514	2 451	112	1 019
Replacement/ repair of parts	2% quarry stones scour protection	625 420	9 859	452	4 098	1 250 841	19 718	904	8 195
	0.2% of interlocking elements	44 433	700	32	291	44 433	700	32	291
Total (1 year)		**1 306 233**	**20 590**	**943**	**8 558**	**1 931 654**	**30 450**	**1 396**	**12 656**
Total (20 years)		**26 124 675**	**411 818**	**18 875**	**171 162**	**38 633 084**	**608 994**	**27 912**	**253 113**
Total (50 years)		**65 311 700**	**1 029 550**	**47 200**	**427 900**	**96 582 711**	**1 522 486**	**69 781**	**632 783**

Table 4-2: Emissions for the lifetime maintenance of the platforms, in kg.

Operational Phase	Activities	CO_2 (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)
Monitoring/ Inspections	Above water	961 733	15 160	695	6 301
	Below water	96 173	1 516	69	630
Total (1 year)		**1 057 906**	**16 676**	**764**	**6 931**
Total (20 years)		**21 158 122**	**333 527**	**15 287**	**138 622**
Total (50 years)		**52 895 304**	**833 818**	**38 217**	**346 555**

Table 4-3: Emissions for the lifetime maintenance of the cables, in kg.

Operational Phase	Activities	CO_2 (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)
Monitors/ Inspections	Underwater	247 303	3 898	179	1 620
Replacement/ repair of parts	Extra coverage for cable	195 854	3 087	142	1 283
	0.1% of the length replaced	964 656	15206	697	6 320
Total (1 year)		**1 407 813**	**22 191**	**1 018**	**9 223**
Total (20 years)		**28 156 260**	**443 820**	**20 360**	**184 460**
Total (50 years)		**70 390 650**	**1 109 550**	**50 900**	**461 150**

4.4 Overview of Findings

For each item in operation phase the total (CO_2, SO_2, PM10 and NO_x) emissions are presented in Table 4-4. Operation costs are the same for all locations. CO_2 emissions show the highest emissions of all gases. The range of operation costs are from **0.049-0.067 Mt CO_2** emissions. Over 20 years the highest operation costs are for the revetment island which emits 19% more CO_2 compared to the caisson island and more than 26% CO_2 emissions than the platforms. A similar magnitude is seen for 50 years.

Table 4-4: Emissions due to the operation phase for the caisson island (all location options), revetment island and platforms, all including its export cables. For one year O&M, total for 20-year O&M (permit duration), and total for 50-year O&M (long term)

Structure	Period (y)	CO_2 (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)
Caisson island + cables	1	1 306 233	20 590	943	8 558
	20	26 124 660	411 800	18 860	171 160
	50	65 311 650	1 029 500	47 150	427 900
Revetement Island + cables	1	1 931 654	30 450	1 396	12 656
	20	38 633 084	608 994	27 912	253 113
	50	96 582 711	1 522 486	69 781	632 783
Platforms (4) + cables	1	1 057 906	16 676	764	6 931
	20	21 158 122	333 527	15 287	138 622
	50	895 304	833 818	38 217	346 555

5 The Decommissioning and Reconstruction Phases

5.1 Full decommissioning of structures

The full decommissioning for the structures removes all aspects of the structure and therefore is the same emissions as the construction phase (see Table 3-9).

5.2 No decommissioning of structures

The second option for decommissioning is to keep the structures in place. It's assumed that there would be limited maintenance (monitoring and inspections) in place to ensure no large pieces of the structure break off. Table 5-1 indicates the emissions from cable removal for the structures.

Table 5-1: Emissions produced in case of no decommissioning of structures, but with limited maintenance.

Structure	CO_2 (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)
Caisson island (all location options) + cables				
Control above water	384 693	6 064	278	2 520
Underwater control – large ship	96 173	1 516	70	630
Underwater control – smaller vessels	155 514	2 452	112	1 019
Cables Underwater control	247 303	3 898	179	1 620
Total	**883 683**	**13 930**	**639**	**5 790**
Revetement island + cables				
Control above water	384 693	6 064	278	2 520
Underwater control – large ship	96 173	1 516	70	630
Underwater control – smaller vessels	155 514	2 452	112	1 019
Cables Underwater control	247 303	3 898	179	1 620
Total	**883 683**	**13 930**	**639**	**5 790**
Platforms (4 platforms) + cables				
Above control	961 733	15 160	695	6 301
Underwater control	96 173	1 516	70	630
Cables Underwater control	247 303	3 898	179	1 620
Total	**1 305 209**	**20 575**	**943**	**8 551**

6 Conclusion

6.1 Total CO_2 emissions

6.1.1 Total for 20 years (permit duration)

All structures and cables are designed to last for the entire permit duration of 20 years. The 20-year time period scenario counts for all emissions during the production, construction, operation (20y) and decommissioning (full decommissioning) phases.

