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Tidal Energy machines: A comparative Life Cycle Assessment Study

Abstract

Marine energy in the UK is currently undergoing a period of growth in terms of development and implementation. The current installed tidal energy capacity is expected to rise to provide 20% of the UK's electricity demand by 2050 [5].

This work used Life Cycle Assessment to study four tidal energy devices, comparing their embodied energy and carbon dioxide emissions. In order to ensure a fair comparison, a hypothetical installation site was used. The device designs studied included a multi-blade turbine, two three blade horizontal axis turbine machines, and an Archimedes' screw device. These machines were chosen to represent a cross section of device, foundation, installation and operation designs. They have all been developed to prototype stage, meaning that actual manufacturing data was available.

Embodied energy was considered over the lifetime of each device, beginning with extraction of raw materials. Energy use from fabrication, transport, installation, maintenance, decommissioning and recycling were all calculated and compared to the energy generated by each device. Finally, the embodied energy, CO_2 intensity, and energy payback periods were compared to those of conventional power generating systems and other renewable energy sources.

Devices were studied based on a functional unit, defined as a 10MW array installed for 100 years. In three cases this was made up of five lifetimes of five devices, and in one case four lifetimes of 10 devices. Of the devices studied, the OpenHydro Open Centre turbine was found to have the best ratio of generated to embodied energy. All devices achieved CO_2 and energy payback within 12 years, and exhibited CO_2 intensity between 18 and 35 gCO_2/kWh. This compares favourably against current energy sources such as Wind (8 – 12 gCO_2/kWh), Solar PV (~30 gCO_2/kWh), Nuclear (~70 gCO_2/kWh) and coal (~1000 gCO_2/kWh) [29]. This figure is also likely to fall as technology improves, array size increases and industry experience progresses.

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1: Introduction

Anthropogenic climate change is now considered unequivocal [1], and its effects are visible in the world's climate. Rising sea levels; glacial retreat; temperature rise; shrinking sea ice; warming oceans and extreme weather events are all evidence of this.

This evidence emphasises the need to reduce greenhouse gas emissions in order to slow or limit the effects of climate change. Though other gases do contribute to the warming of the planet, Carbon Dioxide (CO_2) is considered the most harmful "greenhouse" gas [2]. 184 Mt of CO_2 were emitted in the course of energy generation and supply in the UK during 2011, which is 40% of total emissions for the UK[3]. Clearly, one strategy to reduce the UK's direct carbon dioxide emissions is to decarbonise the national grid.

Since 2005 the proportion of renewable energy contribution to the UK grid has steadily risen, and currently stands at around 4% [4]. Onshore and offshore wind power makes up nearly half of this capacity. The contribution from marine energy is currently negligible, but is predicted to increase dramatically by 2050.

The Carbon Trust estimates that a contribution of up to 20% of total UK energy generation could be provided by marine energy by 2050 [5]. There is an important distinction to be made between the two main types of marine renewable energy device: Tidal stream devices extract power from the movement of the tides and associated undersea currents, whereas wave energy devices extract energy from the movement of the water surface. Tides are caused by the rotation of the earth and the relative orbits of the moon and sun, and as a renewable energy source have a crucial advantage over other energy sources in that they are entirely predictable. This work focuses on the development of tidal stream power as an individual renewable energy source. This is also the focus of the author's other work [6].

Tidal stream technology is in its infancy, though there are a large number of companies working on the development of devices. As is common with technology at this stage of development, a wide spectrum of device types currently exist, and a market leader has yet to emerge, either in terms of a device design analogous to the wind turbine "Dutch model", or an individual company. However, a number of milestones have been achieved. In the UK, the focus of much development in the Tidal energy industry is the Orkney Isles, and specifically the European Marine Energy Centre (EMEC). The centre opened in 2003 and allows device developers to test prototypes in a real but controlled environment, with extensive monitoring. In 2008, OpenHydro became the first tidal energy developer to contribute energy to the UK grid (Figure 1).

Figure 1 – OpenHydro device installation at EMEC (Photo: EMEC)

Since this milestone, numerous other devices have been tested and grid-connected at EMEC. Devices have also been tested and operated in other locations. One of the most extensively tested installations is that of the MCT SeaGen device in Strangford Lough, Ireland. Since its installation in 2008 this twin-turbine device has generated 5GWh of electricity [7].

These successful test devices are paving the way for a viable source of predictable, renewable energy for the UK. However, it is critical that embodied energy and carbon dioxide (that is, the energy used and consequential carbon dioxide emissions during the construction, installation and use of the device) are considered during the development of devices, in order that those which are taken forward to full-scale deployment are the most suitable devices. This paper compares a number of devices and ascertains the life cycle properties of each one, in order to facilitate decision making based on robust environmental information.

1.1 - Life Cycle Assessment

It is inevitable, that over the life cycle of a product some energy will be consumed and most likely this will result in CO_2 emissions during the manufacture, construction, use and the end-of-life phases. In the construction of an energy source such as a tidal energy machine, the amount of energy used and CO_2 emitted are critical. If these levels are above those which will be offset by the device in operation, then the use of the machine has led to a net increase in energy use and CO_2 generation.

In order to ensure that a renewable energy source has a net benefit in energy and CO_2 terms, Life Cycle Assessment (LCA) can be used. This tool calculates the energy and CO_2 required to produce the energy source, and compares these figures to the energy and CO_2 “saved” by the source over its lifetime.

This study compares the energy and CO_2 required to manufacture tidal energy devices, beginning with the requirements of raw materials, through manufacture, transport and installation, to maintenance. End-of-life decommissioning and recycling are also considered. The study uses a functional unit of a 10MW array, operating for 100 years, in order to conduct a fair comparison across different device output levels and lifetimes. Further details are given in Section 3.4.

The quality and relevance of LCA results, and the extent to which they can be applied and interpreted, depends critically upon the methodology used. It is therefore important that methodology is transparent and well documented. ISO standards have been developed to provide guidance on methodological choices and to set down rules for transparency and reporting. The relevant standards are ISO14040 and ISO14044.

Steel forms the largest proportion of the material mass used in tidal energy devices, therefore the Worldsteel LCA methodology [22] was used for this study, as was data from the same source for ferrous materials. This includes consideration of the fate of materials at end of life, essential for a full understanding of the whole life cycle of a product or system. Data from the University of Bath Inventory of Carbon and Energy (ICE) v2.0 [14] was used for non-ferrous metals and other materials. Consequently, recycling was considered only for steel materials, as discussed in Section 5.7.

2: A Hypothetical Site

The location of a tidal energy device is clearly a critical consideration. The UK has a large tidal energy resource [30], but sites must be chosen carefully as each presents a different resource, as well as different challenges to a device developer and installer.

Due to these differences between tidal sites, such as water velocity and grid connection costs, it is imperative that comparisons of tidal energy devices are carried out in fair way.

Rather than selecting an existing site to use as a sample, it was decided to use a fictional site. This allowed the specification of what could be considered an average tidal energy site, without any unusual features or specific conditions which may exist on a real site, and may skew results towards a particular device. The use of a fictional site would also avoid potential problems gathering data for existing sites.

The site conditions have been chosen to represent a site with an exploitable tidal energy resource, but with some realistic challenges remaining.

It is assumed that although a small port exists adjacent to the tidal site, the closest port with a large dock is 50km away by ship. This port will be used for the transport of the devices to the installation site.

2.1 – Tidal site conditions

The hypothetical site was located in the UK, in a 5km wide channel between the mainland and an island. The sea bed area available for tidal energy extraction was assumed to be 1km x 1km, and to have the conditions detailed below, which are based on existing and planned tidal energy installations (eg. [33]).

- 50m water depth
- Max. tidal range of 2.6m
- Mean tidal velocity of 2.5m/s
- 5° angle between tidal ebb and flow
- Bedrock seabed

2.2 – Shore connection

The site will be connected to the shore by cables, and then linked to the local and national grid. It has been assumed that there would be an 11kV substation located on the coast.

