Energy and carbon audit of a tidal array equipped with an innovative power take-off

Miguel Santos-Herran, Encarni Medina-Lopez, Lindsey Entwistle, Henry Jeffrey

Abstract—**If wave and tidal energy devices are to become a significant contributor to the electricity generation mix, their environmental impact and energy and carbon footprints need to be added to the traditional techno-economic assessment. This paper presents the life cycle carbon and energy study of an array of ten tidal stream turbines equipped with the innovative power take-off developed, built and tested under the European H2020 project TiPA. A *'cradle-to-grave'* evaluation was performed, taking account of all energy inputs and CO_2 emissions in the fabrication, transport, installation, lifetime maintenance and decommissioning (including recycling). The calculated energy and carbon intensities were at 445 kJ/kWh and 29.2 g CO_2/kWh, respectively. Under relatively conservative assumptions, the energy payback period for the simulated array was calculated at 30 months, while the carbon payback period was 25 months. The obtained results on intensities and payback periods were found to be competitive with those of existing studies on alternative marine energy concepts, and low relative to the conventional nuclear or fossil-fuelled generation. Given the early developmental stage of the technology, these results are promising, and could be further improved by considering alternatives to steel as a structural material or by improving the environmental performance of the foundation element.**

Keywords—**life cycle analysis, marine energy, tidal energy, energy intensity, carbon payback.**

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I. Introduction

WHEN assessing the potential benefits of marine energy systems, holistic analyses are usually utilised. Such studies evaluate performance from an energy trilemma perspective, which considers economics, security of supply and environmental impacts. To date, multiple studies have covered the economic side, by determining the viability/affordability of marine energy projects. At the same time, techno-economic models are extensively being employed to assist on the roadmap to commercialisation, identifying priority areas of development. Extensive work is also available on supply security, through the characterisation of resource, dispatchability and network operation.

Whilst the environmental benefits of marine energy are known qualitatively, there is little quantitative evidence to support decision makers, in particular regarding carbon footprint. This barrier can be overcome by using Life Cycle Assessment (LCA). LCA is an established technique for identifying and evaluating the inputs, outputs and potential environmental impacts of products or services. When applied to a renewable energy project, LCA is able to produce metrics and indicators such as embodied carbon and energy, energy payback in time and energy return on investment.

Despite the increasing interest in carbon footprint in the sector, still only a few projects are performing this type of assessment. This paper uses the LCA methodology to present a case study on the energy and carbon audit of a theoretical 1-MW tidal stream array, consisting of ten turbines equipped with an innovative direct-drive flooded power take-off (PTO), a prototype of which has been developed, built and tested under the European H2020 consortium project TiPA (*Tidal turbine Power take-off Accelerator*).

A. The TiPA project

The TiPA project was awarded in June 2016 from the European Union's Horizon 2020 research and innovation programme. The TiPA project involves the demonstration and validation of an innovative direct drive PTO solution for tidal turbines. The project consortium is led by Nova Innovation. Project partners are SKF, Siemens, The University of Edinburgh, Delft Technical University, Wood and the Centre for Wind Power Drives RWTH

Aachen University. The TiPA PTO was built and commissioned at Nova's manufacturing facility in Edinburgh after which it underwent performance testing at RWTH Aachen University, Germany. The PTO will then complete in-sea testing in an operational environment in 2019 in Scotland (see Fig. **1**). Independent third-party validation of the PTO design and testing is being carried out by Wood.

Fig. 1. Picture of the TiPA power take-off (courtesy of Nova Innovation).

Once complete, the project deliverables and product will be used to raise market confidence in the maturing tidal energy industry and to maximise the benefit of the project to the ocean energy sector as a whole. The Consortium's aim is to reduce the lifetime cost of tidal power by 20%. The objectives of the project are to achieve improved performance, improved reliability and verified survivability. The expected outcome of this project is the successful validation of a world-leading, commercially viable PTO solution for a tidal turbine.

The innovative TiPA PTO incorporates a permanent magnet direct drive generator directly coupled to the main shaft unit of a tidal turbine. The air gap of the generator is flooded to explore the impacts on cooling and provide a reduced sealing requirement. The PTO power electronics equipment is contained within a separate electrical module which is deployed subsea alongside the PTO. The control system is situated within the power electronic module and operates the device efficiently and safely.

As part of TiPA, an energy and carbon footprint assessment of an array of the innovative tidal turbines was produced, presenting its performance from an environmental perspective. By employing the LCA methodology, environmental impacts associated with the different stages of a product's lifecycle can be assessed [1]. LCA takes into account the extraction of raw materials, manufacture phase, distribution, use, operation and maintenance, and finally decommissioning. It provides an inventory of the materials and processes used during the production and operation of a product, but also relevant energy inputs and carbon dioxide outputs.

B. *LCA in wave and tidal energy*

LCA analysis has been applied to other marine energy converters in the past. In terms of wave energy converters, [2]–[4] assessed the life cycle of the Pelamis device. Other converters, such as Wavestar or Oyster were evaluated under published LCA studies ([5] and [6] respectively). These papers showed how carbon intensities of such wave energy converters were similar to those of offshore wind, and lower than those produced by other types of renewable and fossil fuels. In [6], a comparison between LCAs for wave (Oyster) and tidal (Seagen) energy converters was presented, showing slightly lower carbon and energy intensities for the tidal device. The LCA of different tidal technologies have been assessed in [6], [7] (Seagen) and [8] (Deepgen, Openhydro, Scotrenewables and Flumill devices). The common result in these papers is that tidal energy converters are less harmful for the environment than other renewable technologies.

TABLE I
CHARACTERISTICS OF THE REPRESENTATIVE ARRAY

Parameter	Value
Turbine rated power	103 kW
Cut-in flow speed	0.8 m/s
Rated flow speed	2.5 m/s
Number of turbines	10 units
Project lifetime	20 years
Array location	Shetland (UK)

This research paper relies on an LCA methodology similar to that presented in previous literature outputs, and benefits from Nova's extensive experience in real-sea deployments (especially in the operation & maintenance [O&M] characterisation). This improves the reliability to the LCA results, providing an enhanced methodology to analyse the energy payback and carbon footprint of tidal energy devices.

