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Life Cycle Assessment of a multi-use offshore platform: Combining wind and wave energy production

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ABSTRACT

Due to increasing demand in the use of ocean space for energy and food production, multi-purpose use of marine areas is under concern. Here, a novel semi-submersible floating platform, which unites wave and wind energy converters, is investigated in terms of environmental sustainability. LCA is a methodology, to assess environmental burdens of a product/function including all the phases it experiences, which makes it a perfect tool to determine environmental burdens of renewable energy systems due to their considerably lower impacts during operation. In this study, LCA of an energy farm, constituted of multi-use offshore platforms was executed. Results showed manufacturing of the platform is the main source of pollution. In the manufacturing phase; fixed, moving and mooring parts are the main contributors and the WECs make a minor contribution. Material consumption is the main source for burdens during the life cycle of the system hence recycling ratios considered at the end of life scenarios affect the overall results. Implementation of multi-use floating concept to different locations gives various results changing with the capacity factor and the distances. The comparison between semi-submersible system and the spar platform ended up with comparable results both in terms of environmental burdens and material consumption.

1. Introduction

Multi-use offshore platforms are novel structures which are still at design stage. As indicated by the outlined literature survey, outputs obtained on environmental impacts are affected from quite a lot of factors. Such a picture emphasizes the importance of case by case evaluation for offshore energy structures.

It is a well-known fact that energy generation from renewable energy resources instead of fossil fuels is preferred due to their lower environmental burdens, and also low carbon policies lead governments to increase the ratio of energy generation from renewable sources. According to IPCC (2011) 20% of the world's energy need might be generated from wind energy by the year 2050. Wind energy is converted into electricity by means of turning the rotor by wind power. Wind energy systems are well established technologies where mainly horizontal axis turbines are used although vertical axis turbines also exist. The use of offshore areas for energy generation from renewables has increased in the last decades. In 2014, 2 488 wind turbines with 8 045.3 MW installed capacity in 74 offshore wind farms are operated through Europe. In an average wind year, 29.6 TWh energy is generated in these offshore wind farms which supplies 1% of the total energy in European Union (EWEA, 2015). Offshore areas are preferred due to absence of obstruction and also high wind speeds. Hence while the turbine parts do not change according to the onshore or offshore area, type of the foundation (gravity, monopile, tripod, and steel jacket) varies due to water depth on offshore wind farms. In deeper offshore areas, floating wind turbines are also installed.

Wave energy converters (WEC) are another way of producing renewable energy using marine space generating electricity by using the energy of gravity waves. Total wave energy potential on Earth is calculated to be 8 000–80 000 TWh per year (Soerensen and Weinstein, 2008) and this high potential results in design and installation of a variety of WEC prototypes since 1970s. First commercial WEC, LIMPET 500, which generates electricity with Oscillating Water Column (OWC) principle, has been operating in Britain since 2000. Air is compressed in OWC type WECs due to wave motion and this compressed air forces the turning movement of the turbine. There are more than hundreds types of WECs which can be classified in several ways regarding different criteria such as device location vs. shoreline (shoreline, inshore, offshore), device location vs. wave direction (point absorber, attenuator, terminator) and conversion principle (OWC, Overtopping Devices, Wave Activated

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Bodies) (Koca et al., 2013).

Use of coastal and ocean areas to produce energy has a tendency of increase, also the rise of human population elevates demand for more aquaculture production and transportation. This results in competitive usage of marine areas. Thus, integration possibilities of different usages in offshore structures or using same sea area for several purposes, so called multi-use concept, is emerged. There are studies related to various aspects of multi-use of marine space combining different methods of marine renewable energy production (Astariz et al., 2015; Michailides et al., 2016; Castro-Santos et al., 2016; etc.) as well as combining marine renewables and aquaculture (Michler-Cieluch and Krause, 2008; Buck et al., 2010; Hooper and Austen, 2014; etc.). Multi-use of ocean space is also encouraged by European Commission with project calls in Framework 7 and Horizon 2020. Feasibility of different design concepts bringing together combination of several usages are examined in the context of funded projects (Url-1, Url-2, Url-3).

Life Cycle Assessment (LCA) has been widely used for assessing environmental burdens of renewable energy systems. Due to its quantitative nature, it eases comparison of environmental consequences arising from different energy generation systems. Besides it points out the optimal environmental outputs within a chosen mode of energy generation.

There are various LCA studies which are carried out for existing or planned wind farms and the results of these studies vary despite handling wind turbines with similar technologies and structures (Lenzen and Munksgaard, 2002). The possible causes of these diverse results are outlined as the materials used in the turbines, the ratio of different metals adopted as materials, lifetime of the turbine parts (Raadal et al., 2014), capacity factor (Raadal et al., 2011), wind park location (Guezuraga et al., 2012; Raadal et al., 2014; Tsai et al., 2016), energy mix ratios in the region (Oebels and Pacca, 2013), foundation type (Raadal et al., 2014), O&M activities, etc. (Tremeac and Meunier, 2009; Guezuraga et al., 2012; Raadal et al., 2014).

The review of studies related to LCA of wind energy systems by Arvesen and Hertwich (2012) shows that the biggest amount of the emissions is generated from production of turbine parts. Foundation also takes an important part for offshore wind turbines (OWTs), during the life cycle of the wind turbine. Greenhouse Gas (GHG) emissions per 1 kWh energy production are 20 ± 14 and 16 ± 9.6 gCO_2-equivalents for onshore and offshore wind turbines respectively (Arvesen and Hertwich, 2012). Kaldellis and Apostolou (2017) focuses on comparison of carbon footprint and energy payback time (EPBT) values of onshore and offshore wind turbines. Regarding higher amount and different material demand for construction and installation of offshore wind turbines which withstand harsh environmental conditions, carbon footprint values of mentioned structures are clearly higher than the onshore ones. However, offshore wind turbines have higher energy performance with shorter EPBT values due to greater offshore wind resource. For both offshore and onshore wind turbines, construction phase contributes ~80 to 90% and O&M has ~5 to 20% share in the total environmental impact (Kaldellis and Apostolou, 2017). Offshore wind turbines need more source; however, their emission amounts are close to onshore turbines due to high capacity factors offshore. According to Arvesen and Hertwich (2012) capacity factors are estimated more optimistic than reality which decreases environmental impacts per 1 kWh electricity generation and different estimations on material ratios used in turbine part production cause difference in the LCA results and also End of Life (EoL) scenarios varies in a wide range. Davidsson et al. (2012) also points out that estimated design capacity factors and recycle ratios are higher compared to actual situation in the review study they completed. Cumulative energy demand (CED) and energy return on investment (EROI) are the other parameters in addition to EPBT that defines energy performance of a wind turbine. These parameters highly affected by applied recycling ratios during EoL phase of a wind turbine (Huang et al., 2017).

Human toxicity and impacts from respiratory inorganics were found to be the significant environmental impact categories besides climate change for onshore and offshore wind turbines analysed (Bonou et al., 2016). Kouloumpis et al. (2013) states that acidification, eutrophication, ozone layer depletion, freshwater and marine aquatic potential are less affected by energy production from wind energy and on the contrary terrestric ecotoxicity and abiotic depletion potential are affected more due to resource use. Kouloumpis et al. (2013) also draw attention to the fact that we must be careful not to increase water toxicity while trying to prevent from climate change.

WECs are still emerging technologies, therefore there are a few studies on LCA of WECs. Soerensen et al. (2006) carried out an LCA study on a WEC called Wave Dragon which showed that this type of devices produces 20 times more energy than the energy used for it during its life cycle. Dahlsten (2009) conducted LCA of a WEC and claimed that most of the impacts are related to the material used besides installation, maintenance and decommissioning cannot be disregarded. Thomson et al. (2011) revealed that Pelamis WEC emits 24–30 gCO_2-eq/kWh and EPBT is 21–25 months as results of an LCA study. Collins (2014) used LCA to choose the material to be used in the design of Delos-Reyes Morrow pressure gadget, creating three scenarios for use of different materials in part production. Walker and Howell (2011) used LCA to assess environmental burdens of Oyster wave energy converter and SeaGen tidal turbine comparatively. Mentioned study claimed that these devices had similar environmental impacts with large wind turbines which are expressed in terms of energy and CO_2 payback periods.

In this study integration of wave and wind energy generation in a single device is investigated in terms of environmental sustainability. To combine wind and wave energy converters in a single floating platform requires an innovative design and a new type of structure which has enough space for the shell and additional generators of wave energy converters. This innovative structure might have additional material requirements compared to other types of floating offshore wind turbines, which raises the question of, is this new type of structure produce enough additional energy to compensate the difference in design and is there really an increase in the environmental burdens compared to other floating concepts?