The installation location and layout of each array is given in Section 3.5.

2.3 – Climate

The site was assumed to be located in the north of the British Isles, and to experience a cool temperate climate. Average summer and winter temperatures were assumed to be 12 and 4 °C respectively, with annual rainfall of 900mm and frequently strong winds.

Assumed daylight hours during the height of summer were long, with sunrise at 3am and sunset around 9:30pm. During the winter, however, daylight hours were short, with sunrise at 9am and sunset at 3pm. These conditions are similar to those experienced by developers installing devices at EMEC and other northern-UK sites, and have a significant effect on installation and maintenance windows.

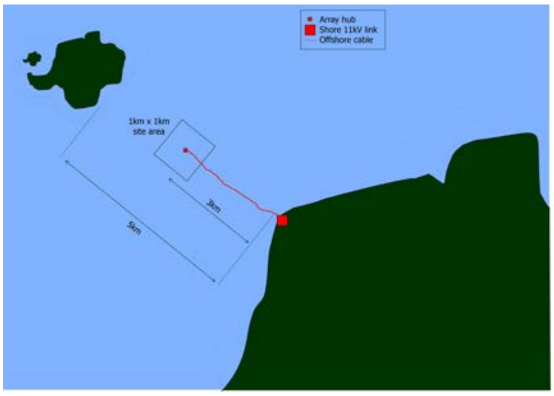


Figure 2 – Location of installation site

3: Selection of devices

3.1 – Device classification

There is a huge range of designs for devices to extract energy from the tides, ranging from full commercially-developed installed devices which are in operation and contribute to the grid, to those which exist only in idea form, but are firmly believed by their inventors to represent the future of the industry. EMEC [31] lists almost 90 tidal device developers on its website.

The first stage of this work was to distil this large number of designs down to a manageable sample to study in detail. Rather than considering specific machines, devices were initially characterised based on four design areas. These areas are:

- Device type
- Ducting
- Support Structure
- Foundations / Base

Within each of these areas, a range of options was defined. Each device was then able to be categorised by its position in each area. The full category list is given in Figure 3.

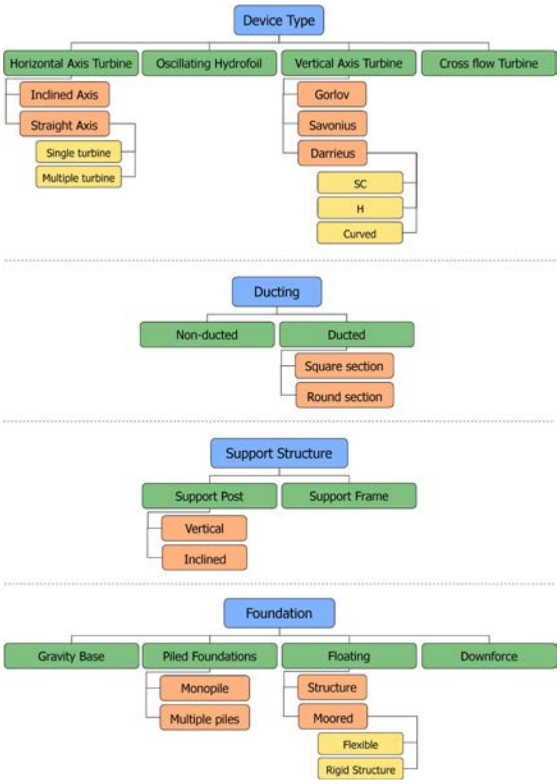


Figure 3 – Tidal device classification system

3.2 – Device selection

Using the system described in Section 3.1, each device known to the author or identified by EMEC was classified. After studying the range of commercial devices it was clear that the horizontal axis turbine was the dominant design, but there are many other types and it was felt that, ideally, a range of devices should be represented in this study.

A certain amount of information is required in order to accurately conduct a Life Cycle Assessment. It was felt that information such as installation procedure and foundation design can only accurately be gathered through the development of a prototype, so devices which were not developed to at least a prototype stage were ruled out.

This excluded a large number of devices. Research showed that of the 18 prototype devices which have been installed in real marine conditions, the following numbers fell into each device type category:

- Vertical Axis Turbine: 3
- Horizontal Axis Turbine: 12
- Flutter Vane / Hydrofoil: 2
- Crossflow Turbine: 1

All devices which had been prototype tested were considered for inclusion in this study, so a review of each was undertaken in order to ascertain its current level of development, and the availability of data relevant to the study. In the majority of cases device designs were not sufficiently developed to allow LCA work to be carried out (for example, the developers had not decided on a foundation type, or the size of the real device). After this consideration, four devices remained. These devices are listed below:

- Tidal Generation Ltd. Deepgen
- OpenHydro Open Centre Turbine
- ScotRenewables SR2000
- Flumill

The final four devices included in this study are detailed in Section 3.3.

3.3 – Selected Devices

3.3.1 – Tidal Generation Ltd.

The Tidal Generation Ltd. (TGL) *DeepGen* device is a tri-blade single turbine design, with a support structure mounted by piles to the seabed. A 500 kW prototype has been undergoing testing at EMEC since 2009.

The body and foundations of the device are constructed largely from steel, with the blades being of composite construction. The company's commercial device is rated at 1MW and has a 25 year design life.

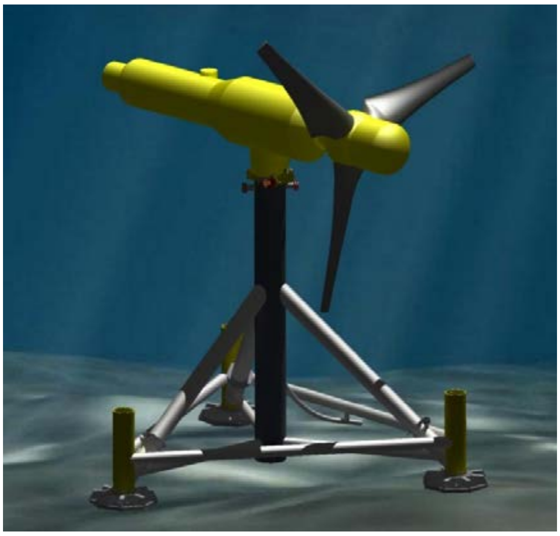


Figure 4 – TGL DeepGen (Photo: TGL)

3.3.2 – OpenHydro

The OpenHydro device is an open-centre horizontal axis multi-blade turbine with a ducted housing, known simply as the *Open Centre Turbine.*

Four commercial-scale devices are currently being installed in an array off the Brittany coast. The device is constructed primarily from steel, with glass reinforced plastic blades. Commercial scale devices are rated at 2MW and as having a 20 year design life. The company has developed an installation method using their own specific installation barge.

Figure 5 – OpenHydro Open Centre Turbine (Photo: OpenHydro)

3.3.3 - ScotRenewables

The ScotRenewables SR2000 device is a floating twin horizontal axis turbine design, with cable moorings, constructed of steel with composite blades.

A 250kW demonstration device has undergone a 12 month testing period at EMEC in Orkney.

The commercial scale device will be rated at 2MW, and is designed for installation in arrays of 10MW, with a 20 year design life.

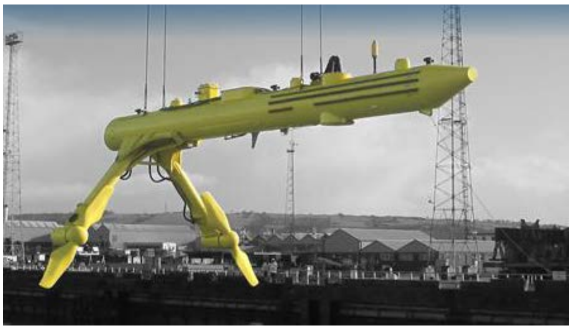


Figure 6 – ScotRenewables SR250 (Photo: ScotRenewables)

3.3.5 – Flumill

Flumill is a unique twin Archimedes' screw design of tidal device, mounted to the seabed by a monopile foundation.