Overall, for all four pollutants, the platforms alternative results in the lowest emissions, followed by the caisson island and last the revetment island alternative (Figure 6-1). This is mainly due to the share of granite rocks. The production phase results in the biggest share in the total emissions (about 80%).

The differences between the scenarios are more pronounced for the CO_2 emissions because those also include the production of the materials. The caisson island with cables results in an emission of around **2 Mt CO_2**, while platforms alternative with cables emits around **0.5 Mt CO_2** and the revetment island with cables around **5 Mt CO_2**. The caisson island results in around 400% higher CO_2 emissions compared to the platforms alternative.

The different variants for the caisson island option results in a variation in the CO_2 emissions of around 20% with the lowest emissions for West 1 with caissons from Belgium and cable pre-ploughing (1.8 Mt CO_2), and the highest for the West 2 option with caissons from Spain and cable pre-trenching (2.2 Mt CO_2). The West 2 location options results in higher emissions from the production phase because this deeper location requires a higher sand plateau and a larger surface of scour protection. However, the cable route to location option North is longer and hence also the North location is characterized by higher emissions for the cable related emissions. Overall, the West 1 location always gives the lowest emissions (least emissions for material production and shortest cable route). The production of the caissons in Spain results in about double emissions for the caisson transport compared to caissons from Belgium, but the importance of this difference is limited in the overall emissions.

The CO_2 emissions for cable installation technique scenario 1 pre-trenching and backfilling is **44-45%** more than scenario 2 the pre-ploughing technique.

CO_2 emissions from trawling the seafloor have little variation between the different structures, the least seafloor emissions are from the platforms **0.002 Mt CO_2** and the most from the caisson island Eiland Nord route 2, **0.003 Mt CO_2**. Emissions of CO_2 from the seafloor are between **1-6%** (all structures) of the total CO_2 emissions from the construction phase for all structures.