This paper will proceed as follows: Section II presents the scope of the assessment. Section III highlights the Life Cycle Inventory Analysis, including the material and processes breakdown, including all stages in the array life cycle. Section IV summarises and discusses the results of the energy and carbon audit in terms of embodied energy and carbon, as well as payback time, and a comparison with other marine renewable energy converters and alternative generation technologies. Finally, Section V draws some conclusions to this paper.

II. SCOPE OF ASSESSMENT & BOUNDARIES

This LCA-based study analyses the incoming and outgoing materials and processes required for the life cycle of a representative tidal array of turbines equipped with the TiPA power take-off. The array lifetime has been established at 20 years (equal to the PTO's projected life), and the studied array is composed of ten devices. Turbine foundations and grid connection are included, as well as installation procedures and operations during the lifetime of the array. Decommissioning and disposal are also integrated in the present analysis. Table I summarises the characteristics of the representative array.

For the sake of producing realistic results, the virtual location of the array under study was set to Bluemull

Sound (Shetland, Scotland, UK), given the availability of data and Nova's better understanding of marine operations in the area thanks to their experience on previous deployments. Synthetic resource data on the virtual site was provided by Nova, which was created by taking real data from a medium-resource tidal site in Shetland and scaling it up to higher flow speeds, making it more representative of a relatively high-resource site, which is more likely to be considered for an early commercial tidal array. The synthetic tidal flow speed histogram is presented in Fig. 2.

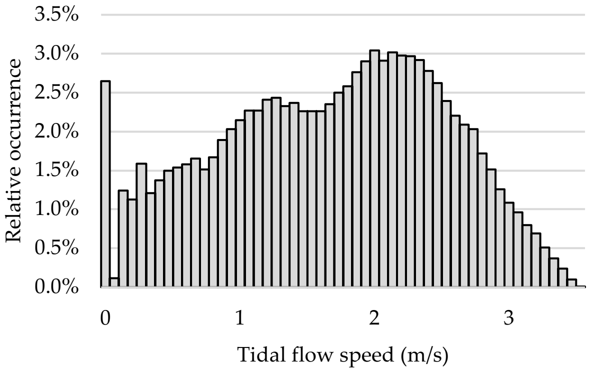

Fig. 2. Synthetic tidal current histogram for the considered site.

This assessment offers a *cradle-to-grave* boundary, which means that all energy inputs and carbon emissions from the extraction of raw materials from their natural state through the manufacturing process to the complete disposal of the devices at end-of-life are considered [7]. In spatial terms, the boundary of this analysis takes into account the sub-sea cable, but the onshore electricity network components (e.g. transformer, substation, connection to main grid) are out of the scope of this study. A simplified flowchart summarising the main components and life cycle stages of the array under study is shown in Fig. 3. Note that maintenance interventions also require some transport (details are given in section III.E), which is not shown in Fig. 3 for the sake of clarity.

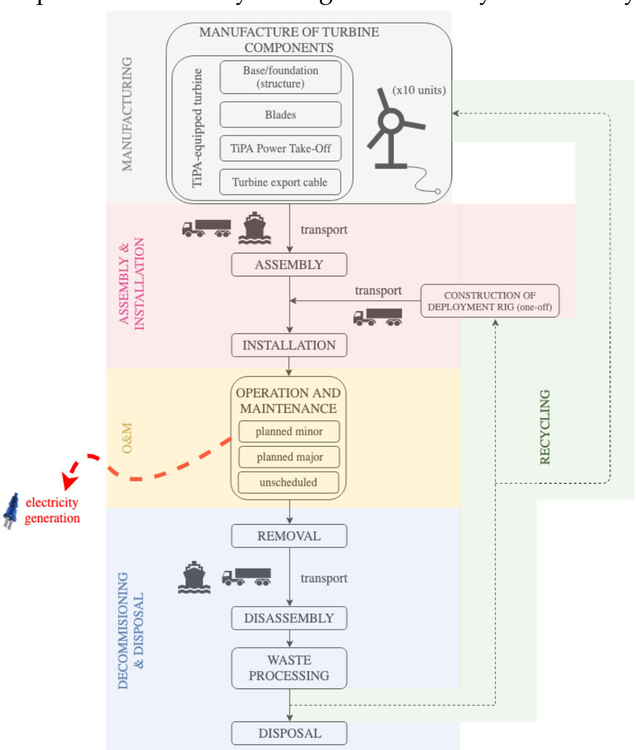

Fig. 3. Flowchart showing the simplified schematic life cycle of the array under consideration.

The energy and emissions related to the construction of manufacturing plants and the fabrication of machinery utilised during the TiPA life cycle have been excluded. This approach is in line with previous studies and assessments about the life-cycle analysis of ocean energy converters [2], [7]. In the present study, the functional unit (i.e. the reference to which the inputs and outputs can be related) was established at one kilowatt-hour of the array's output power (1 kWh).

III. Life Cycle Inventory analysis

C. *Procedure*

The inventory 'foreground data' related to the components and life cycle study of the TiPA array was based on information provided by Nova Innovation. In terms of manufacturing, a list of components was created based on the actual bill of materials of TiPA project. That list was then completed with estimations for the components not currently being manufactured under the TiPA project, such as blades, the turbine foundations and the subsea cable. Regarding installation, operation and maintenance (O&M) and disposal, procedures and vessels were outlined based on Nova's experience with previous deployments in the area, which helped to define the estimated number and type of interventions.

Information on the 'background data', i.e. the embodied energy and carbon for each unit of material/process, was obtained mainly from Inventory of Carbon & Energy [9] and ecoinvent [10] databases, and was complemented in some specific parts by additional sources [11]–[13].