A test device has been installed at EMEC for 3 months. The commercial scale device will be constructed from PVC Foam with a composite shell, and is rated at 2MW for a 20 year design life.

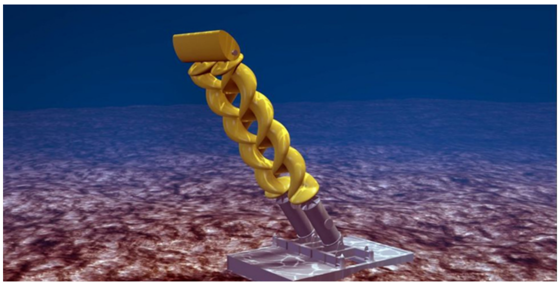


Figure 7 – Flumill (Image: Flumill)

3.4 – Functional Unit

In order to allow direct comparison of devices of different rated power and design life, a functional unit was defined, under which Life Cycle Assessment will be conducted.

The functional unit for this analysis has been defined as a 10MW array, connected to the grid for a period of 100 years. This array size is representative of those expected to be installed during the next decade.

Since the devices under consideration are in the 1-2MW size range, and have lifetimes in the region of 20 years, multiple devices and installations will be necessary to achieve the functional unit. The required number of units and lifetimes required in each case is described in Table 1.

	TGL	**OpenHydro**	**ScotRenewables**	**Flumill**
Devices	10	5	5	5
Lifetimes	4	5	5	5

Table 1 – Device number and lifetimes required to achieve LCA functional unit

4: Array Design

The four devices included in this study are all classed as offshore devices, and are thus designed for deployment in the same area. As described in Section 2, water depth of 50m is found at 3km offshore. This is the area in which the devices will be installed.

All four devices require an array of multiple machines in order to achieve the requirements of the functional unit as described in Section 3.4. The TGL device requires an array of ten devices, while the other three devices each require arrays of five machines.

4.1 – Array Layout

Array layout is a complex part of array design, in which work is currently ongoing in order to optimise layout of devices over the available area. Device spacing assumed during this work is been based on current work [9, 10, 11], and is described in multiples of each device's major diameter (Rotor diameter was used for TGL and OpenHydro devices, with maximum width being used for the Flumill and ScotRenewables devices). Spacing figures used are 15 diameters in the streamwise direction and 5 diameters in the perpendicular direction. The layouts assumed for each device in the study are shown in Figures 8 – 11, below.

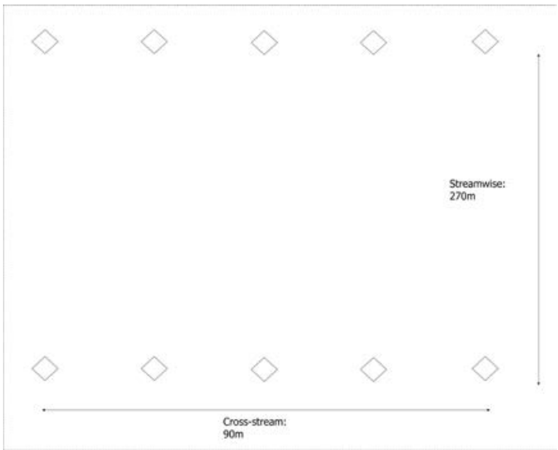


Figure 8 – TGL device 10MW array layout

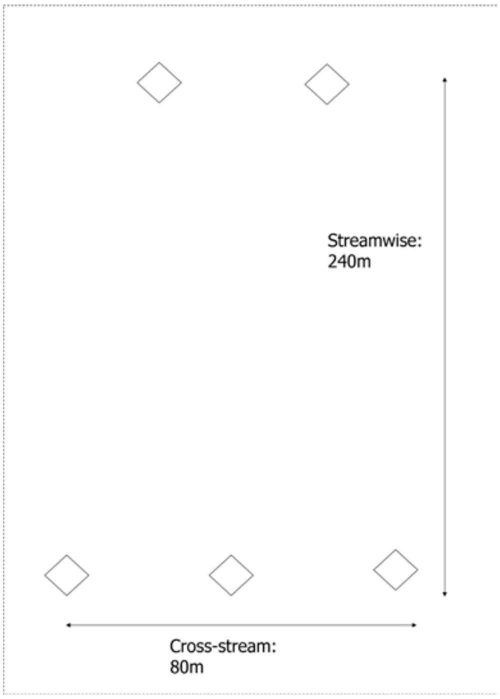


Figure 9 – OpenHydro device 10MW array layout

Figure 10 – ScotRenewables device 10MW array layout

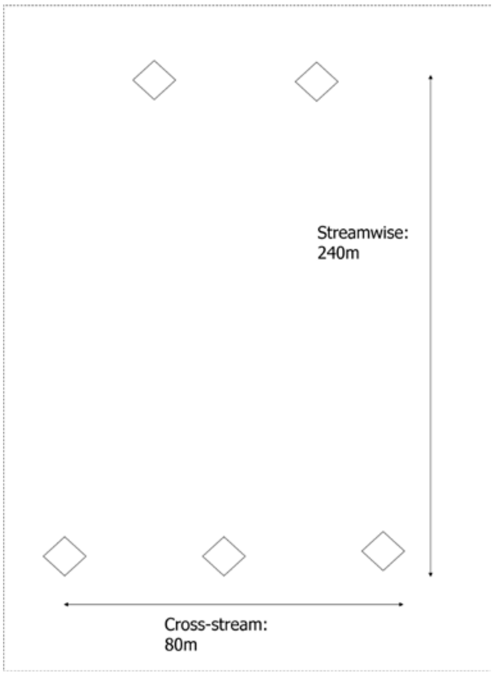


Figure 11 – Flumill device 10MW array layout

4.2 – Power Cables

4.2.1 – Cable Layout

Three main options exist for the layout of power cables within an array. These options are known as Single, Hub and Rail, as illustrated in Figure 12 (from [11]).

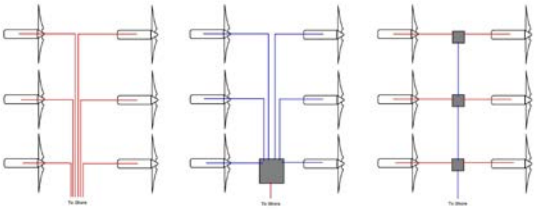


Figure 12 – Tidal array cable layout options: Single, Hub, Rail (l-r)

Due to the number of devices, a hub layout has been assumed for this study. In each case, the hub was assumed to be located at the centre point of the array, 3km offshore. Cable length calculations have been undertaken for each array separately.

Cable length (m)	TGL	OpenHydro	ScotRenewables	Flumill
Device-hub cables	1620	720	1125	720
Hub-shore cables	3000	3000	3000	3000

Table 2 – Cable lengths required for each array

4.2.2 – Cable Specification

Two specifications of cable have been used for the purposes of this study, the first to link the devices to the central hub, and the second to provide the hub to shore link. The shore link cable is assumed in all cases to be an armoured multi-core cable, with a specification based on that used in known installations [12]. The array cable comprises three cores, each of 500mm² copper with polyethylene insulation. The cable also has steel wire armour surrounding the cores. The shore link cable has an overall diameter of 750mm. A cross-section of a similar cable is given in Figure 13.

Figure 13 – Shore link cable cross-section

The cable used to link the devices to the hub is of the same design, but is of smaller diameter. In the case of the TGL device, three cores of 50mm² were assumed, giving a total diameter of 79mm. For the other devices, three 100mm² cores were assumed, giving a total diameter of 112mm.