In this context, the aim of this study is to answer the abovementioned questions by deeply investigating an innovative multi-use offshore platform, designed for Atlantic Ocean Cantabrian offshore site conditions. Appraising the platform through LCA sensitivity and scenario analyses will also give an insight on the effect of estimated recycling ratios and location of the energy farm on environmental impacts of this innovative structure in the early design stage.

2. Material and method

Life Cycle Assessment (LCA) is a method to specify the environmental impacts of a product or a function during its life from cradle to grave. LCA differs from Environmental Impact Assessment (EIA) and Risk Assessment (RA) by its product orienting nature and it might be used for product improvement or comparison of products or functions. Quantitative results produced by LCA studies might be used during decision making processes. By using LCA during design processes, environmental impacts are also considered and this results in environmental benefits, additionally problem shifting due to reducing emissions in one process and increasing in another is prevented by considering all stages from material extraction to waste disposal.

Life Cycle Assessment comprised of four main stages which are described in ISO 14040 Environmental management- Life cycle assessment - Principles and framework. In the goal and scope definition phase; method, functional unit, system boundaries and detail level are designated; Life cycle inventory (LCI) phase is comprised of determining inputs and outputs through the life cycle according to system boundaries and methods specified in the first phase and in the Life Cycle Impact Assessment (LCIA) phase, life cycle inventory results are converted into related environmental impact categories (Baumann and Tillman, 2004). EDIP, CML 2001, TRACI etc. are common methods which are used to convert emissions into impact categories. Interpretation of the results is the last phase. After LCIA, there might be a weighing phase which is optional.

There are several commercial and open source software available to be used during cradle to gate modelling of the product/function, which are generally used with commercial or free database that includes inputs and outputs of production processes. SimaPro, GaBi and Open LCA are examples of software specially developed for LCA, and Ecoinvent and PE are examples of common LCI database.

The aim of this study is to determine life cycle environmental impacts of a floating multi-use offshore platform (MUP). The offshore platform investigated is designed by University of Cantabria (UC) which comprise of an NREL 5 MW wind turbine and three 1 150 kW oscillating water column type WECs (Fig. 1) mounted in the three cylinders at each vertex of the platform (Armesto et al., 2016; Zanuttigh et al., 2016). Hub height of each wind turbine is 90 m and rotor diameter is 63 m. LCA is carried out for a MUP farm comprised of 77 floating MUPs, medium voltage and high voltage cables and an offshore substation. In the original MUP farm design there is also an onshore substation which is not included in the LCA study. The proposed location of the MUP farm is Cantabrian offshore site called Virgen del mar situated 3–13 km away from the shore. MUP farm is estimated to produce 110 GWh energy *per* year by OWCs and 777.25 GWh *per* year by wind turbines (Armesto et al., 2016; Zanuttigh et al., 2016) and the life time of the MUP farm is planned to be 25 years which results 22 181.29 GWh energy produced by the energy farm. Specifications of the MUP farm are listed in Table 1.

The functional unit of the study is 1 kWh electricity. GaBi software was used for data entry and life cycle impact assessment. The common opinion and application about LCA software is that it does not matter whether the LCA practitioner uses a LCA software or the other one. However, impact of LCA software selection is a matter of concern of latest studies. Comparison of LCIA results of two commonly used LCA software for four basic materials using identical input data, database and impact

Table 1
Specifications of the MUP farm.

Feature	Data
Total installed capacity	385 MW (wind)+265.5 MW (wave)
Number of platforms	77
Design life time	25
Foundation type	Floating structure
Distance from the shore	3-13 km

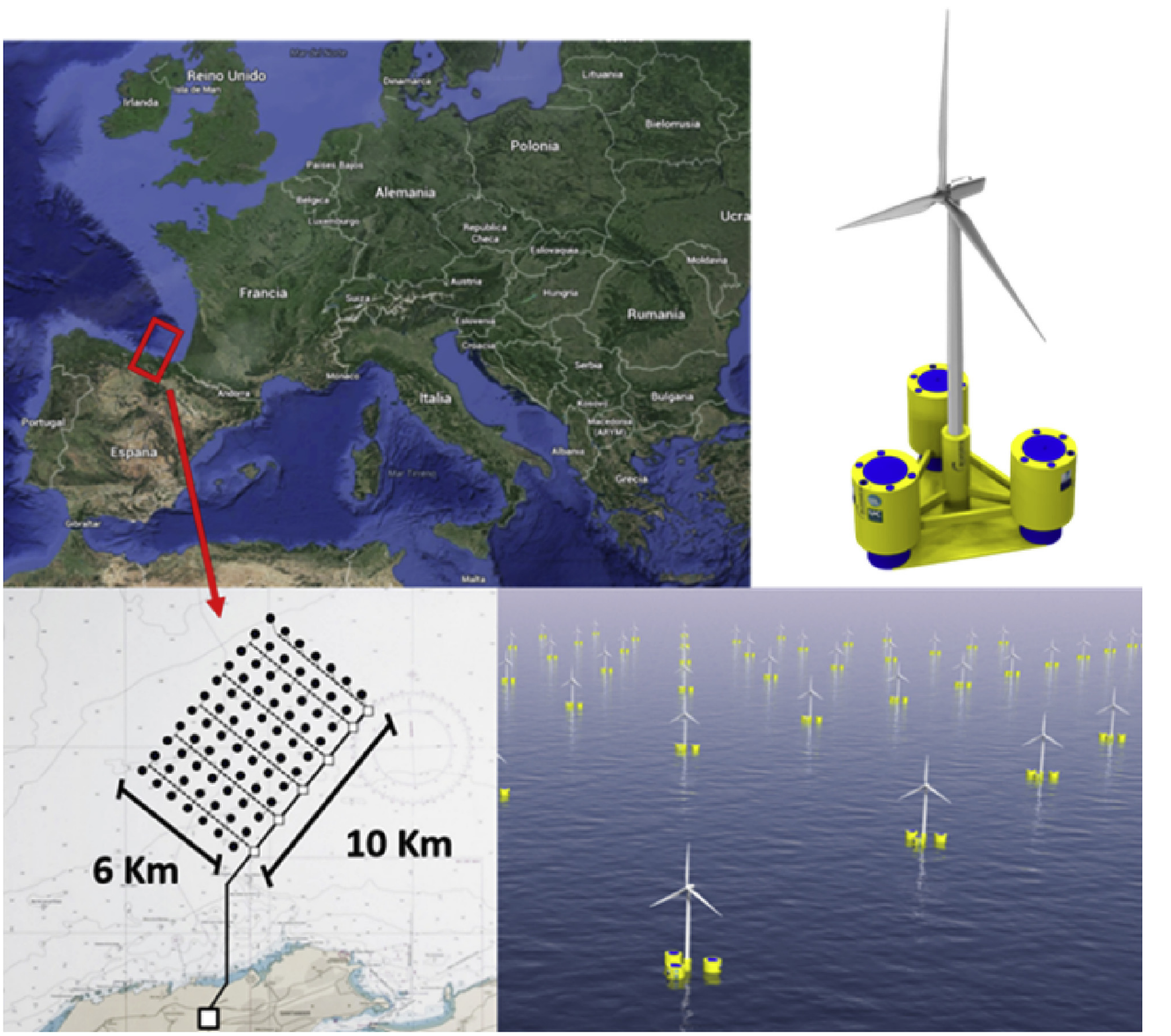

Fig. 1. a) WEC integrated floating wind turbine platform, b) plan of MUP farm (courtesy of UC).

assessment methodology resulted with the conclusion of the software selection was effective on the results which may end up with leading the decision makers on a wrong direction. This is explained with lack of consistency of existence and quantity of characterization factors of substances between two software (Speck et al., 2015). Herrmann and Moltesen (2015) reached the same coclusion, the software selection is an effective parameter on LCA results by analysing 100 randomly selected unit processes using SimaPro and GaBi. Due to the financial budget and time concerns, it was decided to use only one software for this study which resulted in usage of GaBi which is one of the two widely used LCA softwares.

Environmental impact assessment methodology is also a crucial factor for a LCA study. CML and Eco-indicator 99 methods are the most common methods used for wind turbine LCA studies which make comparison of results with previous studies straightforward. These two methods are advantageous due to ending up with more substantial results (Martínez et al., 2015). Thus, CML 2001 method (Guinée et al., 2002) is chosen for characterization of the results. In CML 2001 method, results are presented in terms of following impact categories: Abiotic depletion, acidification, eutrophication, freshwater aquatic ecotoxicity, global warming (GWP 100 years), human toxicity, ozone layer depletion, photochemical ozone creation, terrestric ecotoxicity and marine ecotoxicity. According to Pettersen and Hertwich (2008) & Weinzettel et al. (2009), CML 2001 produce inaccurate results in terms of marine ecotoxicity impact category. Thus, this impact category was excluded in characterization process and interpretation of results.