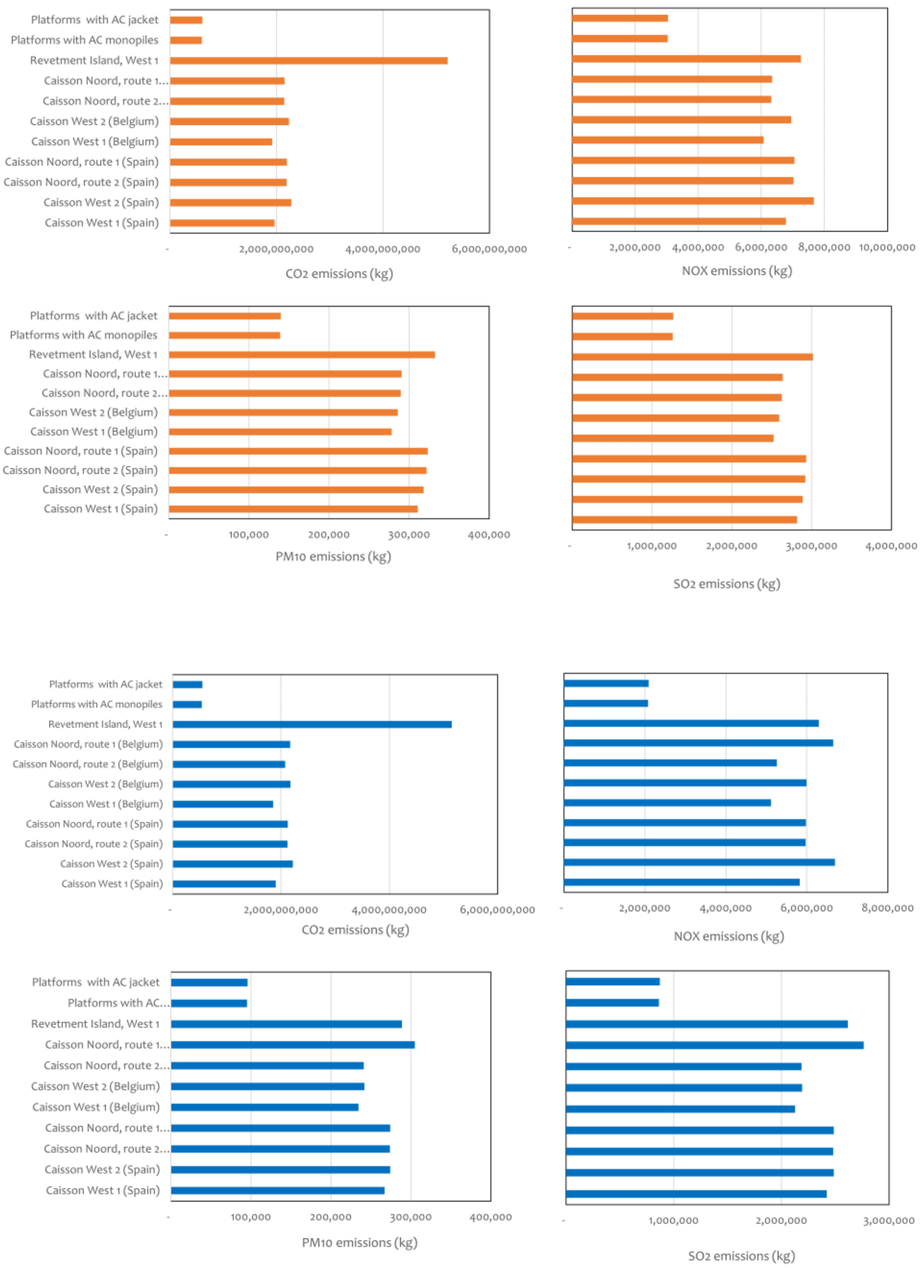

Figure 6-1 : Total emissions for four pollutants for all scenario's for the permit duration of 20 years: cable pre-trenched scenario on top (orange) and cable pre-ploughing bottom (blue).

6.1.2 Total for 50 years (long term)

Since the island is designed for a life duration of at least 50 – 100 years, also the long term of 50 years is evaluated. Due to their lifetime limitation of the platforms and cables are expected to be decommissioned twice and constructed twice in the long-term period of 50 years (lifetime platforms 35 years, and for export cables 40 years). Overall, the same conclusions hold for the 50y scenario. The caisson island has the advantage of a long-life duration. With the platforms rebuild within the 50y time span, the total emissions of the caisson island or platforms alternative get more similar although the emissions of the caisson island remain the highest (including export cables that are also rebuild within the 50y time span).