4.3 – Foundations

The TGL, OpenHydro and Flumill devices each use piled foundations, whereas the ScotRenewables device employs a cable mooring system, with gravity bases at the end of each cable. The basic specification of the foundation system of each device is given below:

TGL:
Three 10m x 2m steel piles, set in concrete inside drilled sockets.

OpenHydro:
Two 10m x 2m steel piles, set in concrete inside drilled sockets.

Flumill:
Single monopile steel pile, 10m x 4m, set in concrete inside drilled socket.

ScotRenewables:
Four cable catenary mooring system, with cables extending to adjacent devices in streamwise and lateral directions. Cables mounted on 500t concrete gravity bases.

5: Embodied Energy

The first stage of the Life Cycle Assessment was the calculation of the embodied energy and CO_2 for each of the individual devices described in Section 3, which was undertaken using Microsoft Excel. These numbers can then be multiplied by the values calculated in Table 1 to give embodied CO_2 and energy figures for the total functional unit.

In order to ensure a fair comparison between devices, the installation site has been developed as described in Section 2. Additionally, it has been assumed that all devices are manufactured in the same location (as discussed in Section 5.2).

5.1 – Materials

The initial stage of calculation of energy and CO_2 embodied in the materials of each device was to ascertain the mass of materials used in the construction of each device.

The mass of each material was calculated for each device, based on data supplied by manufacturers and available through other sources such as literature, brochures and presentations. Calculations were carried out for the major device structure, the foundation or mooring system, and cabling to shore. Values for single devices were then multiplied as appropriate to represent array sizes given in Table 1.

The TGL, OpenHydro and ScotRenewables devices are manufactured primarily from steel, and this makes up a large part of the material usage in these devices. The Flumill device uses less steel as its Archimedes screws are manufactured from PVC Foam with a composite shell, leading to large usage of these materials. Foundations in all cases use large amounts of steel (as piles in the TGL, OpenHydro and Flumill devices, and cables in the ScotRenewables device) and concrete. Iron and Copper are used in electrical components like generators, and stainless steel is used in gearboxes and shafts.

Total material mass for each device array is given in Table 3.

Material (tonnes)	**TGL**	**OpenHydro**	**Flumill**	**ScotRenewables**
Plate Steel	1139	313	149	1295
Section Steel	757	1688	850	0
Welded pipe Steel	732	1129	244	0
Wire rod Steel	15	15	15	519
Stainless Steel	274	1	1	69
Composite	261	0	106	249
PVC Foam	0	0	550	0
Cement	1473	491	981	0
Iron	83	28	28	80
Copper	62	61	61	62
Concrete	0	0	0	7500
Polyethylene	9	9	9	9
GRP	0	182	0	0

Table 3 – Material mass in each array, including foundations/mooring and power cables (single device lifetime)

Following these calculations, embodied energy and CO_2 factors were applied to the mass of each material in order to calculate the total embodied energy and CO_2 for each device. Data for these calculations was provided by worldsteel [13] (via TATA Steel) for steel plate, section, rod and pipe materials, and from the University of Bath ICE (v2.0) [14] for all other materials. For steel materials (excluding stainless steel), it should be noted that the figures assume a proportion of recycled material, in accordance with Worldsteel recycling methodology [22]. Steel plate, section, pipe and rod have been assumed to have an 85% recycling rate, based on global construction sector averages. Recycling at end-of-life is discussed in Section 5.7.

Summaries of material-derived embodied energy and CO_2 emissions for each device are shown in Figure 14a, with array totals as in Table 3 given in Figure 14b.

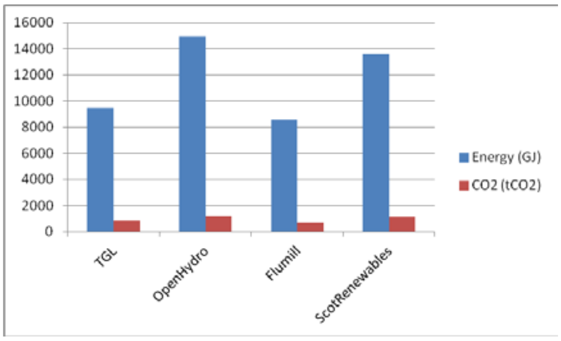


Figure 14a – Embodied energy and CO_2 (Materials – single device)

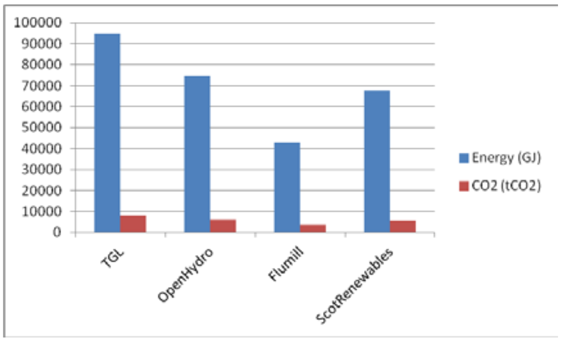


Figure 14b – Embodied energy and CO_2 (Materials – array, single device lifetime)

5.2– Manufacture

Having ascertained the embodied energy and CO_2 in the production of the materials used in the manufacture of each device, the next stage was to calculate the energy and CO_2 requirement of the fabrication stage to turn these materials into the devices themselves. For each device, a summary of the major manufacturing processes required to achieve this was generated. The manufacturing processes for each device are shown in Table 4.

TGL	OpenHydro	Flumill	ScotRenewables
Main body welding	Main body welding	Base welding	Main body welding
Base welding	Base welding	Screw shell casting	Blade casting
Blade casting	Blade casting	Screw core cutting	Main body machining
Main body machining	Main body machining	Base machining	Body painting
Base machining	Base machining	Body painting	
Body painting	Body painting		
Base painting	Base painting		

Table 4 – Major manufacturing processes for each device

Total energy and CO_2 embodied in the manufacture of each device was then estimated using data from previous studies [12] and ICE data [14]. Painting data was based on calculated surface areas.

A summary of manufacture-derived embodied energy and CO_2 emissions for the four devices are shown in the figure below.

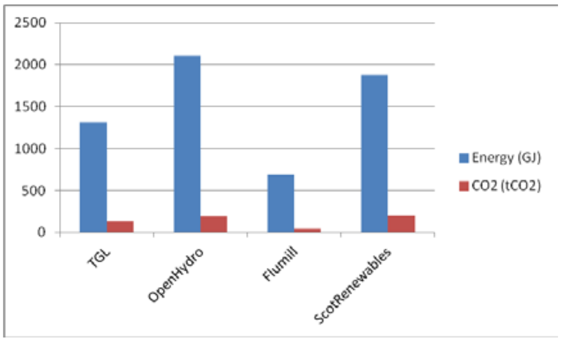


Figure 15 – Embodied energy and CO_2 (Manufacture – single device)

5.3 – Transport

Once manufactured, tidal energy devices must be transported to their installation location. Due to the remoteness of typical tidal locations, transport distances can be significant. This section of the study aimed to calculate the embodied energy and CO_2 in the transport of the devices to site.

In order to carry out a fair comparison of the four devices in this study, it was decided to assume a single manufacturing location for all devices. This would negate the additional energy use in the transport of devices manufactured far from the installation site, the inclusion of which would unfairly skew results. It was therefore assumed that devices were manufactured at a site 300km from the nearest port to the installation site. From this port the devices will be transported 50km by sea to the installation site. Transport of the devices by sea is included in installation calculations (Section 5.4). Transport to the port was assumed to be undertaken by road, using a specialist heavy haulage contractor.

The tractor units and trailers operated by such contractors are typically able to transport loads of up to 600tonnes [16]. Since the total calculated weight of each of the devices, excluding power cables and foundations, is less than this figure, it was assumed that a single device could be transported from manufacturing site to installation port in one trip.