Conducted LCA covers a) Manufacturing and Processing, Transportation, Installation (MTI), b) Operation and Maintenance, and c) Decommissioning stages. Parts manufactured in the first stage are transported by trucks to the shore and by barges to the MUP farm location, installation takes place in the offshore MUP farm location, operation and maintenance continues for 25 years and finally the MUP farm is decommissioned. Life cycle stages and the flow chart are given in Fig. 2.

2.1. Data collection

The platform is designed by UC, so the main data about the MUP farm and individual platforms is directly collected from the design team. The collected data include total installed capacity, capacity factor, and design life time of the MUP farm, mooring system specifications, and transportation distances by barge and by truck, submarine cable type, material types and amounts. Ecoinvent database is used throughout the LCA for background production processes like steel production, aluminium production etc. Since part production is supposed to take place in Europe, geographical boundary is Europe, Ecoinvent 2.2 RER processes are used. Published reports (Dones et al., 2007), thesis (Birkeland, 2011) and scientific papers (Weinzettel et al., 2009; Raadal et al., 2014) are adopted as valuable data sources to fill the data gaps. Approximations and estimations for non-available material amounts, operation and maintenance and end of life scenario are explained in the sections below.

2.2. Life cycle inventory

Manufacturing and Processing, Transportation, Installation (A) stage is divided into four parts A1) Offshore wind turbine and WEC platform, A2) Offshore substation, A3) High voltage cable, and A4) Medium voltage cable.

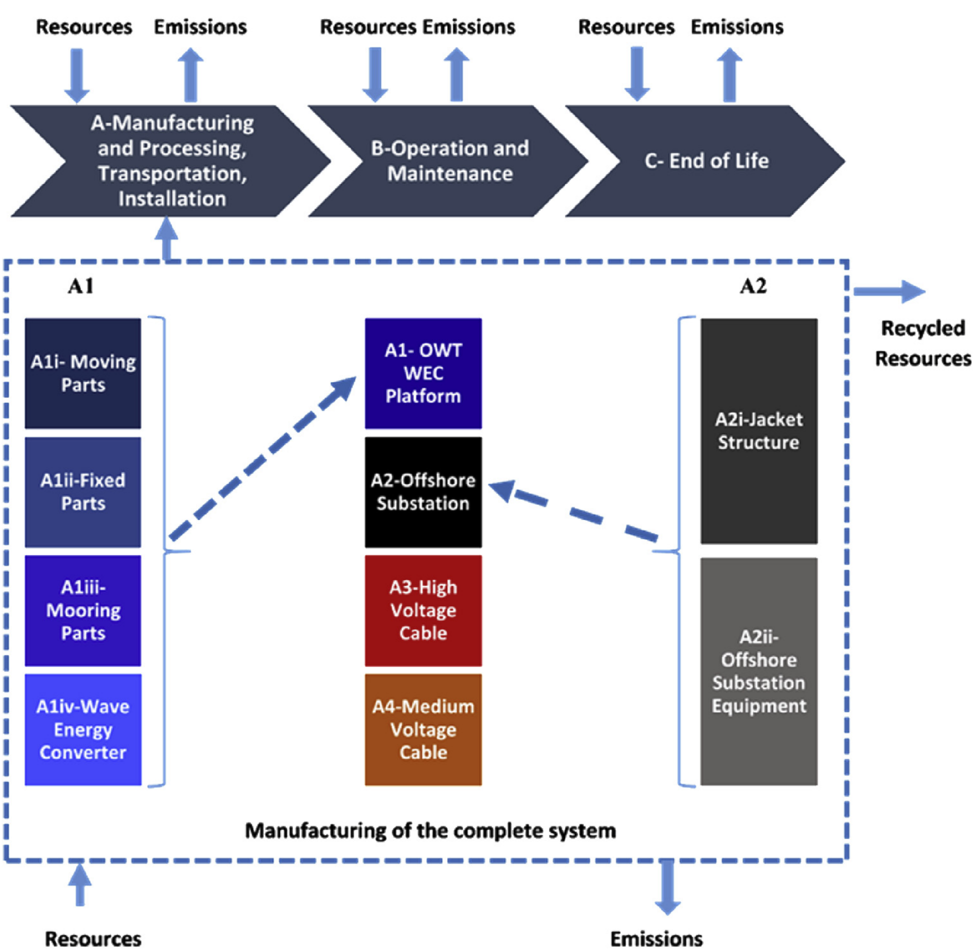

Fig. 2. Life cycle phases and flow chart of MUP farm.

2.2.1. Offshore wind turbine and WEC platform

Moving Parts (A1-i) including rotor (composed of blades and hub) and nacelle is investigated under this title. The amount of glass fibre reinforced plastic used for blades and steel for hub manufacturing is taken from the data form filled out by UC design team. All the steel is assumed to be processed as sheet rolling. Steel, aluminium, copper and glass fibre reinforced plastic are used for manufacturing nacelle and for each material, related Ecoinvent processing is used. The amounts of materials for production of nacelle is taken from Raadal et al. (2014) in which NREL 5 MW is also investigated. The total mass of nacelle is compatible with the data taken from the design team.

Fixed parts (A1-ii) of the wind turbine are tower and platform. Steel sheets are used for tower production. They are welded and then painted with epoxy resin. The amount of steel is taken from the data form. Welding amount is calculated using welding amounts for wind turbine towers in Ecoinvent given for different powers. Welding amount versus hub height graph is drawn using Ecoinvent data. The equation for best fit with the highest coefficient of determination value ($R^2 = 0.99$) was used and welding amount for a wind tower with 90 m hub height is calculated. Similar approximations are made through the LCA model where data is not available. In these approximations relevant parameters are considered, for example we estimate that the welding amount is directly proportional with hub height. On the other hand, we assume that lubricating oil used in moving parts is directly proportional with rotor diameter. By the aim of determining painting amount, the total surface area of the tower is calculated and 0.25 kg/m^2 paint (Hagedorn and Ilmberger, 1991) is considered. For coverage epoxy resin was chosen in line with Ecoinvent 2 MW OWT model (Dones et al., 2007). The amount of electronics for control units is 4 000 kg for NREL 5 MW according to Raadal et al. (2014). Mainly steel (passive reinforced and active reinforced) and concrete is used for manufacturing the platform where the amounts are sourced from the design team.

Mooring System (A1-iii) of the floating platform is composed of four mooring cables, each of being 400 m length and 4 anchors. Steel chains used for the mooring cables weigh 186 kg/m and each steel anchor is assumed to weigh 31 t similar to the value reported by Fowler et al. (2014). WEC (A1-iv) embedded on the platform includes three 1 150 kW generators other than its casing which is considered in the context of fixed parts. Each generator consist of steel, chromium steel, copper and silica sand where the materials and amounts are taken from Birkeland (2011).

2.2.2. Offshore substation

Offshore substations are mainly composed of Jacket structure (A2-i) and the substation equipment on top of it. Hence there is no design for offshore substation in the context of MERMAID project Atlantic MUP farm design, an available offshore substation design is considered. The inventory data for the chosen substation is collected from Url-4 which presents the technical features of an offshore substation platform with a steel six-legged jacket foundation of 3 500 t with a 1 500 t topside excluding equipment. The material amounts are estimated where main constituent is 6 830 t steel. 5 577 m welding and 3648213 MJ electricity is considered during the construction. 10 kg sand per m^2 steel is considered for sandblasting process through which 0.0033 kW/cm^2 sandblasted surface electricity consumed (Neri et al., 2001). Epoxy resin is used to cover the steel surface against harmful effects of sea water by applying spray painting. Substation equipment (A2-ii) is composed of 5 HV transformers, 5 gas insulated switch gears and a generator. Material amounts for these equipment are collected from different sources (Birkeland, 2011; ABB n.d.a, b; Utomo et al., 2014). For the installation of the substation, 4000 m^3 excavation with hydraulic digger for seabed preparation and 2 892 t gravel usage is estimated for scour protection.

2.2.3. High voltage and medium voltage cables

High voltage cables (132 kV HVAC) are used to transmit the produced electricity by the MUP farm from offshore substation to onshore substation and medium voltage cables (33 kV HVAC) are used as internal cables of the MUP farm. Materials used in both cables are sourced from Birkeland (2011), which are used by converting the amounts into kg material per 1 m cable, using average cable density values. Excavation of the trenches for cables are estimated as 0.6 m^3 and 0.8 m^3 for medium voltage and high voltage cables, respectively.

