An LCA of the Pelamis Wave Energy Converter

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Supplementary Material to:

An LCA of the Pelamis Wave Energy Converter

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S1 Input Data

S1.1 Key parameters

The analysis presented in this paper is an LCA of a single case-study manufacturing and installation scenario of the Pelamis Wave Energy Converter (WEC). In order to facilitate the use of this analysis in any “meta-models” of wave energy, it has been suggested by Astudillo et al. (2017 #1497) that a number of key parameters should be clearly reported. These are all detailed in the main text, but for clarity are summarised below.

- **Location**: Off the north-west coast of Scotland
- **Technological maturity**: First production machines; i.e. ascent stage
- **Installation year**: 2006
- **Period of validity**: 2006-2010
- **Capacity**: 750 kW
- **Operating lifetime**: 20 years
- **Capacity factor**: 45%
- **Annual energy production**: 2.97 GWh
- **Technology type**: Attenuator-type floating oscillating body system wave energy converter
- **Data type**: Empirical from cradle to completed installation, Theoretical for maintenance, decommissioning and disposal
- **Plant production and decommissioning**: Included
- **Characterization factors**: ReCiPe midpoint method, hierarchist version with European normalisation, Cumulative energy demand
- **Mass**: 1040 tonnes

S1.2 Data from manufacturer and detailed life cycle

The process of calculating the Life Cycle Inventory is described in Figure S1.1. Table S1.1, Table S1.2, Table S1.3 and Table S1.4 summarise the input data derived from information provided by Pelamis Wave Power Ltd (PWP), along with the selected process from ecoinvent v3.3 and the uncertainty indicator scores. The last refer to ratings used to estimate the uncertainty according to the same pedigree matrix used in the ecoinvent database, and described in Section 3.5 of the main report (Weidema, 2013 #1515). Figure S1.2 describes the life cycle flows included/excluded from the study.

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2 Device design was superceded in 2010, but no data was gathered for an LCA of the later version of the machine before the manufacturer went into administration in 2014.
Figure S1.1 - Process of calculating life cycle inventory data from input data provided by Pelamis Wave Power Ltd.
Figure S1.2 - Flow chart describing the system evaluated. Processes framed in green are assumed to be included in the ecoinvent data. Processes framed in a red dashed line are excluded from the analysis.
### General Data

| Data from Manufacturer | Quantity | Unit | SD² | Uncertainty Indicators | Selected Inventory Process |
|------------------------|----------|------|-----|-------------------------|----------------------------|
| Annual energy production | 2.97 | GWh | 1.050 | 2, 1, 1, 1, 1 | Steel, low-alloyed (GLO) | market for |
| Design life | 20 | years | 1.196 | 4, 1, 1, 1, 1 | Steel, low-alloyed, hot rolled (GLO) | market for |
| Recycling rate | 90 | % | 1.204 | 4, 1, 1, 2, 2 | |

### Stock Material

| Stock Material | Quantity | Unit | SD² | Uncertainty Indicators | Selected Inventory Process |
|----------------|----------|------|-----|-------------------------|----------------------------|
| Steel - cast | 221982 | kg | 1.058 | 1, 1, 3, 1, 1 | Steel, low-alloyed (GLO) | market for |
| Steel - plate | 345901 | kg | 1.058 | 1, 1, 3, 1, 1 | Steel, low-alloyed, hot rolled (GLO) | market for |
| Sand | 475722 | kg | 1.058 | 1, 1, 3, 1, 1 | Sand (GLO) | market for |
| Stainless steel | 550 | kg | 1.058 | 1, 1, 3, 1, 1 | Steel, chromium steel 18/8 (GLO) | market for |
| Nylon 6 | 416 | kg | 1.058 | 1, 1, 3, 1, 1 | Nylon 6 (GLO) | market for |
| Polyurethane³ | 3.5 | m³ | 1.058 | 1, 1, 3, 1, 1 | Polyurethane, rigid foam (GLO) | market for |
| Glass reinforced plastic (GRP) | 90 | kg | 1.058 | 1, 1, 3, 1, 1 | Glass fibre reinforced plastic, polyamide, injection moulded (GLO) | market for |
| PVC pipe | 55 | kg | 1.058 | 1, 1, 3, 1, 1 | Polyvinylchloride, suspension polymerised (GLO) | market for⁴ |