A typical fully-loaded heavy haulage vehicle has a fuel consumption figure of around 0.54 l/km [17]. This equates to 162 litres of diesel for the journey required. Studies [17, 18] show that this type of vehicle has a typical energy intensity of 0.36 MJ/km-tonne and CO_2 intensity of 40.6 g/km-tonne. Applying these figures to the mass of each complete device gives the embodied energy and CO_2 in the transport of a single device, as described in Table 5. A one-way journey has been assumed, since a haulage contractor would aim to move from one job to another rather than return empty.

	TGL	**OpenHydro**	**Flumill**	**ScotRenewables**
Total mass (t)	251	621	339	343
Energy (GJ)	27.1	67.1	36.6	37.0
CO_2 (t CO_2)	3.1	7.6	4.1	4.2

Table 5 – Embodied energy and CO_2 (transport)

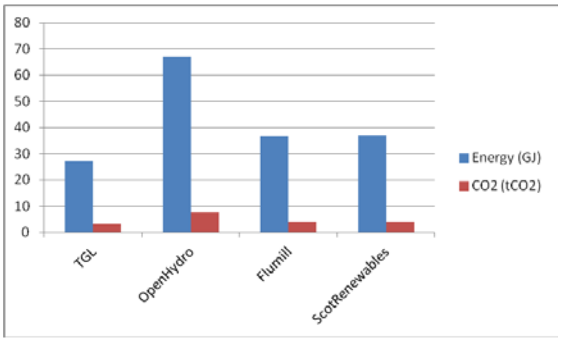


Figure 16 – Embodied energy and CO_2 (Transport – single device)

In order to meet the requirements of the functional unit, the transport of multiple devices must be considered. In the case of the TGL device, an array of ten devices is assumed, which is replaced four times, giving a total of 40 journeys. In the other three cases, an array of five units is replaced five times, giving a total of 25 journeys. The total embodied energy and CO_2 from device transport is given in Table 6.

	TGL	OpenHydro	Flumill	ScotRenewables
Energy (GJ)	1084	1677	915	926
CO_2 (t CO_2)	122	189	103	104

Table 6 – Embodied energy and CO_2 for total functional unit (transport)

It should be noted that transport of devices for maintenance and after their service lifetime has not been included in this section, but is considered in Section 5.6.

5.4 – Installation

The installation of a tidal energy device is a complex process with numerous stages. In order to correctly calculate the embodied energy and CO_2 of each device's installation, a comprehensive list of the processes required in each case was created, based on information from manufacturers and installation contractors. The method of completing each process was then ascertained, allowing the calculation of embodied energy and CO_2 for each process.

A general summary of the process areas identified is given below.

- Drilling of pile sockets*
- Pile placement*
- Placement of support structure on piles*
- Cable trench cutting
- Cable laying
- Transport of device to site
- Installation of device on support
- Connection of device to cable

* processes do not apply to ScotRenewables device

Many processes, such as pile drilling and support structure installation, require the use of large ships. In some cases, there is a requirement for vessels with Dynamic Positioning (DP) capability. This requirement is sometimes considered a disadvantage, as these vessels can cost up to £150,000 per day [19] to charter. The installation process is considered by many to be an area in which large cost and efficiency savings can be made as tidal stream technology develops, and many device manufacturers are trying to develop installation procedures which do not require these vessels.

Embodied energy and CO_2 were calculated initially for a single device installation, excluding cabling between the array and shore connection. This was then calculated separately and added to the sum of installation requirements for the size of array defined by the functional unit. It was assumed that at the end of the lifetime of the first array of devices it would be necessary to remove and re-install the entire array, including all support structures and cables. This is discussed further in Section 5.6.

Embodied energy and CO_2 in the installation of a single unit (excluding shore cabling) is given in Figure 17.

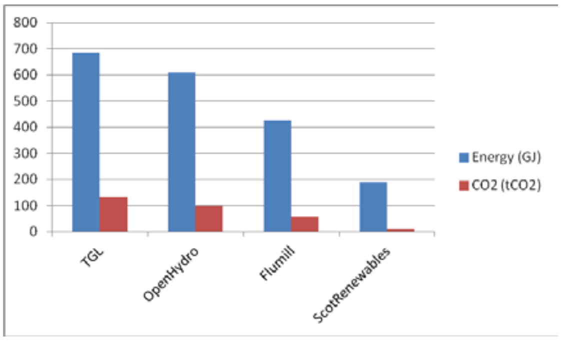


Figure 17 – Embodied energy and CO_2 (Installation – single device)

5.5 – Maintenance

Maintenance schedules have been calculated for each device based on the current estimates of device manufacturers. Embodied energy and CO_2 arising from maintenance was found to depend heavily on the frequency and method of maintenance, i.e. whether the device requires removal from its installation site, and the ease of doing so.

The TGL, OpenHydro and Flumill devices are all designed to be removed from their location and returned to shore for maintenance, whereas the ScotRenewables device is designed to allow minor maintenance in-situ. The maintenance strategy assumed for each device is given below:

TGL:
Routine maintenance every two years. Device is towed to shore. 100 hours maintenance assumed.

OpenHydro:
Routine maintenance every five years. Device is lifted and towed to shore. 300 hours maintenance assumed.

Flumill:
Routine maintenance every five years. Device is lifted and towed to shore. 200 hours maintenance assumed.

ScotRenewables:
Minor in-situ maintenance every two years (access by RIB).

Routine maintenance every 10 years. Device is towed to shore. 200 hours maintenance assumed.

Maintenance calculations included embodied energy and CO_2 from vessel transport, removal from foundations, winching or craning the device to and from its working location, and maintenance by technicians. Values for each device are given below.

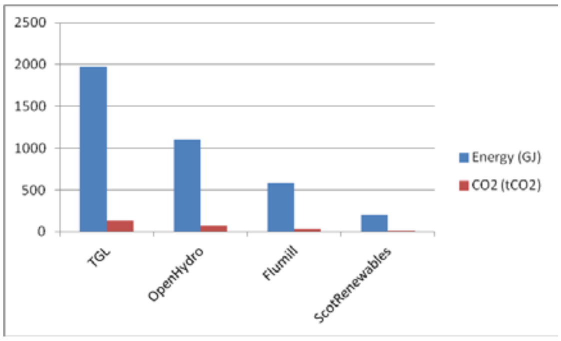


Figure 18 – Embodied energy and CO_2 (Maintenance – single device)

5.6 –Decommissioning

End-of-life considerations must be taken into account in order to complete a full LCA study. In the case of tidal energy devices, decommissioning is likely to have a significant embodied energy and CO_2 impact, particularly as numerous device installations are required in order to meet the requirements of the functional unit.

A key question in installation and decommissioning calculations for the four tidal devices in question was whether or not the entire system would need to be removed at the end of each device lifetime, or whether cabling or foundations could remain in situ for multiple device lifetimes. Studies of monopile wind turbine installations [20] and subsea cable installations [21] suggest that both piled foundations and subsea cables have lifetimes in the region of 20 – 30 years, so it was decided to assume full replacement of foundations and cables at the end of each array lifetime.

Decommissioning figures were calculated by reversing the order of installation processes and calculating the embodied energy and CO_2 in each process. Clearly some installation processes, such as pile drilling, are not reversed during decommissioning, so these processes were not included in decommissioning calculations. Similarly, in some cases the reversed process may be less or more energy-intensive than the installation process. In these cases, a separate calculation for the removal process was undertaken.

The embodied energy and CO_2 of the decommissioning process is given below.