2.2.4. Transportation

All materials used in the manufacturing stage are assumed to be transported by truck to the location where part production takes place. The distances for material transport are considered as Ecoinvent standard distances (Ecoinvent, 2010). After part production, 15 km transport by barge and 300 km transport by truck is considered to transport the parts to the installation area. Due to being a floating platform, excavation is not considered for the MUPs.

2.2.5. Operation and maintenance (O&M)

Lubricating oil replacement, transport by barge and by helicopter is considered in the Operation & Maintenance phase while part or platform replacement during the lifetime of the energy farm is not considered. Lubricating oil used in the operation phase is considered as 10 times of beginning lubricating oil and maintenance by barge is assumed to be 10 times a year and transport by helicopter is considered as once a year.

2.2.6. Land use

According to Ecoinvent database land transformation of 2 MW offshore wind turbine with 76 m rotor diameter is 22.5 m^2 and land occupation is 450 m^{2}yr (Dones et al., 2007). Using these values land transformation and land occupation for a 5 MW offshore wind turbine with 126 m rotor diameter is estimated as 37.3 m^2 and 746 m^{2}yr, respectively.

2.2.7. End of life (EoL) scenario

As it is explained in detail in the previous sections, LCI constituted in this study includes a wide list of materials. EoL scenario cover the methods that are used for disposal of the project components at the end of the product lifetime. In this study, disposal methods were chosen as compatible with the common attitude in the reviewed studies related to LCA of wind turbines (Martinez et al., 2009; Tremeac and Meunier, 2009; Vestas, 2006; Guezuraga et al., 2012). List of considered EoL methods are presented in Table 2. As it can be seen, metals are assumed to be recycled with a ratio of 90% while the materials that might be classified as hazardous waste are disposed by municipal incineration and stored in landfills if they do not have hazardous characteristics. For the disposal of electronics, Ecoinvent process 'RER: disposal, electronics for control units' which includes manual dismantling of electronics for control units, assuming that big metal pieces are recycled, big plastic parts incinerated, and the cables and PWB are recycled through further treatment steps is used (Ecoinvent, 2010).

2.2.8. Data quality

Data quality of the constituted LCI evaluated in terms of its completeness, consistency and representativeness. All of the processes through the life cycle of the MUP design were considered in LCI for

Table 2
Considered EoL methods for materials in the main analysis.

Material	Type of disposal and ratios
Plastics	Municipal incineration
Used mineral oil, lubricating oil, paint	Hazardous waste incineration
Concrete	Landfill
Electronics	Dismantling, recycling, incineration
Steel	Recycle 90%, Landfill 10%
Aluminium	Recycle 90%, Landfill 10%
Copper	Recycle 90%, Landfill 10%
Lead	Recycle 90%, Landfill 10%

providing completeness of the data for the LCA study. Data consistency were ensured with checking all of the material and energy inputs/outputs to the studied system. As previously stated, foreground data for all life cycle stages were collected directly from the designers of the system. The geographical coverage for this study is Europe. Thus, the data which is represented as the European average or related to a region in Europe was selected from Ecoinvent 2.2 database at LCI construction phase.

Data quality of the study analysed by using data quality evaluation part of GaBi software. In this context, all of data entered to the model evaluated due to three data indicators (DQIs): technological correlation, geographical correlation and temporal correlation. Each data is evaluated for these DQIs in a range of completely presentative, partly representative, not presentative and also no statement.

All of the calculated data using foreground data evaluated as completely representative of all of the DQIs while secondary data for production processes are evaluated as completely representative for geographical correlation and partly representative for other two DQIs. Some of the production processes are listed as completely representative of technological correlation due to their temporally consistent characteristics. Transport processes are accepted as completely representative of technological and geographical correlation and partly representative for temporal correlation. According to the results, 63.4% of all data are evaluated as completely representative of technologic correlation and the rest is evaluated as partly representative. 77.7% of data considered is determined as completely representative of geographical location while the ratio for partly representative data is 19.2% and the rest is no representative data. 84.4% of data is partly representative of temporal correlation and 16.4% of data is completely representative of temporal correlation.

3. Results and discussion

3.1. General outlook

Environmental impacts of producing 1 kWh electricity by the MUP farm, are calculated and given in terms of chosen impact categories in Table 3.

Processes constituting the whole project plan contribute to each environmental impact category in different ratios. In Fig. 3, percentages of these contributions are presented as classified according to environmental impact categories and processes without recycling credits gained. MTI of OWT WEC Platform is the main factor generating the burdens for the whole environmental impact categories (except ADP) with varying ratios between 81 to 91% which is compatible with previous studies related to marine renewable energy systems (Weinzettel et al., 2009; Guezuraga et al., 2012; Raadal et al., 2014; etc.). In ADP category, the contribution of MTI of OWT WEC platform is 51% and MTI of high voltage and medium voltage cables contribute 47%, due to lead and copper usage in cable composition.

A closer look at the main contributions to MTI of OWT WEC platform is presented in Fig. 4. Manufacturing of fixed parts of the wind turbine is the highest contributor to all of the impact categories –30 to 49%- which is followed by manufacturing of moving parts -19 to 41%- and mooring system -9 to 29%-. The role of transport of manufactured materials through highway and seaway, and used electricity are the least important ones. Impact of WECs production which are installed on floating platforms is quite low with contribution of ~4% for ADP and EP with lower values for the rest.

When MTI of OWT WEC Platform is analysed in terms of material consumption, it was detected that for the fixed parts, concrete and steel are mainly responsible for environmental burdens for all of the impact categories, additionally electronics for control units is an important contributor to ADP and EP. For the moving parts, steel and glass fibre are the highest contributors in ODP and GWP, and copper is the main contributing material for ADP, AP, EP, FAETP, HTP and POCP. For the production of mooring system, steel is the main contributor in all of the environmental impact categories.

Table 3
Total environmental burdens in term of impact categories per 1 kWh electricity.

Environmental Impact Category	Unit	Total Amount
Abiotic depletion	kg Sb-Eq	2.73E-07
Acidification	kg SO_2-Eq	7.82E-05
Eutrophication	kg PO_4-Eq	4.72E-05
Freshwater aquatic ecotoxicity	kg DCB-Eq	3.77E-02
Global warming	kg CO_2-Eq	1.81E-02
Human toxicity	kg DCB-Eq	6.31E-02
Ozone layer depletion	kg R11-Eq	1.63E-09
Photochem. ozone creation	kg C_2H_4-Eq	9.32E-06
Terrestric ecotoxicity	kg DCB-Eq	1.60E-03

3.2. Scenario analysis

The first part of scenario analysis includes EoL scenarios with various recycling ratios of the materials used. Electricity consumption for the manufacturing and installation of OWT WEC Platform is also investigated.

Recycling ratios that are applied in the LCA studies of wind turbines are a matter of discussion due to the potential realization of recycling in the future (Davidsson et al., 2012). As previously stated, the base scenario of this study considers 90% of recycling ratios for the metal resources used. For the scenario analysis, two different scenarios (EoL1, EoL2) were constituted including 50% and 25% recycling ratios for the metals used (steel, copper, lead, aluminium) instead of 90% as in the base study. By this way, it is aimed to present possible environmental impacts of the MUP design in the case of the high recycling ratio is not accomplished in the future and present the sensitivity of the study for various recycle ratios. In Fig. 5, model results for above scenarios are presented as normalized compared to the base scenario. The main results show that one of the major contributors to all impact categories is steel consumption, therefore the decrease in estimated metal recycling ratios cause an increase in all of the impact categories. It is evident that freshwater aquatic ecotoxicity and abiotic depletion are the environmental impact categories which are distinctly far from the base scenario elevated up to 4.5 times for FAETP and 2.5 for ADP. Also the decrease in recycling ratios cause milder increases in all the other impact categories. Accelerated variation of FAETP results source from increasing amounts of disposed copper with decreasing recycling ratios in scenarios. Disposal of copper via municipal incineration ends up contamination of freshwater with various emissions. ADP results also have distinct behaviour compared to other environmental impact categories. ADP is the impact category on which EoL is the most effective on LCA results among other impact categories. In addition, gained credits with recycling are sourced from lead and copper recycling for this category. However, steel recycled in the form of pig iron is the leading recycled material for others which explains different behaviour of ADP scenario results.

Regarding the electricity usage for manufacturing and installation of OWT WEC Platform, three scenarios (E1, E2, E3) were created as they include higher electricity consumption related to the main study with ratios of 20%, 30% and 40%, respectively. The results of increased electricity consumption show that a minor increase by 1.01 in total impacts.