D. *Raw materials*

The total gross mass utilised in the manufacturing of each of the TiPA-equipped turbines in the array under study is around 99.6 ton. That figure reduces to a net mass of 98.3 tons once the processes involving material removal have been done (e.g. machining). The gross material breakdown of each TiPA-equipped turbine can be observed in Fig. 4. Steel-reinforced concrete accounts for 62.7% of the turbine's mass. This is present in the base/foundation of the turbine. The foundation represents the majority of the turbine's mass, as seen in Fig. 5. Steel is the second most relevant material, accounting for 33.3% of the total turbine mass, being the prominent metal present in all parts with structural responsibility. Copper is the third most abundant material, mainly present in the stator wire windings and the sub-sea connection cable. The rest of the materials represent less than 1% of the turbine's total each. Should the foundations not be considered in the analysis, steel would be the main component, accounting for the 80.5% of the total turbine mass.

TABLE II
SUMMARY OF EMBODIED ENERGY AND CO2 INTENSITY OF THE MAIN MATERIALS

Material	Embodied energy (MJ/kg)	Embodied carbon (kg CO_2/kg)
Steel [9]	35.30	2.75
Laminated steel[9]	31.50	2.51
Stainless steel[9]	56.70	6.15
Concrete (steel reinforced) [9]	1.99	0.20
Copper [9]	70.00	3.83
Fibreglass [9]	28.00	1.53
Aluminium [9]	218.00	11.50
XLPE [10]	77.29	1.95
PVC [10]	124.76	4.79
Magnets [10]	868.94	56.35
Resin [9]	120.00	5.91
Oil (mineral) [12]	49.90	3.09
Synthetic rubber [9]	120.00	4.02

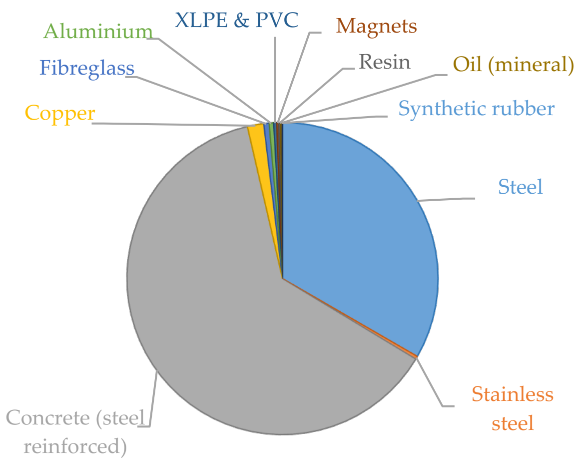

Fig. 4. Gross mass breakdown of each TiPA turbine by material (*N.B.: values cannot be shown for confidentiality reasons*).

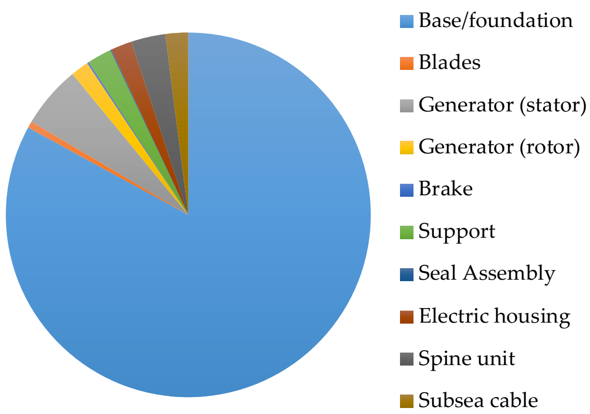

Fig. 5. Net mass breakdown of each TiPA turbine by component (*N.B.: values cannot be shown for confidentiality reasons*).

Information on material embodied energy and carbon is shown in Table II. As mentioned previously, it is primarily based on the Inventory of Carbon & Energy (ICE) [9] and ecoinvent [10] datasets by the University of Bath and the Swiss Centre for Life Cycle Inventories respectively. These databases provide *cradle-to-gate* assessments, which cover materials lifetime from the exploration and extraction of the raw and feedstock

TABLE III
SUMMARY OF EMBODIED ENERGY AND CO2 FOR THE MANUFACTURING PROCESSES

Process	Unit	Energy input (MJ/unit)	CO_2 emission (kg CO_2/unit)
Rolling [13]	kg	19.38	1.17
Welding [10], [21]	m	2.20	0.18
Machining[21]	kg removed	10.00	0.70
Masking and blasting [7]	m^2	12.00	1.44
Painting [21]	m^2	55.00	0.79
Laser cut [10]	h	684.23	46.60
Wire drawing (copper) [10]	kg	11.40	0.74

materials to readiness for collection at the factory gate. Carbon and energy associated with the remaining lifetime of the material, i.e. from *gate* to *grave*, needs then to be accounted for separately and added in order to be able to compute the final *cradle-to-grave* result.

The present study considers and quantifies the recycling of materials at end of the project lifetime activities. Consequently, when sourcing the ICE database, 'primary' values of embodied carbon and energy were employed, in order to avoid double crediting recyclability. 'Primary' here means virgin materials, i.e. as if totally extracted from the natural source, without any recycled content. Similarly, when using the ecoinvent dataset, values were extracted for the 'Allocation at the point of substitution' model. In this model, by-products of treatment processes are considered to be part of the waste-producing system and are allocated together [10].

Steel-only elements represent approximately half the mass share in the turbines when compared with reinforced concrete (33.3% vs 62.7%, see Fig. 4). However, it is expected that the pure-steel will be the major source of global embodied energy and carbon, since its energy and CO_2 intensities are around 18 and 14 times greater, respectively, than the reinforced concrete's. In contrast, reinforced concrete, while representing the majority in terms of mass, contributes to a much lower share of the global embodied energy and carbon.

E. Manufacturing

1) Manufacturing processes

Table III summarises the energy and CO_2 requirements for the selected manufacturing processes considered in the present study.