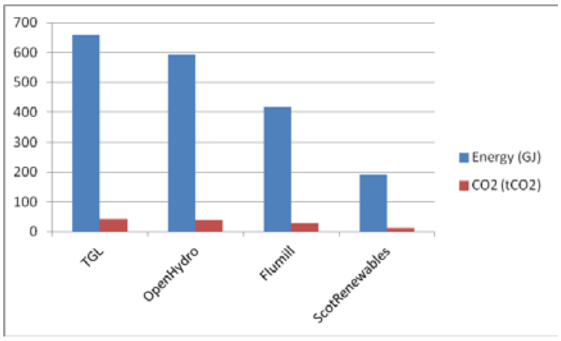


Figure 19 – Embodied energy and CO_2 (Decommissioning – single device)

5.7 – Recycling

The final area to be considered during embodied energy and CO_2 calculations was the recycling of parts after decommissioning. Recycling was assumed only for steel materials. Non-steel materials identified in Table 3 are Concrete, Cement, Iron, Copper, Polyethylene, PVC, GRP and Composite materials.

Concrete and cement are used in foundations, and discussions with manufacturers suggest that no provision will be made for the recycling of foundation materials due to the inherent difficulties of doing so.

Iron and Copper materials are used in generators and in cables and are able to be recycled following the dismantling and processing of these components, but unfortunately the recycling of these materials is beyond the scope of this study. These materials make up between 1% and 3% of material mass in each array.

Reinforced plastics and composite materials have again been assumed not to be recycled. Particularly in the case of composite materials used in blade manufacture, recycling methods are currently in their infancy and reliable data on recoverable energy is not available [34].

Recycling of steel materials was addressed using the end-of-life methodology, as described in the worldsteel report [22]. This methodology assumes that all recycled material is used in another life cycle, and states that the product system (the system under consideration) receives a credit for the avoided burden of virgin materials in the next system. The use of recycled steel in the manufacture of the devices in question has already been considered in Section 5.1, so this section considers only end-of-life impacts.

In each case, the volume of steel available was calculated by considering the fraction of installed steel that could be removed, and multiplying by the recycling rate. Subsequent available volumes of steel from each device were used to calculate the saving in virgin material usage. More than 1kg of scrap steel is required to generate 1kg of usable recycled steel, so a calculation must be undertaken to ascertain the energy and CO_2 associated with generation of the recycled steel. This can then be deducted from the values of the displaced virgin material to give the credit to the product system. The following equation was applied (from [22]):

$$LCI_{scrap} = Y\,(X_{pr} - X_{re})$$

Y = mass scrap required to produce 1kg steel
X_{pr} = Energy or CO_2 intensity of 1kg 100% virgin steel
X_{re} = Energy or CO_2 intensity of 1kg 100% recycled steel

All steel products (excluding rebar, though this was not used) were assumed to have a recycling rate of 85%. This is based on a global average for the construction sector, as calculated by worldsteel [22]. Recovery rates were estimated to be 100% for device materials, and 90% for foundation materials. It was thought reasonable to assume a 100% device recovery rate since all the devices in this study are designed for full recovery at the end of their life. Foundation materials above the seabed are also designed to be fully recovered, with those installed subsea left in situ, leading to the 90% value.

These factors were applied with Y above, to ascertain the energy and CO_2 credit applicable to each kilogram of steel recycled. These values were then used to calculate total energy and CO_2 credits applicable to each device, which are shown below.

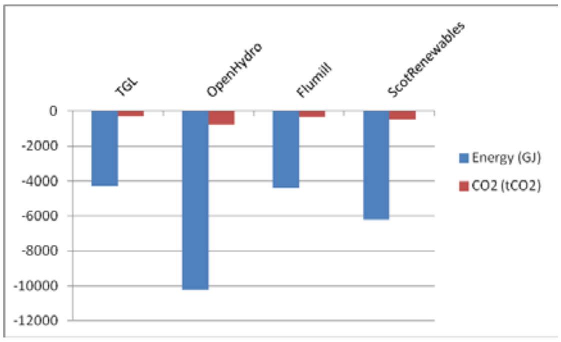


Figure 20 – Embodied energy and CO_2 credits (Recycling – single device)

5.8 – Lifetime Energy and CO_2

By combining the calculated embodied energy and CO_2 as described in sections 5.1 – 5.7, a total picture of the energy and carbon intensity of a 100 year, 10MW array of each device type can be ascertained, as illustrated in the figure below.

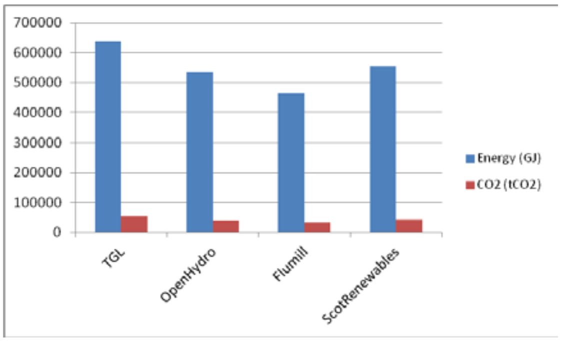


Figure 21 – Total embodied energy and CO_2 (100 year, 10MW functional unit)

As shown, the TGL device has the highest embodied energy and CO_2 values of the four devices. This is largely due to the increased material and installation requirements of this 1MW device, as opposed to the 2MW devices used in the other three arrays.

The remaining three devices show lower values of maintenance energy, due to the increased efficiency of maintenance travel for a larger device. The OpenHydro device has the second highest overall energy requirement, largely due to its high material intensity. Conversely, the relatively lightweight structure of the Flumill device means it has a significantly lower energy requirement in the materials section, leading to the lowest overall energy requirement. The ScotRenewables device benefits from its cable mooring system in terms of maintenance and installation energy requirements, though this does require extensive manufacture of conrete.

A full breakdown of the embodied energy and CO_2 from each section of the study is given below.

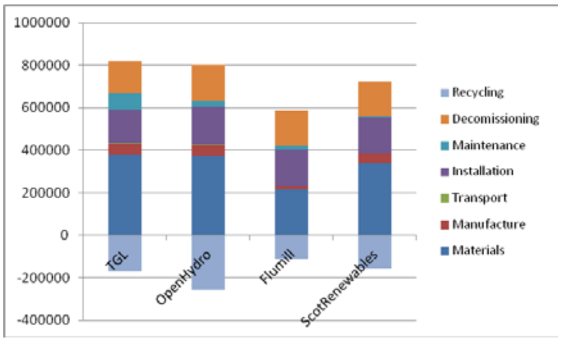


Figure 22 - Total embodied energy per functional unit (GJ)

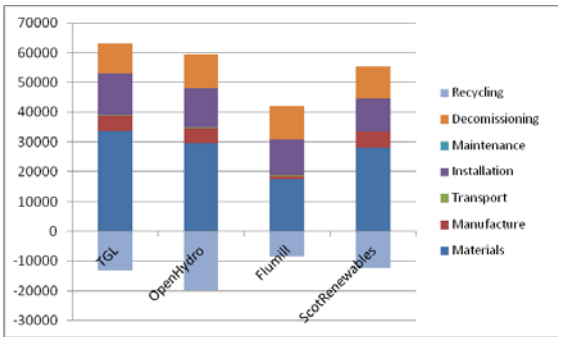


Figure 23 – Total CO_2 emissions per functional unit (t CO_2)

Having calculated the embodied energy and CO_2 of each device's functional unit, the next stage of the LCA study involved calculating the energy output of each device array, in order to offset this against the embodied requirements to calculate the overall energy and CO_2 balance in each case. This calculation is detailed in Section 6.

6: Energy Output

The predicted energy output of each of the four devices was calculated based on the hypothetical installation site described in Section 2. The site has a tidal range of 2.6m at spring tides, and a mean tidal velocity of 2.5m/s. The tidal height variation over a sample month at the site is shown below.