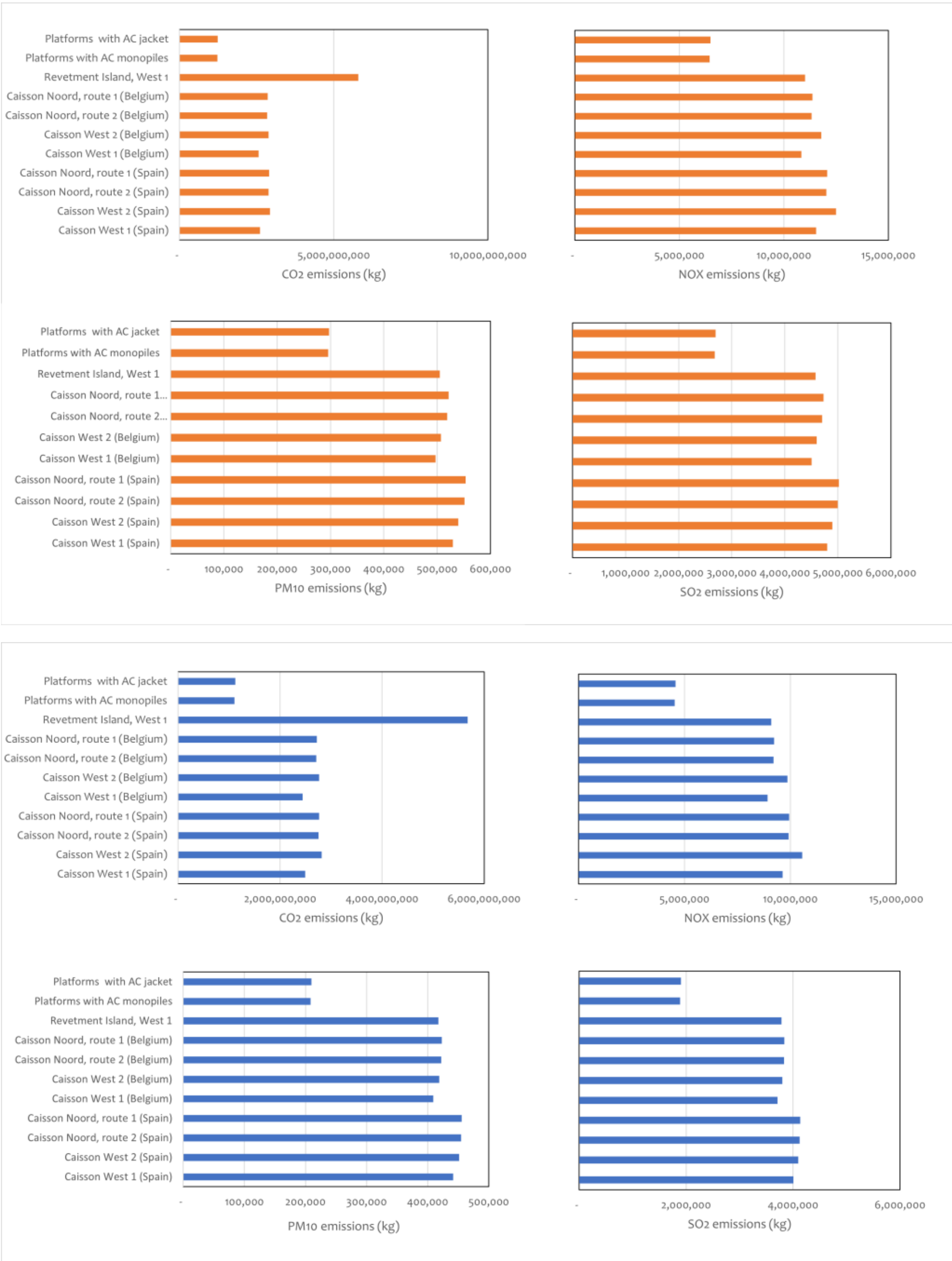

Figure 6-2 : Total emissions for four pollutants for all scenario's for the long term scenario 50 years: cable pre-trenched scenario on top (orange) and cable pre-ploughing bottom (blue).

6.2 Other transport emissions

Transportation also results in additional emissions of NO_x, SO_2 and PM10. The differences between scenario's depend on transport distance (eg caissons from Belgium versus Spain), and dredging activities (eg cable installation with dredging and backfill, versus ploughing). The platform alternative requires less transport and dredging activities compared with the caisson island (about 50% less total emissions).

7 References

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Annex A Cable production details

A.1 AC Cable production phase of the Life cycle analysis

The estimations of the technical specifications for a six 220 kV AC electric power cable are applied for the calculation of for cable production phase of the life cycle analysis.

The energy needed to produce the raw materials for a 1 km 220 kV AC export cable is about 3340 GJ. During the production of the raw materials a total amount of about 266 tonnes of CO_2 is emitted. Birkeland (2011) states that the amount of energy needed to combine the different parts of the cable into one is about the same as the amount of energy needed to produce the raw materials of a cable. Most of the important cable producing factories are in Northern Europe, where an important amount of the energy is produced from sustainable energy sources like hydro-electric and wind power. Therefore, 392 tons CO_2/GWh is used as a conversion factor from energy use to CO_2 emission. By application of this factor, the amount of emitted CO_2 during the combination of the different raw materials into one cable is about 363 tons. The total amount of emitted CO_2 during the production process of one kilometer of 220 kV AC export cable, becomes about **629 tonCO_2/km** cable.

In the next pages, some illustrative picture, data, and calculation are presented.

Table 7-1: Standard values for cable production life cycle analyses.

Raw material	Density (kg/m³)	Energy (GJ/t)	CO_2 emission (t/t)	Source
Galvanised steel	7930	21.6	1.4	
HDPE (used for XLPE en conducting PE)	970	27.7	1.8	(Alsabri *et al.*, 2021)
Copper wire	8900	48.9	3.8	(Hammond and Jones, 2019)
Bitumen	1050	4.9	0.3	
Polypropylene	946	73.8	2.2	(Alsabri *et al.*, 2021)
Lead	11340	32	3.2	

Table 7-2: Measurements for cable production life cycle analysis.

Section of the cable	Internal diameter (mm)	External diameter (mm)
Individual core (3)		
Copper conductor	0	50.9
Conductor screen	53.3	55.3
XLPE isolator	53.3	75.5
Insulator screen	75.5	77
Lead screen	77	80.2
Outer cable		
Polypropylene yarns -layer 1	2.2	4.2
Bitumen	4.2	11.1
Polypropylene yarns -layer 2	11.1	14.1
Fiber optic cable (3)		
Stainless steel tube	3.4	3.6
Polyethylene – layer 1	6.1	8.6
FRP wires and steel wires	8.6	12
Polyethylene – layer 2	12	16