2) Components

a. Base/foundation

The foundation for the TiPA-equipped turbine consists of steelwork composed of standard beams and rolled steel which are then welded and eventually painted. It also incorporates 14 steel-reinforced-concrete ballast blocks, as well as the nacelle clump weight. The turbine base is manufactured in Shetland and then shipped to the assembly site ready to be deployed.

TABLE IV
SUMMARY OF ENERGY AND CARBON INTENSITIES IN THE ASSEMBLY AND INSTALLATION

Assembly & installation element	Unit	Energy input (MJ/unit)	CO_2 emission (kg CO_2/unit)	comments
Electricity (crane) [10]	kWh	11.70	0.69	Assumed an electrical consumption of 18 kWh/h for the crane[4]
Diesel (fork-lift truck & multi-cat)[10]	MJ	1.45	0.09	Fork-lift truck: assumed a fuel consumption of 2.55 kg of diesel per hour[4]
Coastal shipping [11]	ton*km	0.27	0.019	Distance Aberdeen to Shetland: 358 km
Road transport (truck) [11]	ton*km	0.94	0.067	Distance Leith to Aberdeen: 206 km; Lerwick to assembly site: 50 km

b. Blades

Rotor blades are made of resin infused fibreglass.

c. TiPA PTO components:

Generator: the cylindrical main body of the stator is made of rolled steel, which is welded along its length and completed with end plates. The body is also machined for a better finish and masked, blasted and painted. Lamination stack is formed by thousands of layered, laser-cut units of thin laminated steel. The stator also includes two steel pressure plates, the copper windings and resin protection. Finally, an internal can, together with its supports, holds the oil that cools the system. The rotor is also a cylindrical body obtained by rolling and welding steel plates. Magnets are then inserted into the lateral area of the cylinder and protected with resin.

Brake: the brake is composed of steel laser-cut precision components, together with rolled and welded steel in the rotating fab and machined and welded plate in the static fab. The component is finished with a cover plate. The sub-elements are also masked, blasted and painted.

Support: the PTO also incorporates a stiff support structure that locates the spine and stator housing. The structure is made of rolled steel plates, which are welded, machined, masked, blasted and painted.

Seal assembly: the seal consists of a machined steel housing, closed with another machined steel plate, which are painted afterwards. A synthetic rubber debris seal completes the seal set.

Electric and electronic housing: this component includes the instrumentation terminal box, the power electronics terminal box, the two terminal box plates, the spine cap, the support structure sealing ring, the spine cap cable protection plate, the electrical cabinet housing and door, and the two grand plates. All of these sub-elements are made of steel, with most of them going through welding, machining, masking, blasting and painting processes.

Spine unit: the unit comprises the bearing assembly, hub, spine, main seal assembly and spine mounting coupling. Again, all elements are steel-made, with several machining, masking, blasting and painting involved. Seals also include synthetic rubber rings.

Power electronics: it was not possible to obtain detailed information on all materials and processes involved in the manufacturing and supply of the power electronics. Instead, building on a similar previous LCA study for a wave energy converter [2], electronic systems were estimated to represent 3% or the total turbine (without the base/foundation) embodied carbon and energy.

Miscellaneous: hundreds of minor PTO elements are grouped here, such as fasteners and plugs, small rubber seals, small cables, sensors, electrical connectors and minor wiring. Time and resource constraints make a comprehensive and very detailed classification of all the materials and processes involved unfeasible and impractical (given the uncertainties in other areas such as the power electronics or the lifetime operating cycle). This is particularly difficult especially in the case of electronic components, which often follow complex sub-assembly processes. Nevertheless, an alternative method based on ratios between capital cost and embodied energy/carbon was utilised. This method was developed by Takayoshi et al. [14], and has been employed in similar LCA studies in the literature [2]. In the present study, miscellaneous items were assigned the factors for "connecting components" in [2]: an energy conversion factor of 2.352 MJ/£, and carbon conversion of 0.103 kg CO_2/£.

d. Subsea cable

Each turbine is connected to the network via a subsea cable to shore. The 3.3 kV cable has three copper cores, surrounded by a layer of XLPE insulation each. The full assembly is protected by a steel armour and a PVC outer sheath.

F. Assembly and installation

It was assumed that the turbine nacelles would be mounted in Nova's workshop in Leith (Edinburgh), and then shipped to Shetland, where the final turbines would be assembled in a harbour site by integrating the nacelles and the turbine bases. The carbon and energy footprint in the nacelle assembly process was based on estimations of crane and fork-lift usage derived from a previous LCA study of a Pelamis wave energy converter [4]. Crane and fork-lift hours were scaled with mass, and then converted into carbon and energy impacts by using the factors in Table IV.

It was assumed that the turbine nacelles would be shipped by road transport to Aberdeen and then embarked on a ferry to the harbour assembly site in Shetland. The bases/foundations were supposed to be manufactured in Lerwick and then road-transported to

TABLE V
REMOVAL SCENARIO FOR MATERIALS

Material	Recyclability
Steel	90%
Stainless steel	90%
Copper	90%
Aluminium	90%
Synthetic rubber	0%
Resin	0%
Fibreglass	0%
Concrete (steel reinforced)	90%
Magnets	95%
Oil (mineral)	0%
XLPE	0%
PVC	0%

the assembly site. Energy input and carbon emissions intensities in the shipments/transportation are detailed in Table IV.

A deployment rig was also considered under the installation carbon footprint. This is a one-off structure (i.e. one per array) designed to facilitate the installation and removal of the turbines. It is made of steel components, which are later welded, machined, masked, blasted and painted. This is assumed to be manufactured in Lerwick and shipped to the harbour prior to the installation.

The installation was assumed to require the usage of one working day of multi-cat per turbine. The average fuel consumption for the vessel, based on previous real deployments, was set at 814 litres per day [15].