In the second part of scenario analysis, to evaluate the impacts of location on environmental burdens of multi-use semi-submersible OWT WEC platform, two additional scenarios are conducted; one for a site in Dutch North Sea and Kriegers Flak in Baltic Sea. These locations are specified locations for offshore wind farms; in the chosen Dutch North Sea site, Gemini wind farm is already built and the capacity factor for this location is calculated according to the information given in the wind park's web site (www.geminiwindpark.nl). For the Kriegers Flak location information is obtained from a conceptual design of wind plus aquaculture farm (Zanuttigh et al., 2016). For both locations monopile

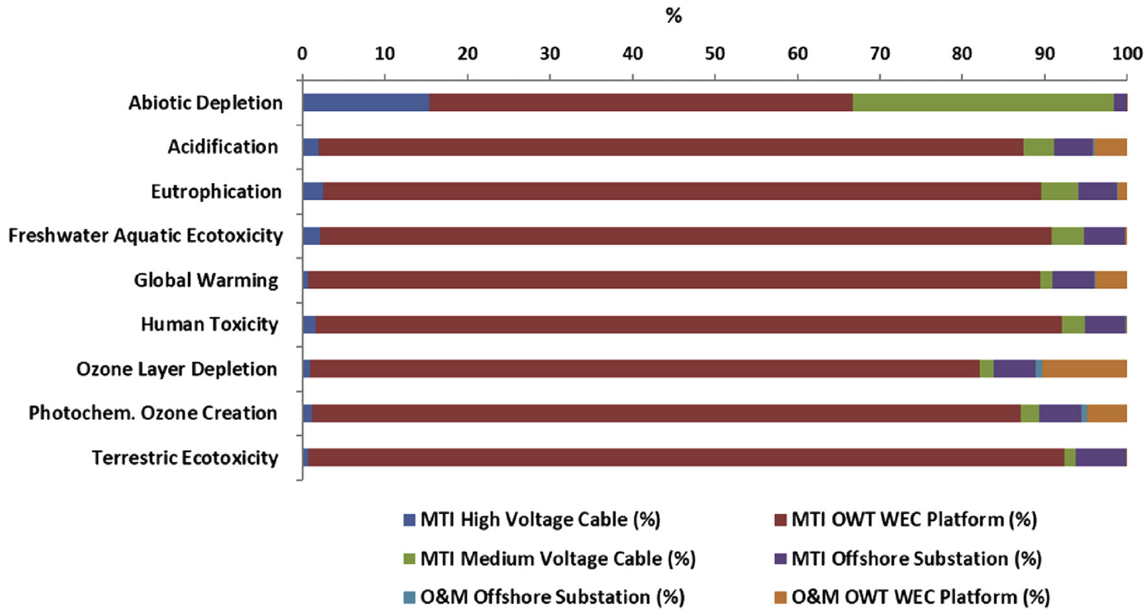

Fig. 3. Contribution analysis per environmental impact category.

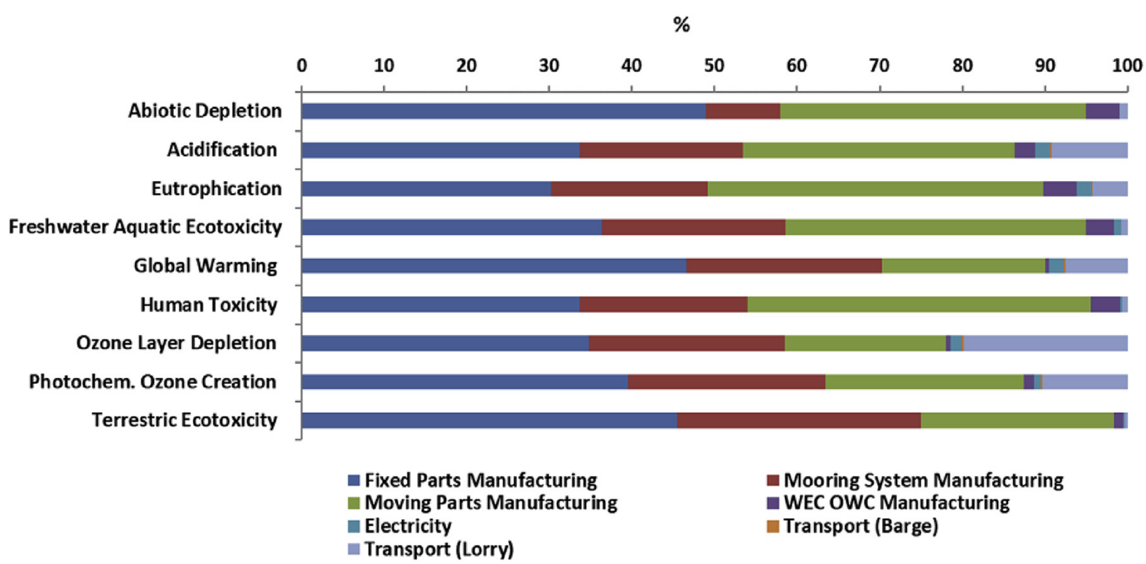

Fig. 4. Process contribution per environmental impact category for MTI of OWT WEC Platform.

foundations are realized in the original designs. In this study above-mentioned semi-submersible OWT WEC platforms are adapted to these locations.

In these locations, alterations from the base scenario are; (1) change in capacity factor for the wind turbines (wave turbine capacity factors are considered 5% for all locations), (2) change in transportation distances; from manufacturing site to the installation site, (3) length of high voltage cables, (4) transportation distances in O&M phase. The rest is assumed to be the same with the base scenario. Capacity factors for wind energy; in the base scenario, Dutch North Sea site and Kriegers Flak are 23%, 49% and 25%, respectively. In the base scenario transportation by truck is 300 km and transportation by barge is 15 km. For Dutch North Sea site these distances are 250 km by truck and 100 km by barge and for Kriegers Flak 100 km by truck and 80 km by barge. High voltage cable lengths are estimated as the distance of the wind farm from the shore. Transportation by barge and by helicopter in the O&M phase are calculated for Dutch North Sea site and Kriegers Flak.

Normalized results of location scenarios (Fig. 6) show that the capacity factor, which is strongly correlated with offshore location, has a vital importance on the results. All impact categories –except ADP- have lowest values in Dutch North Sea where capacity factor has the highest value. On the other hand, 2% increase in capacity factor, while moving from Atlantic site to Kriegers Flak does not cause a 2% decrease in the impact categories due to the fact that, inland transportation is 3 times higher for Atlantic site which increases both truck transportation burdens arised from manufacturing to installation site and in the O&M phase. The results of ADP however show a different trend, it has the lowest value in Atlantic, increases almost two times and three times in Dutch North Sea and Kriegers Flak, respectively. As mentioned above, cables have a high contribution to ADP due to copper consumption. Length of medium voltage cables do not change in these three scenarios, however high voltage cable length increases with the distance from the shore where it is 15 km for Atlantic site, 80 km for Kriegers Flak and 100 km for Dutch North Sea site. The lower ADP value of Dutch North Sea in comparison with Kriegers Flak, on contrary to the longer distance from the shore, is due to the high capacity factor in this site.

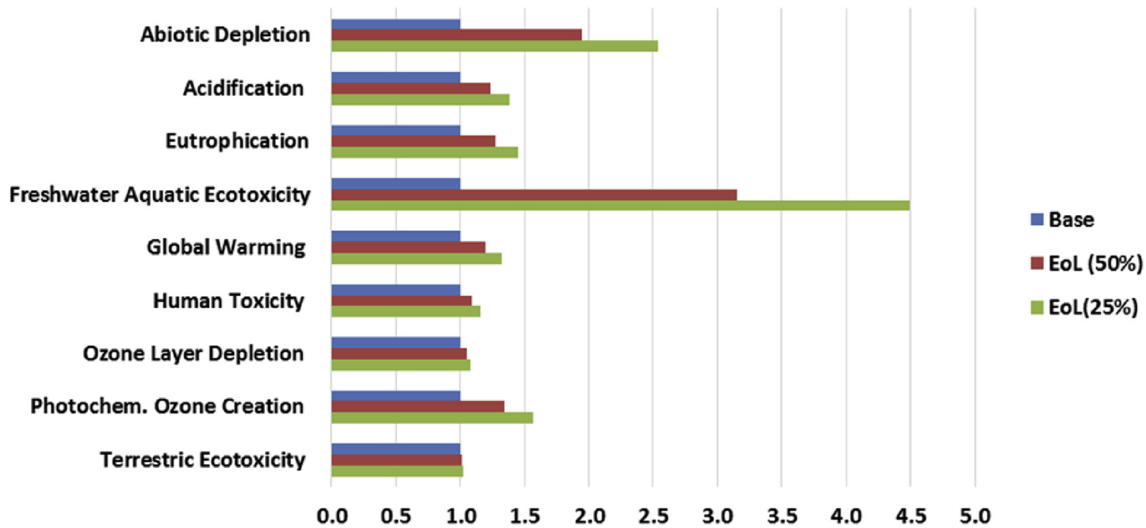

Fig. 5. Scenario analysis results - Variation of recycling ratio.