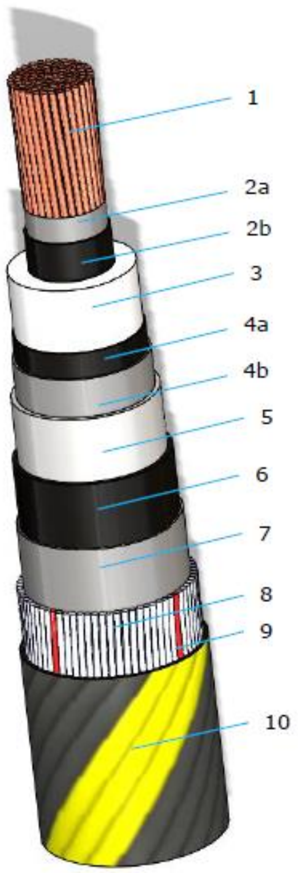
Table 7-3: Results for cable production life cycle analysis.

Section of the cable material	Amount for 1 km cable (m^3)	Amount for 1 km cable (ton)	Energy use during production (GJ/km)	CO_2 emission during production (t/km)
Individual core				
Copper conductor	6.10	54.33	2,656.72	206.45
Conducting/insulating screen (polyethylene)	1.05	1.02	28.23	1.83
XLPE isolator	6.74	6.54	181.02	11.76
Lead screen	1.19	13.44	430.11	43.01
Outer cable				
Polypropylene yarns	0.07	0.07	4.87	0.15
Bitumen	0.08	0.09	0.43	0.03
Fiber optic cable				
Stainless steel tube	0.00	0.03	0.57	0.04
Polyethylene	0.35	0.34	9.42	0.61
FRP wires and steel wires	0.17	1.31	28.27	1.83

A.2 HVDC Cable production phase of the Life cycle analysis

The estimations of the technical specifications for three HVDC electric power cable of 525 kv with a are applied for the calculation of for cable production phase of the life cycle analysis.

The energy needed to produce the raw materials for a 1 km HVDC export cable is about 6242 GJ. During the production of the raw materials a total amount of about 467 tonnes of CO_2 is emitted. Birkeland (2011) states that the amount of energy needed to combine the different parts of the cable into one is about the same as the amount of energy needed to produce the raw materials of a cable. Most of the important cable producing factories are in Northern Europe, where an important amount of the energy is produced from sustainable energy sources like hydro-electric and wind power. Therefore, 392 tons CO_2/GWh is used as a conversion factor from energy use to CO_2 emission. By application of this factor, the amount of emitted CO_2 during the combination of the different raw materials into one cable is about 678 tons. The total amount of emitted CO_2 during the production process of one kilometer of HVDC export cable, becomes about **1145 tonCO_2/km** cable**.**



Item	Description
1	Conductor
2a	Semi conductive water swelling tape
2b	Semi conductive extruded layer
3	Insulation
4a	Semi conductive extruded layer
4b	Longitudinal water penetration barrier
5	Metallic Sheath
6	Anti-corrosion sheath
7	Bedding tape
8	Armour wires
9	Integrated optical element
10	Serving

Figure 7-1: Construction of a 525 kV HVDC export cable with aluminum conductor (Prysmian Powerlink, 2021)

Table 7-4: Standard values for cable production life cycle analyses.

Raw material	Density (kg/m³)	Energy (GJ/t)	CO_2 emission (t/t)	Source
Galvanised steel	7930	21.6	1.4	
HDPE (used for XLPE en conducting PE)	970	27.7	1.8	(Alsabri *et al.*, 2021)
Copper wire	8900	48.9	3.8	(Hammond and Jones, 2019)
Polypropylene	946	73.8	2.2	(Alsabri *et al.*, 2021)
Lead	11340	32	3.2	

Table 7-5: Measurements for cable production life cycle analysis.

Cable	Internal diameter (mm)	External diameter (mm)
Conductor Cu	0	60.7
Semi conductive extruded layer PE	60.7	62.7
Insulation PE -Layer 1	62.7	117
Insulation PE -Layer 1	117	118.8
Metallic Sheath Lead	119.2	122.4
Anti-corrosion sheath PE	122.4	134
Armour wires steel	135.3	141.3
PP yarn (2 layers)	141.3	147.3

Table 7-6:Results for cable production life cycle analysis.

Material	Amount for 1 km cable (m³)	Amount for 1 km cable (ton)	Energy use during production (GJ/km)	CO_2 emission during production (t/km)
Conductor Cu	8.68	77.26	3,778.22	293.60
Layer PE	31.58	30.63	848.54	55.14
Metallic Sheath Lead	1.82	20.66	661.03	66.10
Armour wires steel	3.91	31.01	669.79	43.41
PP yarn (2 layers)	4.08	3.86	284.84	8.49