G. Operations and maintenance

The operation and maintenance schedule for the TiPA-equipped array considers different types of actions. First, it involves biennial minor intervention cycles, which include detachment from foundation, towing ashore, inspections at the harbour site and re-deployment. Completion of all detachments for the whole array was assumed to take three days, with an equivalent time to re-install them. Turbines were assumed to be towed individually using the same multi-cat vessel type, with a fuel consumption of 381 litres per hour [16] when towing, and an approximated towing time of 0.5 hours (each way). As a reminder, the distance to be towed is one kilometre, which is the array's distance to shore and length of the subsea connection cable. A crane was assumed to be needed for one hour per turbine.

Second, apart from the minor planned maintenance, major activities were also included in the model, occurring every four years. In this case turbines were assumed to be detached one by one, spending one day on each of them. Turbines are then towed to shore but transported back to the workshop in Edinburgh for the inspections and maintenance activities, again following a combined road + ferry route. Five hours of crane utilisation per turbine were also incorporated. Once the preventive maintenance activities are completed, turbines are sent back to site following this process in reverse.

TABLE VI
SUMMARY OF EMBODIED ENERGY AND CO2 FOR THE WASTE TREATMENT ACTIVITIES

Process	Unit	Energy input (MJ/unit)	CO_2 emission (kg CO_2/unit)
Scrap steel (incl. stainless): landfill	kg	0.167	0.005
Scrap other metals (Cu + Al + magnets)	kg	0.167	0.005
Scrap other materials: landfill	kg	0.170	0.005
Waste rubber: incineration	kg	0.473	3.156
Waste concrete: sorting plant	kg	0.242	0.011
Waste concrete: recycling	kg	0.063	0.004
Waste concrete: landfill	kg	0.167	0.005

Finally, the life cycle model also covered the unscheduled interventions, with an expected biennial occurrence. The carbon and energy modelling of the unscheduled interventions followed the same model as the major planned O&M, but it was assumed that, on average, only 50% of the events would require the turbines to be sent to Edinburgh, whereas the remainder 50% could be solved in Shetland on the harbour site.

The embodied energy and CO_2 of replacement components was out of the scope of this analysis, and could potentially be included in further work once significant real-sea experience is gained from the testing of demonstration units and projects.

H. Decommissioning and disposal

Decommissioning is expected to be, to a great extent, a reversal of the assembly & installation process as defined in section III.D. All components would be recovered from the sea, with the bases/foundations and deployment rig shipped back to Lerwick for scrap and recycling, and the nacelles to Edinburgh for a final disassembly before recycling.

Past LCA studies on offshore renewable energy have shown that the recycling stage of the life cycle has a relevant impact on embodied carbon and energy [7], [17]. Thanks to recycling, the energy input and carbon emission associated to the raw material extraction and primary processing can be avoided, and hence credited or subtracted from the total carbon and energy footprint figures. Percentages of recyclability for the different materials are listed in Table V and were mainly sourced from a Life Cycle Assessment of offshore and onshore sited wind farms by Elsam Engineering [17], except for steel reinforced concrete (sourced from [13]) and magnets, which were not considered in the report. The recyclability figure for magnets was then set at 95%. All non-recycled materials are deposited in landfill, except rubber, which is assumed to be incinerated.

Carbon and energy intensities of waste treatment processes were sourced from the ecoinvent database [10] and are shown in Table VI.

IV. Results and Discussion

I. *Energy consumption and CO_2 emissions*

Results on embodied CO_2 emissions and energy for the life cycle of the TiPA-equipped-turbine array are displayed in Fig. 6. The gross embodied energy (i.e. excluding credit from recycling) is 45,620 GJ, the most relevant stage being O&M, which represents 49.4% of lifetime gross energy consumption, as it can be observed in Fig. 7 (top). However, it is closely followed by manufacturing. The gross life cycle production of CO_2 is 3,144 t, again with the greatest shares represented by O&M and manufacturing (see Fig. 7[bottom]).

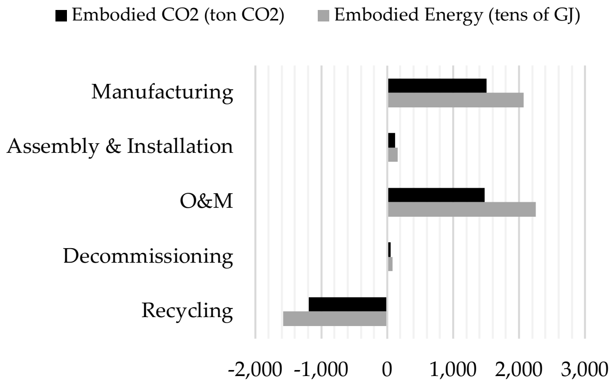

Fig. 6. Energy consumption and CO_2 emissions per life-cycle stage *(N.B.: stages as per Fig. 3. For units in the horiz. axis, see legend).*

Recycling accounts for a significant credit and lowers the net embodied energy by 15,800 GJ (35%) to 29,820 GJ. The 38% carbon credit reduces the embodied CO_2 to 1,955 t CO_2. The recycling credits are similar to the 30% figures for wind turbines [18].

Although reinforced concrete represents almost double the mass of steel in the turbines (Fig. 4), the latter is the main contributor to embodied carbon and energy. This disproportion is especially noticeable for instance when comparing the turbine breakdown by component in terms of mass (Fig. 5) with the disaggregation in terms of energy (Fig. 8) or carbon (Fig. 9). It can be observed that the energy and carbon impact shares of steel components such as the generator (both the rotor and the stator) are much higher than their respective mass shares. The opposite phenomenon occurs with the foundations, which are mainly made of concrete: their energy and carbon shares (42.4% and 45.8% respectively) are much lower than their mass share (82.9%).

J. *Energy and carbon intensity*

In order to facilitate comparisons of LCA performances between different electricity generation technologies, lifetime carbon emissions and energy inputs need to be 'normalised' by dividing them by the lifetime electricity production figure. This allows the derivation of the so-called energy and CO_2 'intensities'.