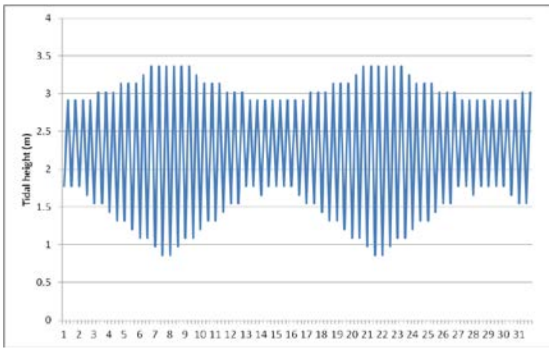


Figure 24 – Tidal height variation (typical month)

In order to calculate the output of each device during the tidal cycle shown in Figure 27, power curves for each device were created from data given by manufacturers [23, 24, 25, 19], including cut-in and cut-out speeds. Having calculated tidal velocity from the range shown above, these curves were then used to calculate the power produced by each machine during each tidal ebb or flow period. Maintenance periods were then deducted from the total array output for each device, with all maintenance assumed to take place during the summer months, as discussed in Section 2.3.

Two devices (OpenHydro and Flumill) do not rotate to follow the tidal direction, so are only able to achieve their theoretical maximum output at sites with 0° offset between ebb and flow. Since the site in question has an offset of 5°, the power output of these two devices was multiplied by a factor of 0.996 (cosine of 5°) during ebb tides in order to account for this.

Following the calculation of energy output for each device type, a similar calculation was carried out for CO_2 emissions. This calculation assumed that energy generation using tidal power would replace generation by conventional sources. It was therefore assumed that the current intensity of grid electricity [32] was offset. It should be noted that the CO_2 factor of the national grid is likely to change over the 100 year functional unit period, and the use of future grid scenarios is discussed further in Section 7.1. The energy generated and CO_2 saved calculated as described above for each device are shown below:

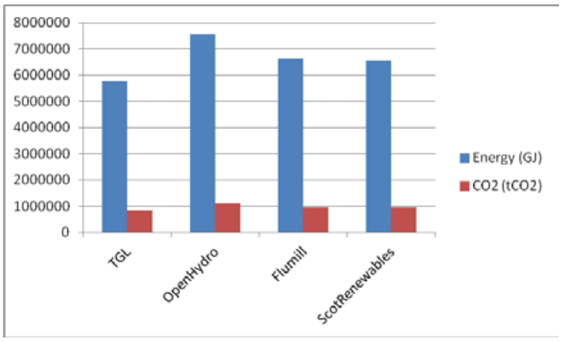


Figure 25 – Lifetime energy generation and CO_2 savings for total functional unit

The OpenHydro functional unit generates just over 7,500,000 GJ, in comparison to the Flumill and ScotRenewables figures of around 6,500,000 GJ and TGL of approximately 5,800,000 GJ. This is due largely to the different shape of the power curve of each device, with the relatively low cut-in speed (0.7m/s) of the OpenHydro device allowing it to generate electricity at lower speeds than the other devices. It should be noted, however, that the TGL device reaches its maximum power output at lower speed than the other devices, so at a site with very high average tidal velocity this device would achieve greater output than the others.

7: Life Cycle Assessment

Having calculated the embodied energy and CO_2 (Section 5) in each functional unit, and the lifetime energy generation and CO_2 saving (Section 6), these two sides can be compared in order to ascertain the life cycle properties of each device. The figures below illustrate the relative energy and CO_2 inputs and outputs for each device. The term “debt” is used to mean energy used or CO_2 emitted, with “credit” used to describe energy generation or CO_2 offset. The figures below are based on the current UK grid CO_2 factor of 0.45453 kg CO_2/kWh [32].

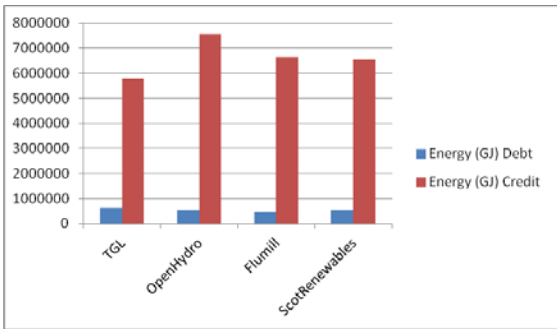


Figure 26 – Life Cycle Energy debt and credit (full lifetime functional unit)

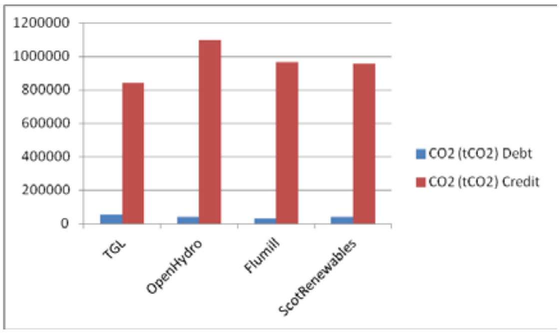


Figure 27 – Life Cycle CO_2 debt and credit (full lifetime functional unit)

Figures 26 and 27 show a similar pattern to Figure 25, with the OpenHydro device generating the most energy, followed by Flumill and ScotRenewables, and finally TGL. However, the comparison of energy and CO_2 credit and debt reveals that energy and CO_2 debt of the OpenHydro and Flumill devices represent 7% and 4% of credit respectively (i.e. total embodied energy is 7% of the energy generated by the functional unit). The ScotRenewables device yields values of 8% and 5% respectively, and TGL 11% and 7%, with the lower rated output of this device again counting against it.

7.1 – Future Energy Scenario

In the future, as electricity generation sources move away from fossil fuel-based sources towards lower carbon sources, the UK's grid carbon intensity will reduce. DECC [28] has conducted modelling to estimate the effect of this progression. The DECC "Gone Green" scenario is based on the UK meeting its CO_2 emission targets, and assumes a gradual reduction in total UK energy use.

The scenario modelled by DECC assumes a gradual change in electricity supply, from current sources towards a 2050 scenario dominated by nuclear and wind. DECC does not provide projected data beyond 2050, but by extrapolating the prediction forward to 2100 a projection of carbon intensity of grid electricity was generated, as shown below.

Year	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
CO_2 g/kWh	454{1}	222{1}	48{1}	38	33	30	26	22	18	14

{1} – DECC “Gone Green” scenario [28]. Remainder extrapolated from [28] using [29]

Table 7 – National grid projected CO_2 intensity

Using the data in Table 7, CO_2 credit from the tidal energy devices under consideration was re-calculated. As the grid CO_2 intensity reduces, the emissions offset reduce each year. This re-calculated data is shown in comparison to the original scenario (shown in Figure 29) below.

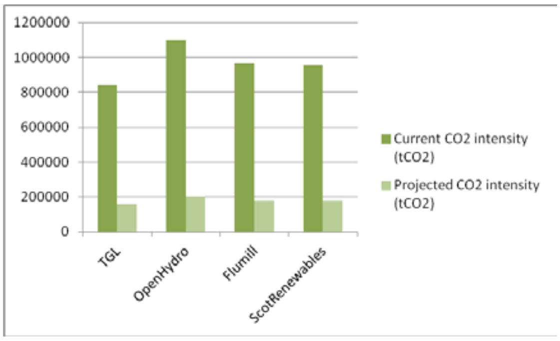


Figure 28 – Lifetime CO_2 savings, comparison of current and projected grid intensity (full functional unit)

The projected grid CO_2 intensity yields much lower CO_2 savings than the current intensity. The following figure illustrates the functional unit life cycle credit and debt for each device, using both the current and projected CO_2 intensities.

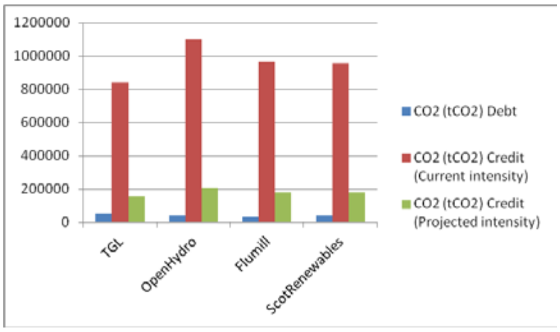


Figure 29 – Lifetime CO_2 credit and debt (full functional unit, current and projected CO_2 intensity)

It should also be noted that as grid decarbonisation takes place, the energy and CO_2 efficiency of life cycle processes will also reduce. Hence CO_2 debt will decrease alongside credit. Detailed calculations of this reduction are beyond the scope of this study, but may form part of future work.