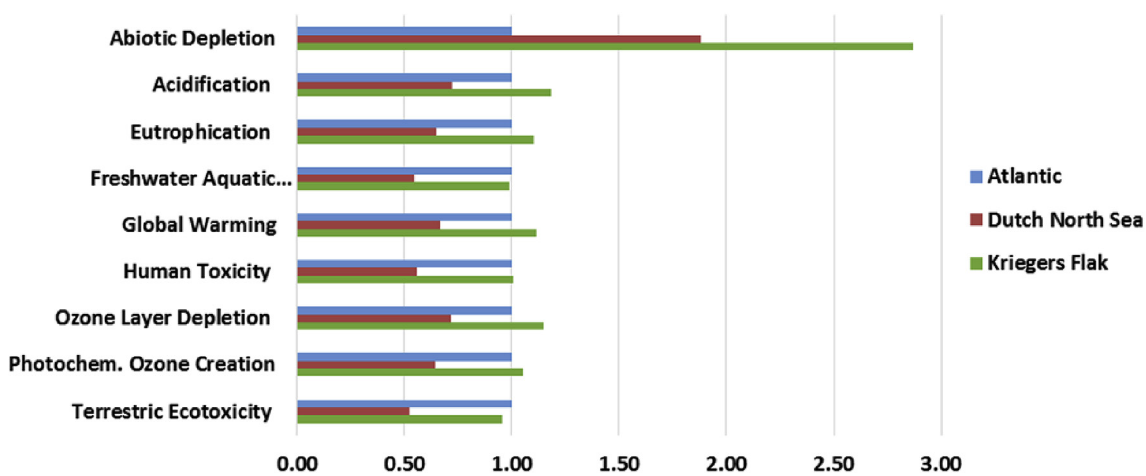

Fig. 6. Impacts per 1 kWh electricity, internally normalized to Atlantic site.

3.3. Other floating concepts

There are various floating wind turbine concepts developed for deep offshore conditions. To make a comparison between semi-submersible floating platform concept and one of the other floating concepts, the first action executed is extraction of generators of the WEC system from the multi-use concept. This concept, which converts only wind energy, is named single-use semi-submersible system.

When the generators of WECs are extracted from the system to investigate single-use semi-submersible system, energy production of the system decreases 12% compared to multi-use system and the total environmental impacts (Table A7) increase with varying values between 8 and 17% per 1 kWh energy.

Secondly, obtained LCA results of single-use semi-submersible system are compared with environmental impacts of a spar platform (Weinzettel et al., 2009). Weinzettel et al. (2009) carried out LCA of a floating offshore wind turbine which is designed by Sway Company and composed of rotor, nacelle, tower, torsion leg and mooring, nominal power of this turbine is 5 MW. Weinzettel et al. (2009) used SimaPro software and Ecoinvent version 1.3 and they used CML2 baseline 2000 V2.03 method for LCIA. To obtain a fair comparison, capacity factor for semi-submersible concept is boosted to 53% as in Weinzettel et al. (2009) and the results of single-use semi-submersible is recalculated using CML 2001 Dec. 2007.

Comparison of environmental impact results for single-use semi-submersible system versus spar platform showed that various characteristics for impact categories (Fig. 7). Single-use semi-submersible system has higher impacts in TETP, FAETP and EP while other impact categories are higher for spar platform. In the light of this information, it is not possible to claim the superiority of one concept over the other in terms of environmental burdens.

When resource consumption is considered for both systems, spar platform requires 3.37E-03 kg steel and 1.27E-04 kg copper per 1 kWh energy production. For the same functional unit, the amount of steel and copper used for single-use semi-submersible system are 2.51E-03 kg and 5.5E-05, respectively. Total metal processing assumed for spar platform and single-use semi-submersible system are 2.93E-03 kg/1 kWh and 2.60E-03/1 kWh, respectively. Some of the materials differ for the mentioned floating concepts due to their structural characteristics. In spar concept, gravel is used as ballast material (6.98E-03 kg/kWh energy). On the other hand, the main material for the platform of semi-submersible is concrete (7.68E-06 m^3/kWh energy) which has 22.7% contribution to total GWP. Electronics for control units (6.88E-06 kg/kWh energy) are also only considered for semi-submersible system and it contributes to 8% to EP and 3.4% to AP.

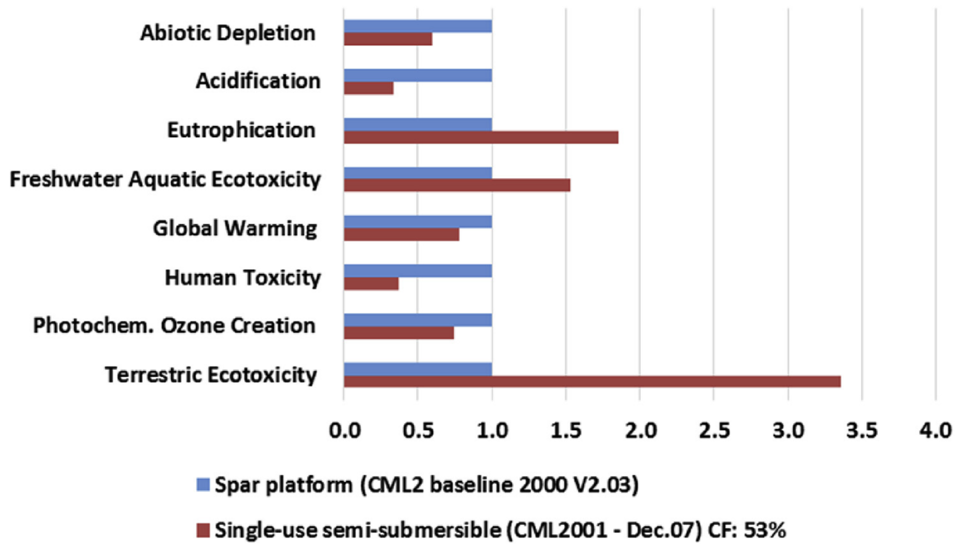

Fig. 7. Comparison between single-use semi-submersible system and spar platform.

4. Conclusion

Life cycle assessment of an innovative multi-use offshore platform design, which unites wind and wave energy production in one platform, was executed in this study. By all means, the main contributor to all of the impact categories was manufacturing processes of MUP design. Due to having a design which requires a wide range of resources and production technologies, it was a foreseeable result of this study. When MTI phase was analysed in its components, it was found out that the fixed parts of wind turbine, moving parts of the wind turbine and mooring system were responsible for most of the environmental burdens, respectively, due to high amounts of material usage. Wave energy converters embedded to the platform are minor contributors to the total environmental impacts. Effect of O&M and transport activities were very low despite having a design far from the coast and at deep water.

Following the base study, conducted scenario analysis showed that, applied recycling ratios for used resource materials are important in the context of obtained total environmental impacts. Variation of high recycling ratios applied in the base study to lower values in two scenarios resulted an increase in all of the categories, however freshwater aquatic ecotoxicity and abiotic depletion categories are more sensitive to recycle ratios compared to the rest of the categories. This result corroborated with previous determinations which considers effect of recycling ratios in LCA studies of renewable energy systems. Besides, it was tested that an increase in electricity consumption amount during MTI phase barely affects the total results.

Implementing the investigated multi-use system to different offshore locations resulted in variation of total environmental impacts due to change in capacity factor, and change in distances from manufacturing site to the shore and distances from shore to the installation site. Distance from shore to the installation site affect the sea transportation amount and also effective in high voltage cable length which cause an important variation in copper consumption.

The comparison of semi-submersible floating concept with Sway spar platform concept showed that the two concepts are comparable to each other. Terrestic ecotoxicity, freshwater aquatic ecotoxicity and eutrophication results are higher in semi-submersible concept and photochemical ozone creation human toxicity, global warming, acidification and abiotic depletion are higher in spar platform. The comparison of material consumption in two concepts shows no evidence for obvious increase in material consumption in the semi-submersible floating concept compared to spar platform.

Acknowledgements

This study was funded by EC FP7 collaborative project "Innovative Multi-purposE offshoRe platforMs: plAnnIng, Design and operation (MERMAID)" (Grant agreement number: 288710). We would like to thank University of Cantabria MERMAID team for sharing the detailed design of MUP and also would like to thank Sedat Kabdasli and Ozgur Kirca for estimations in offshore construction works. We would also like to thank the reviewers for their invaluable comments.