At Nova's synthetic site, the Annual Energy Production (AEP) for a single turbine was calculated to be 335.1 MWh/year. This figure was obtained by combining

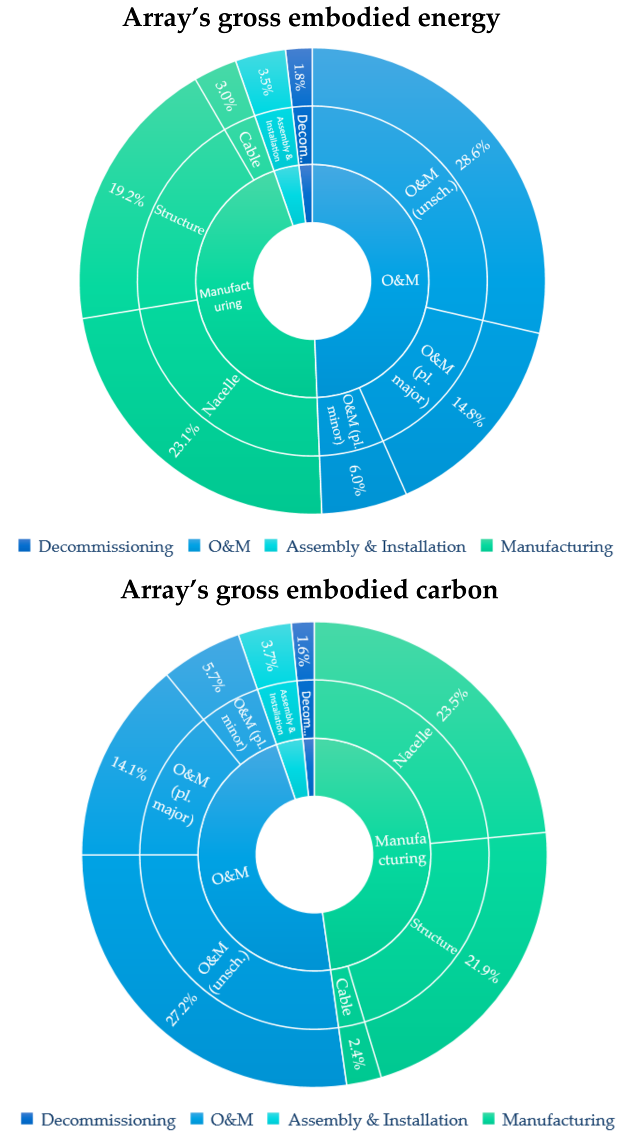

Fig. 7. Gross embodied energy (top) and carbon (bottom) breakdown for the array over its life-cycle.

the distribution of tidal current flow speeds (Fig. 2) with the TiPA power curve. Hence, the array's energy production over its 20-year lifetime is estimated at 67,020 MWh. An energy intensity of 445 kJ/kWh is then obtained by dividing the net life cycle energy consumption by the lifetime energy production. Equivalently, the life cycle CO_2 emissions indicate a carbon intensity of 29.2 g CO_2/kWh. Should the recycling credits be omitted, the respective intensities would increase to 680 kJ/kWh and 47 g CO_2/kWh.

The LCA performance of the representative array can also be assessed in terms of payback periods, which inform on how rapidly embodied energy and carbon are 'regained' by the carbon-free electricity generated by the TiPA-based project. Derivation of energy and carbon payback periods is shown in (1) and (2).

$$Energy\ payback = \frac{Embodied\ energy\ over\ lifetime}{AEP} \quad (1)$$

$$CO_2\ payback = \frac{Embodied\ CO_2\ over\ lifetime}{annual\ CO_2\ saved} \quad (2)$$

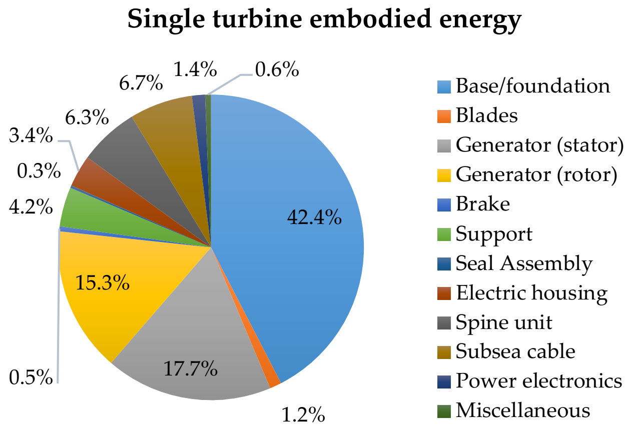

Fig. 8. Embodied energy breakdown by component of each TiPA-equipped turbine.

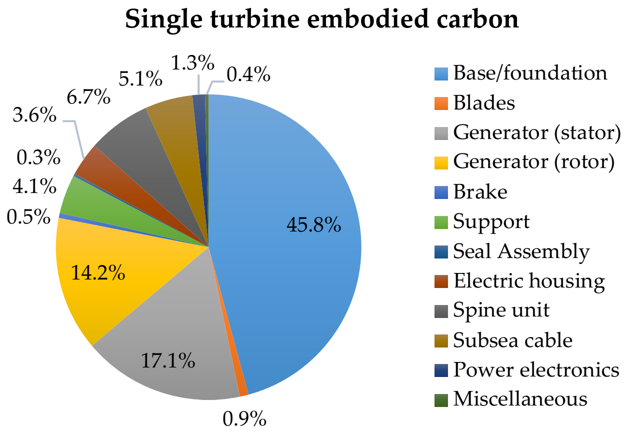

Fig. 9. Embodied carbon breakdown by component of each TiPA-equipped turbine.

The energy payback for the present study is around 29.7 months (2.5 years). Should the recycling credits be omitted, the payback period would raise to 45.4 months (3.8 years).