8: Discussion

This study has taken four tidal energy devices and studied the embodied energy and CO_2 in each, based on a 10 MW array installed for a 100 year lifetime. Each of the four devices achieves greater energy output and CO_2 offset than its energy requirement and CO_2 debt, meaning that they can all be classed as a net contributors.

Using these figures it is possible to calculate the payback period of each device, in energy and CO_2 terms. These periods are defined as the time required to offset the energy and CO_2 debt, and can be thought of as the length of time the array must be installed before it is contributing net energy to the grid. The energy and CO_2 payback periods for each of the four devices are given in Table 8 (CO_2 payback is calculated against current grid CO_2 intensity).

Payback Period	**TGL**	**OpenHydro**	**Flumill**	**ScotRenewables**
Energy (yrs)	11.2	7.3	7.2	8.7
CO_2 (yrs)	5.9	3.6	3.5	4.5

Table 8 – Embodied energy and CO_2 Payback periods for 10MW array

As shown in this table, all four devices repay their embodied energy and CO_2 within the first device lifetime.

8.1 –Device Comparison

Of the four devices studied, the Flumill has the shortest payback period for both energy and CO_2. The OpenHydro device has the second shortest in both cases, followed by the ScotRenewables and TGL devices respectively. Reasons for these payback periods are highlighted in Figures 24 and 25, which illustrate the higher embodied energy and CO_2 of the TGL and ScotRenewables devices. The Flumill device particularly has noticeably lower embodied values from materials. This is due to the relatively simple construction of the device, its low mass and the use of PVC form for a large part of its construction. This material was found to have comparatively low material and fabrication energy values, though it does not have the strength of steel.

The ScotRenewables device has the lowest energy requirement for installation, maintenance and decommissioning. These low values are due primarily to the mooring system, which allows the device to be easily towed to the installation site and installed more easily than the other three devices, which all require piled foundations.

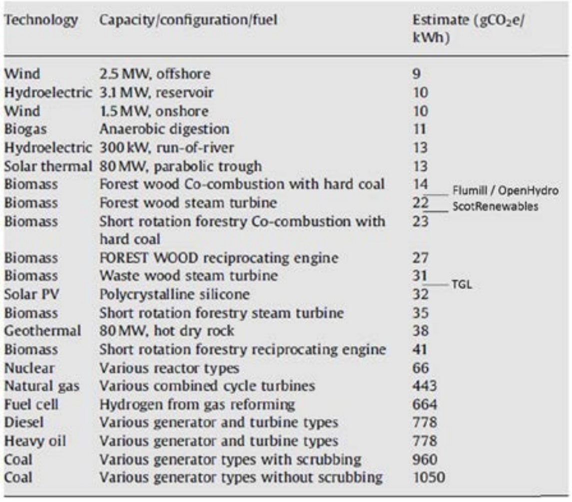
Due to its size, the TGL device is at a disadvantage in comparison the larger 2MW devices. Due to the use of 1MW machines, the TGL array requires twice as many installation, maintenance and decommissioning processes, and this has a significant impact on its overall energy and CO_2 intensity.

8.2 –Further Comparison

By using [29], it is possible to compare the CO_2 intensity of the devices studied in this study against previous work carried out for a range of other energy sources. The intensity for the four devices studied is given in Table 9, with their position relative to other energy sources given in Figure 32.

	TGL	**OpenHydro**	**Flumill**	**ScotRenewables**
g CO_2/kWh	34.2	19.6	18.5	23.8

Table 9 – CO_2 intensity of 10MW arrays



Technology	Capacity/configuration/fuel	Estimate (gCO_2e/kWh)
Wind	2.5 MW, offshore	9
Hydroelectric	3.1 MW, reservoir	10
Wind	1.5 MW, onshore	10
Biogas	Anaerobic digestion	11
Hydroelectric	300 kW, run-of-river	13
Solar thermal	80 MW, parabolic trough	13
Biomass	Forest wood Co-combustion with hard coal	14
Biomass	Forest wood steam turbine	22
Biomass	Short rotation forestry Co-combustion with hard coal	23
Biomass	FOREST WOOD reciprocating engine	27
Biomass	Waste wood steam turbine	31
Solar PV	Polycrystalline silicone	32
Biomass	Short rotation forestry steam turbine	35
Geothermal	80 MW, hot dry rock	38
Biomass	Short rotation forestry reciprocating engine	41
Nuclear	Various reactor types	66
Natural gas	Various combined cycle turbines	443
Fuel cell	Hydrogen from gas reforming	664
Diesel	Various generator and turbine types	778
Heavy oil	Various generator and turbine types	778
Coal	Various generator types with scrubbing	960
Coal	Various generator types without scrubbing	1050

Figure 30 – Relative CO_2 intensity of tidal energy and other energy sources [29]

It should be noted that the range of studies incorporated in this data applied differing methods of analysis, and therefore the comparisons may contain relative errors. However, the position of these four devices relative to other sources does give an indication of their current position in terms of CO_2

intensity. Due to the infancy of the technology, its position relative to more established renewable energy sources such as Solar PV and Biomass is positive. Developments in the technology, economies of scale and the installation of larger arrays are all likely to reduce this CO_2 intensity further.

8.3 – Limitations

As with any LCA with a long timescale of the functional unit, it is difficult to predict changes which may occur during the lifetime of the study.

A major change is the comparative embodied energy and CO_2 in current energy sources, which will reduce as time progresses. This has been considered using current forecasts (Section 7.1).

As well as UK grid, the development of technology during the 100 year lifetime is one of the primary factors which could reduce the accuracy of this study. Primary areas in which such changes could occur have been identified as:

- Manufacturing: Technology may improve and reduce the embodied energy in manufactured parts.
- Transport: Vehicle power source and efficiency are likely to improve.
- Installation: Vessel power source and efficiency are likely to improve. Methods of installation are also likely to improve as contractors become more experienced.

The design of devices themselves is also likely to improve, resulting in reduced embodied energy and CO_2 requirement, and improved output performance. However, these improvements are impossible to predict with any certainty, and it is felt that the current study uses the best available current data.

It should also be noted a Life Cycle Assessment can only consider the environmental effects defined in its scope. In this case, wider environmental effects such as those on marine life are not considered.

9: Conclusions

This study has considered four tidal energy devices in terms of life cycle performance. Energy and CO_2 processes included were materials; manufacture; transport; installation; maintenance; decommissioning and recycling. Results from these processes yielded the overall energy and CO_2 debt in the development of a functional unit of 10MW over 100 years. A secondary set of calculations were then carried out to ascertain the energy output of each functional unit, assuming a hypothetical site as described in Section 2. Using power curves for each device and current national grid electricity carbon intensity allowed the calculation of energy and CO_2 credit for each functional unit.

The results of the study indicate that the OpenHydro device produces the largest amount of energy over the functional unit, followed by the Flumill and ScotRenewables devices, and finally the TGL Deepgen turbine. All four devices achieved payback of both energy and CO_2 in less than 12 years.

Each device has advantages. The OpenHydro device achieves energy payback quicker than the others but has high materials energy requirements, whereas the Flumill device has low materials energy requirements due to its low weight design. The ScotRenewables device uses an innovative foundation system which lowers installation energy, and the TGL device power curve means it performs well in high tidal velocity areas.

On the whole, these results are positive for the tidal energy industry. CO_2 intensity values of all four devices are comparable with well-developed renewable energy sources such as Solar PV and Biomass (Figure 30).

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