Appendix A

Table A1
Aggregated inventory dataset for MUP design.

MUP design				
Material	Amount per platform	Unit	Amount per 1 kWh	Unit
Glass fibre	5.522E+04	kg	1.917E-04	kg
Steel, converter, low alloyed	3.178E+05	kg	1.103E-03	kg
Steel, low alloyed	1.151E+06	kg	3.995E-03	kg
Chromium steel	3.600E+02	kg	1.250E-06	kg
Aluminium	8.000E+03	kg	2.777E-05	kg
Copper	3.620E+04	kg	1.257E-04	kg
Lubricating oil	2.875E+03	kg	9.980E-06	kg
Electronics for control units	4.000E+03	kg	1.389E-05	kg

(continued on next page)

Table A1 (*continued*)

MUP design				
Material	Amount per platform	Unit	Amount per 1 kWh	Unit
Epoxy resin	7.379E+02	kg	2.562E-06	kg
Concrete	4.467E+03	m	1.551E-05	m
Silica sand	3.000E+02	kg	1.041E-06	kg
Processing				
Sheet rolling, steel	1.040E+06	kg	3.611E-03	kg
Average metal working, steel,	4.288E+05	kg	1.489E-03	kg
Sheet rolling, aluminium	8.000E+03	kg	2.777E-05	kg
Wire drawing, copper	3.200E+04	kg	1.111E-04	kg
Welding, arc, steel	3.230E+02	m3	1.121E-06	m3
Transport				
Transport, lorry>32t	6.540E+05	tkm	2.270E-03	tkm
Transport, lorry>16t	3.662E+06	tkm	1.271E-02	tkm
Transport, barge	1.831E+05	tkm	6.357E-04	tkm
Energy				
Electricity	8.269E+05	MJ	2.870E-03	MJ
O&M				
Lubricating oil	2.875E+04	kg	9.980E-05	kg
Transport, barge	1.400E+04	tkm	4.860E-05	tkm
Transport, helicopter	2.621E+03	h	9.098E-06	h

Table A2
Aggregated inventory dataset for offshore substation.

Offshore substation				
Material	Amount per substation	Unit	Amount per 1 kWh	Unit
Sand	1.000E+05	kg	4.508E-06	kg
Epoxy resin	1.253E+04	kg	5.651E-07	kg
Steel, low alloyed	7.144E+06	kg	3.221E-04	kg
Aluminium	5.477E+04	kg	2.469E-06	kg
Nickel	1.500E+01	kg	6.762E-10	kg
Alkyd paint	2.650E+02	kg	1.195E-08	kg
Cast iron	5.400E+02	kg	2.434E-08	kg
Chromium steel	2.175E+03	kg	9.806E-08	kg
Copper	7.322E+04	kg	3.301E-06	kg
Glass fibre	3.090E+03	kg	1.393E-07	kg
Kraft paper	5.000E+01	kg	2.254E-09	kg
Lubricating oil	1.337E+05	kg	6.028E-06	kg
Polycarbonate	2.500E+01	kg	1.127E-09	kg
Polyester resin	4.000E+02	kg	1.803E-08	kg
Polyethylene	1.100E+02	kg	4.959E-09	kg
Sawn timber	1.345E+01	m3	6.064E-10	m3
Silver	5.000E+00	kg	2.254E-10	kg
Sulphate pulp	1.475E+04	kg	6.647E-07	kg
Sulphur hexafluoride	2.670E+03	kg	1.204E-07	kg
Synthetic rubber	3.250E+02	kg	1.465E-08	kg
Gravel	2.892E+06	kg	1.304E-04	kg
Processing				
Average metal working, steel	7.144E+06	kg	3.221E-04	kg
Welding, arc, steel	5.577E+03	m	2.514E-07	m
Energy				
Electricity	4.955E+06	MJ	2.234E-04	MJ
Natural gas	5.021E+06	MJ	2.264E-04	MJ
Diesel	1.926E+06	MJ	8.682E-05	MJ
Heavy fuel oil	7.189E+05	MJ	3.241E-05	MJ
Transport				
Transport, lorry>32t	2.374E+05	tkm	1.070E-05	tkm
Transport, lorry>16t	2.265E+06	tkm	1.021E-04	tkm
Transport, barge	1.566E+05	tkm	7.061E-06	tkm
Installation				
Excavation, hydraulic digger	4.000E+03	m3	1.803E-07	m3
O&M				
Lubricating oil	4.600E+05	kg	2.074E-05	kg

Table A3
Aggregated inventory dataset for submarine cables.

Medium voltage cable				
Material	Amount per 1 m cable	Unit	Amount per 1 kWh	Unit
COPPER	6.148E+00	kg	2.522E-05	kg
Lead	7.888E+00	kg	3.236E-05	kg
Polyethylene	1.856E+00	kg	7.614E-06	kg

Table A3 (*continued*)

Medium voltage cable				
Material	Amount per 1 m cable	Unit	Amount per 1 kWh	Unit
Polypropylene	1.218E+00	kg	4.997E-06	kg
Steel, low-alloyed	1.195E+01	kg	4.902E-05	kg
Processing				
Injection moulding	3.074E+00	kg	1.261E-05	kg
Average metal working, steel	1.190E+01	kg	4.882E-05	kg
Wire drawing, copper	6.148E+00	kg	2.522E-05	kg
Transport				
Transport, lorry>32t	2.900E+00	tkm	1.190E-05	tkm
Transport, lorry>16t	5.800E-01	tkm	2.379E-06	tkm
Transport, barge	4.350E-01	tkm	1.785E-06	tkm
Installation				
Excavation, hydraulic digger	6.000E-01	m^3	2.462E-06	m^3
High voltage cable				
Copper	2.205E+01	kg	1.491E-05	kg
Lead	2.216E+01	kg	1.498E-05	kg
Polyethylene	7.850E+00	kg	5.308E-06	kg
Polypropylene	4.382E+00	kg	2.964E-06	kg
Steel, low-alloyed	3.154E+01	kg	2.133E-05	kg
Processing				
Injection moulding	1.223E+01	kg	8.272E-06	kg
Average metal working, steel	3.154E+01	kg	2.133E-05	kg
Wire drawing, copper	2.205E+01	kg	1.491E-05	kg
Transport				
Transport, lorry>32t	8.800E+00	tkm	5.951E-06	tkm
Transport, lorry>16t	1.760E+00	tkm	1.190E-06	tkm
Transport, barge	1.320E+00	tkm	8.926E-07	tkm
Installation				
Excavation, hydraulic digger	8.000E-01	m^3	5.410E-07	m^3

Table A4
Aggregated inventory dataset for EoL phase.

Disposal				
Processing	Amount per energy park	Unit	Amount per 1 kWh	Unit
disposal, concrete, 5% water, to inert material landfill	8.186E+08	kg	3.691E-02	kg
disposal, glass, 0% water, to municipal incineration	2.766E+06	kg	1.247E-04	kg
disposal, inert waste, 5% water, to inert material landfill	1.429E+05	kg	6.441E-06	kg
disposal, paint remains, 0% water, to hazardous waste incineration	6.962E+04	kg	3.139E-06	kg
disposal, plastics, mixture, 15.3% water, to municipal incineration	1.489E+06	kg	6.714E-05	kg
disposal, used mineral oil, 10% water, to hazardous waste incineration	3.029E+06	kg	1.365E-04	kg
disposal, electronics for control units	3.080E+05	kg	1.389E-05	kg
disposal, building, waste wood, untreated, to final disposal	6.053E+03	kg	2.729E-07	kg
disposal, hazardous waste, 25% water, to hazardous waste incineration	1.004E+05	kg	4.526E-06	kg
disposal, packaging paper, 13.7% water, to municipal incineration	5.000E+01	kg	2.254E-09	kg
disposal, polyethylene, 0.4% water, to municipal incineration	2.871E+05	kg	1.294E-05	kg
disposal, rubber, unspecified, 0% water, to municipal incineration	3.250E+02	kg	1.465E-08	kg
disposal, polypropylene, 15.9% water, to municipal incineration	1.767E+05	kg	7.967E-06	kg
disposal, steel, 0% water, to inert material landfill	1.218E+07	kg	5.492E-04	kg
disposal, aluminium, 0% water, to sanitary landfill	6.708E+04	kg	3.024E-06	kg
disposal, copper, 0% water, to municipal incineration	3.751E+05	kg	1.691E-05	kg

Table A5
Environmental impacts of the main components of multi-use semi submersible platform per 1 kWh electricity.