In order to assess the annual CO_2 saved by the TiPA-based array, it is common practice [5], [7], [8] to use the average carbon intensity of electricity generation, in this case (UK-based project) sourced from the Department for Business, Energy & Industrial Strategy (BEIS) and the Department for Environment, Food & Rural Affairs (DEFRA) [19]. In their latest conversion factor release [19], which refers to year 2016, a value of 0.28088 kg CO_2/kWh is suggested for electricity generation. Use of this figure yields an avoided carbon figure of 941.2 t CO_2. Based on BEIS and DEFRA's current UK grid factor, the carbon payback for the TiPA-equipped array is 24.9 months (2.1. years). Omission of the recycling credit from the calculation increases that figure to 40.1 months (3.3 years). Nevertheless, in practice the actual CO_2 saved is determined by the specific generation that is being displaced and it is time and location dependent. This is further expanded in section *IV.C.3) Carbon payback.*

K. Comparison with other sources of electricity

LCA metrics of the TiPA-based representative array can be compared with other marine renewable technologies of electricity generation. As mentioned in the introduction, some examples of specific alternative technologies with available LCA results are as follows:

- Wave devices: Pelamis [2]–[4]; Wavestar [5]; Oyster [6].
- Tidal stream devices: Seagen [6], [7]; Tidal Generation Ltd (TGL) Deepgen, OpenHydro, ScotRenewables & Flumill [8].

1) Carbon intensity

Fig. 10 shows a comparison of carbon intensities of several marine (wave and tidal) energy generating technologies, including the TiPA-based one. It can be observed that TiPA technology offers carbon intensities of the same order of magnitude as other wave and tidal technologies. Regarding tidal stream alternatives, TiPA is positioned in the higher end of the carbon intensity range. However, it must be highlighted, as stated in [7], that *"direct comparison with values from other LCA studies can be problematic, as the assumptions may be different and often non-conservative as well as issues regarding compliance with the ISO standards"*. For instance, energy and carbon intensity values used in Seagen's study [7] were lower than the ones employed in the present analysis. The reason for that is that the ICE database provides ranges of uncertainty in their intensity values, and in [7] the authors used less conservative figures than in the present study. Should the authors in [7] have used more conservative values (i.e. higher material values) in the LCA study of the Seagen device, the carbon intensity would have risen to 19.8 g CO_2/kWh (+ 32%).

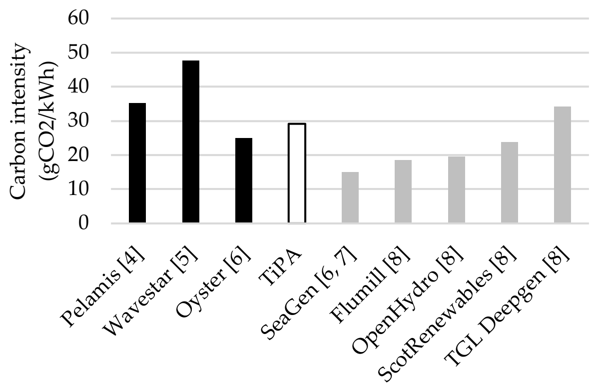

Fig. 10. Carbon intensity comparison of marine (wave [black] and tidal [grey]) energy generating technologies.

Additionally, the Seagen study benefited from lower carbon emissions associated to shipment and transportation because of its near-shore mainland location, whereas the present study considers a more remote example, with much larger distances to workshop.

Fig. 11 presents a comparison of TiPA with a range of other devices from an additional study completed in 2016 [20], in which the LCA performance of different anonymous ocean energy concepts was evaluated and classified by technology. The TiPA-based array's carbon intensity result is positioned in the lower three-quarters of all concepts considered.

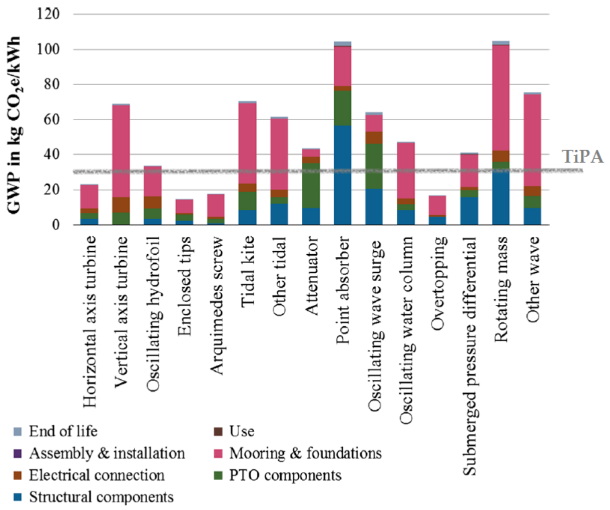

Fig. 11. Global warming potential according to life cycle step (adapted from [20]).

The TiPA-based array becomes especially environmentally-beneficial when compared to more traditional electricity generation alternatives such as fossil fuels. It also shows a good performance against better-established renewable technologies such as solar PV or geothermal. As can be observed in Fig. 12, TiPA's carbon intensity is significantly lower than that of nuclear power plants and even slightly lower than the 32 g CO_2/kWh quoted for solar photovoltaic cells [8]. Finally, it is also worth mentioning that further beneficial impacts would be expected for future TiPA-based arrays when progressing to larger (multi-MW) farms, thanks to economies of volume and scale.

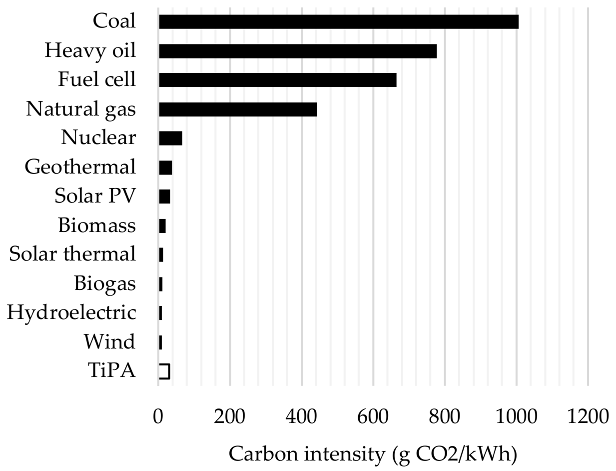

Fig. 12. Life cycle carbon intensities of the TiPA-based array and alternative energy generation technologies, after reference [8].

2) *Energy payback*

In terms of energy payback, the TiPA-based array's performance is even better positioned than it is with respect to carbon intensity. Fig. 13 displays an energy payback comparison of the TiPA technology versus the specific technologies previously analysed in Fig. 10.

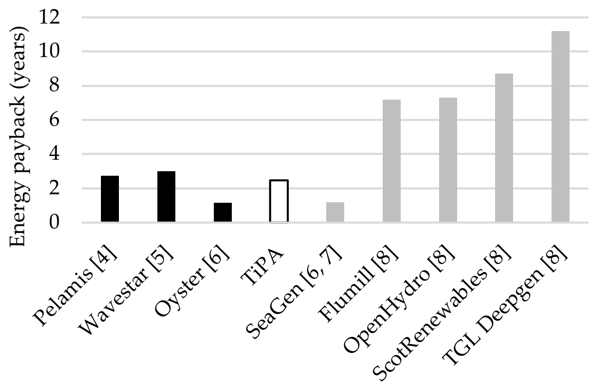

Fig. 13. Energy payback comparison of marine (wave [black] and tidal [grey]) energy generating technologies.

The contrast between the results plotted in Fig. 10 and Fig. 13 is partly caused by the different assumed energy yield performances for each technology. For the same value of embodied energy, the higher the capacity factor or AEP, the lower the energy payback, as can be concluded from (1). For instance, on the left-hand side of the graphs, studies on Pelamis and the Oyster considered optimistic equivalent capacity factors of 45% and 55% respectively, while studies on the last four tidal stream technologies on the right-hand side were based on capacity factor figures ranging from 18% to 24%, derived from manufacturers' power curves. This results in an apparently poorer (i.e. higher) energy payback for the latter with respect to the former.

3) *Carbon payback*

Finally, Fig. 14 shows the result comparison in terms of carbon payback. Again, the TiPA-based array offers a good performance when compared with alternative tidal stream generation technologies.

It must be also highlighted that the carbon payback figure is strongly dependent on the carbon intensity value used for the grid, as previously seen in (2) and explained in section B. The value used in the present study was the latest available (corresponding to year 2016), of 0.28088

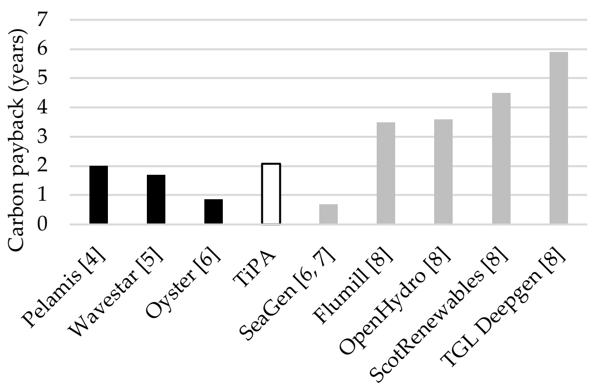

Fig. 14. Carbon payback comparison of marine (wave [black] and tidal [grey]) energy generating technologies.

kg CO_2/kWh. However, this figure has experienced a significant drop in the last years, from 0.49023 kg CO_2/kWh in 2012, to 0.4585 kg CO_2/kWh in 2013, 0.40957 kg CO_2/kWh in 2014 and 0.34885 kg CO_2/kWh in 2015. In fact, the studies on the technologies in Fig. 14 use past and hence higher grid carbon intensity values, such as 0.43 kg CO_2/kWh for Pelamis [2], Oyster and SeaGen [6]; 0.45453 kg CO_2/kWh for Flumill, Openhydro, ScotRenewables and TGL Deepgen [8] or 0.55874 kg CO_2/kWh for Wavestar [5]. Should one of those higher values had been used in the present study, for instance 0.43 kg CO_2/kWh, TiPA's carbon payback would have decreased considerably from 24.9 to 16.3 months.

Furthermore, although theory found in the literature recommends the use of the average carbon intensity of electricity generation available in the grid when computing the CO_2 payback, in practice the relevant displaced electricity would probably be fossil-fuelled dispatchable electricity generation [4]: for instance, in Shetland's case, the tidal energy projects deployed by Nova to date are displacing some particularly environmentally-unfriendly diesel generation rather than cleaner electricity sources such as wind. Again, should a fossil-fuel-like carbon intensity value had been used in the calculations, TiPA's carbon payback would be significantly reduced.

V. Conclusions

The present energy and carbon audit study covered the materials, components and life cycle stages that contribute to energy input and carbon emissions of the representative TiPA-equipped array. In each case, the most significant contributors were also identified. Both the manufacturing and the O&M phases were found to be equally important in terms of carbon footprint associated. The base/foundation was found to be the component with the highest representation in associated energy input and carbon emissions, due to its significantly increased associated mass.

Steel is the main contributor to the TiPA-based array's embodied energy and carbon. This is expected because of the preference towards steel given its good structural behaviour in large structures such as wave and tidal energy converters. At the same time, steel also provides most of the recycling credit, which reinforces the importance of its waste and disposal management.

It was found that, by providing a carbon intensity of 29.2 g CO_2/kWh and an energy intensity of 445 kJ/kWh, the LCA performance of the TiPA technology can compete with alternative ocean electricity generating technologies and offers many environmental advantages compared to fossil-fuelled generation. The energy payback period is approximately 30 months, and the carbon payback is 25 months.

Taking into account the early stage of development of the TiPA technology, result comparison with alternative and more established technologies is very encouraging.

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