Environmental impact categories	Unit	Total	EOL Wind Farm	MTI High Voltage Cable	MTI OWT WEC Platform	MTI Medium Voltage Cable	MTI Offshore Substation	O&M Offshore Substation	O&M OWT WEC Platform
Abiotic Depletion	kg Sb-Eq	2.73E-07	−5.82E-07	1.32E-07	4.38E-07	2.71E-07	1.33E-08	8.21E-11	4.77E-10
Acidification	kg SO_2-Eq	7.82E-05	−3.87E-05	2.26E-06	1.00E-04	4.36E-06	5.37E-06	1.95E-07	4.74E-06
Eutrophication	kg PO_4-Eq	4.72E-05	−2.84E-05	1.90E-06	6.58E-05	3.41E-06	3.51E-06	7.75E-08	8.98E-07
Freshwater Aquatic Ecotoxicity	kg DCB-Eq	3.77E-02	1.34E-02	5.32E-04	2.16E-02	9.63E-04	1.23E-03	5.94E-06	5.11E-05
Global Warming	kg CO_2-Eq	1.81E-02	−7.13E-03	1.71E-04	2.24E-02	3.48E-04	1.29E-03	2.17E-05	9.89E-04
Human Toxicity	kg DCB-Eq	6.31E-02	−1.28E-02	1.18E-03	6.87E-02	2.17E-03	3.70E-03	1.52E-05	1.55E-04

(*continued on next page*)

Table A5 (*continued*)

Environmental impact categories	Unit	Total	EOL Wind Farm	MTI High Voltage Cable	MTI OWT WEC Platform	MTI Medium Voltage Cable	MTI Offshore Substation	O&M Offshore Substation	O&M OWT WEC Platform
Ozone Layer Depletion	kg R11-Eq	1.63E-09	−7.02E-11	1.53E-11	1.38E-09	2.84E-11	8.59E-11	1.34E-11	1.76E-10
Photochem. Ozone Creation	kg C_2H_4-Eq	9.32E-06	−6.69E-06	1.84E-07	1.38E-05	3.58E-07	8.27E-07	1.01E-07	7.84E-07
Terrestric Ecotoxicity	kg DCB-Eq	1.60E-03	−5.66E-05	1.05E-05	1.52E-03	2.19E-05	1.01E-04	2.13E-07	1.94E-06

Table A6
Environmental impacts of the Manufacturing Transportation and Installation phase of multi-use semi submersible platform per 1 kWh electricity.

Environmental impact categories	Unit	MTI OWT WEC Platform Total	Fixed Parts Manufact.	Mooring System Manufact.	Moving Parts Manufact.	WEC OWC Manufact.	Electricity	Transport (Barge)	Transport (Lorry)
Abiotic Depletion	kg Sb-Eq	4.38E-07	2.14E-07	3.96E-08	1.62E-07	1.75E-08	1.23E-10	7.11E-12	4.30E-09
Acidification	kg SO_2-Eq	1.00E-04	3.36E-05	1.98E-05	3.30E-05	2.40E-06	1.80E-06	2.14E-07	9.21E-06
Eutrophication	kg PO_4-Eq	6.58E-05	1.99E-05	1.25E-05	2.68E-05	2.63E-06	1.17E-06	6.47E-08	2.82E-06
Freshwater Aquatic Ecotoxicity	kg DCB-Eq	2.16E-02	7.85E-03	4.78E-03	7.84E-03	7.30E-04	1.89E-04	2.77E-06	1.60E-04
Global Warming	kg CO_2-Eq	2.24E-02	1.04E-02	5.30E-03	4.43E-03	1.22E-04	3.99E-04	2.95E-05	1.69E-03
Human Toxicity	kg DCB-Eq	6.87E-02	2.31E-02	1.40E-02	2.85E-02	2.46E-03	1.91E-04	5.15E-06	4.06E-04
Ozone Layer Depletion	kg R11-Eq	1.38E-09	4.79E-10	3.26E-10	2.68E-10	7.92E-12	1.89E-11	3.09E-12	2.73E-10
Photochem. Ozone Creation	kg C_2H_4-Eq	1.38E-05	5.44E-06	3.28E-06	3.32E-06	1.61E-07	1.10E-07	2.30E-08	1.42E-06
Terrestric Ecotoxicity	kg DCB-Eq	1.52E-03	6.90E-04	4.48E-04	3.55E-04	1.76E-05	2.07E-06	7.99E-08	5.36E-06

Table A7
Environmental impacts of the main components of single-use semi submersible platform per 1 kWh electricity.

Environmental impact categories	Unit	Total	EOL Wind Farm	MTI High Voltage Cable	MTI OWT Platform	MTI Medium Voltage Cable	MTI Offshore Substation	O&M Offshore Substation	O&M OWT Platform
Abiotic Depletion	kg Sb-Eq	3.20E-07	−6.35E-07	1.50E-07	4.80E-07	3.09E-07	1.51E-08	9.38E-11	5.44E-10
Acidification	kg SO_2-Eq	8.77E-05	−4.31E-05	2.58E-06	1.11E-04	4.98E-06	6.12E-06	2.23E-07	5.41E-06
Eutrophication	kg PO_4-Eq	5.23E-05	−3.10E-05	2.16E-06	7.21E-05	3.89E-06	4.01E-06	8.84E-08	1.02E-06
Freshwater Aquatic Ecotoxicity	kg DCB-Eq	4.07E-02	1.38E-02	6.07E-04	2.38E-02	1.10E-03	1.41E-03	6.78E-06	5.84E-05
Global Warming	kg CO_2-Eq	2.06E-02	−8.07E-03	1.96E-04	2.54E-02	3.97E-04	1.48E-03	2.48E-05	1.13E-03
Human Toxicity	kg DCB-Eq	7.00E-02	−1.38E-02	1.35E-03	7.56E-02	2.47E-03	4.23E-03	1.74E-05	1.77E-04
Ozone Layer Depletion	kg R11-Eq	1.85E-09	−7.73E-11	1.74E-11	1.56E-09	3.24E-11	9.80E-11	1.53E-11	2.00E-10
Photochem. Ozone Creation	kg C_2H_4-Eq	1.05E-05	−7.55E-06	2.10E-07	1.55E-05	4.09E-07	9.44E-07	1.15E-07	8.95E-07
Terrestric Ecotoxicity	kg DCB-Eq	1.81E-03	−6.12E-05	1.20E-05	1.71E-03	2.49E-05	1.15E-04	2.43E-07	2.21E-06

Table A8
Environmental impacts of the Manufacturing Transportation and Installation phase of single-use semi submersible platform per 1 kWh electricity.

Environmental impact categories	Unit	MTI OWT Platform Total	Fixed Parts Manufact.	Mooring System Manufact.	Moving Parts Manufact.	Electricity	Transport (Barge)	Transport (Lorry)
Abiotic Depletion	kg Sb-Eq	4.80E-07	2.44E-07	4.52E-08	1.85E-07	1.41E-10	8.10E-12	4.90E-09
Acidification	kg SO_2-Eq	1.11E-04	3.84E-05	2.27E-05	3.76E-05	2.06E-06	2.44E-07	1.05E-05

Table A8 (*continued*)

Environmental impact categories	Unit	MTI OWT Platform Total	Fixed Parts Manufact.	Mooring System Manufact.	Moving Parts Manufact.	Electricity	Transport (Barge)	Transport (Lorry)
Eutrophication	kg PO_4-Eq	7.21E-05	2.27E-05	1.43E-05	3.05E-05	1.34E-06	7.37E-08	3.21E-06
Freshwater Aquatic Ecotoxicity	kg DCB-Eq	2.38E-02	8.96E-03	5.46E-03	8.95E-03	2.16E-04	3.16E-06	1.82E-04
Global Warming	kg CO_2-Eq	2.54E-02	1.19E-02	6.05E-03	5.05E-03	4.56E-04	3.36E-05	1.93E-03
Human Toxicity	kg DCB-Eq	7.56E-02	2.64E-02	1.60E-02	3.25E-02	2.18E-04	5.87E-06	4.63E-04
Ozone Layer Depletion	kg R11-Eq	1.56E-09	5.47E-10	3.73E-10	3.06E-10	2.15E-11	3.52E-12	3.11E-10
Photochem. Ozone Creation	kg C_2H_4-Eq	1.55E-05	6.21E-06	3.75E-06	3.79E-06	1.25E-07	2.62E-08	1.62E-06
Terrestric Ecotoxicity	kg DCB-Eq	1.71E-03	7.88E-04	5.12E-04	4.06E-04	2.36E-06	9.11E-08	6.11E-06

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