### Manufacturing Processes

| Manufacturing Processes | Quantity | Unit | SD² | Uncertainty Indicators | Selected Inventory Process |
|-------------------------|----------|------|-----|-------------------------|----------------------------|
| Drawing of steel pipes | 6383 | kg | 1.058 | 1, 1, 3, 1, 1 | Drawing of pipe, steel (GLO) | market for |
| Drawing of steel wire | 460 | kg | 1.058 | 1, 1, 3, 1, 1 | Wire drawing, steel (GLO) | market for |
| Extruding plastic pipes | 55 | kg | 1.058 | 1, 1, 3, 1, 1 | Extrusion, plastic pipes (GLO) | market for |
| Machining | 53924 | cm³ | 1.206 | 1, 1, 3, 1, 3 | Steel removed by milling, average (RER) | steel milling, average⁵ |
| Welding | 1995 | m | 1.058 | 1, 1, 3, 1, 1 | Welding, arc, steel (RER) | processing |
| Flame cutting | 41 | m | 1.058 | 1, 1, 3, 1, 1 | Approximated from gas welding. Detailed in Table S1.5. |
| Abrasive blasting | 2025 | m² | 1.058 | 1, 1, 3, 1, 1 | Derived from published information. Detailed in Table S1.5. |
| Painting | 2025 | m² | 1.058 | 1, 1, 3, 1, 1 | Derived from published information. Detailed in Table S1.5. |

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³ Density 110 kg/m³ from Trelleborg (, 2009 #260).
⁴ With pipe extrusion, as detailed under Manufacturing Processes.
⁵ The PWP data for machining includes all small-scale precision removal of material, such as milling, grinding and drilling.
| Data from Manufacturer | Quantity | Unit | SD²  | Uncertainty Indicators | Selected Inventory Process |
|------------------------|----------|------|------|------------------------|---------------------------|
| Pre-fabricated components |          |      |      |                        |                           |
| Main Generator, 175kW  | 1        | unit | 1.119| 1, 1, 3, 2, 3          | Generator, 200kW electrical (GLO) | market for⁶               |
| MV Switchgear and TSG Control Panel | 1 | unit |      |                        | Derived from published information. Detailed in Table S1.9. |
| Transformer, 315kVA, 11kV | 1 | unit |      |                        | Derived from published information. Detailed in Table S1.9. |

⁶ Generator for a gas cogeneration unit.

Table S1.2 - Information on electrical components provided by PWP, with details of corresponding inventory processes and uncertainty indicator scores.
Table S1.3 - Input data for transport of components for power conversion modules provided by PWP or estimated, with details of corresponding inventory processes and uncertainty indicator scores.

| Data from Manufacturer | Quantity | Unit | SD² | Uncertainty Indicators | Selected Inventory Process |
|------------------------|----------|------|-----|------------------------|---------------------------|
| **Transport**          |          |      |     |                        |                           |
| Distance uncertainty - city of origin known | 2.003 | kg | 2, 1, 1, 1, 1 |
| Distance uncertainty - country of origin known | 2.011 | kg | 3, 1, 1, 1, 1 |
| **Small lorry**        |          |      |     |                        |                           |
| From UK to Methil - estimated | 0.48 | kg | 1.221 | 4, 1, 3, 1, 1 |
| From UK to Methil - manufacturer's data | 1.35 | kg | 1.094 | 1, 1, 3, 1, 1 |
| **Large lorry**        |          |      |     |                        |                           |
| From Scotland to Methil - estimated | 0.06 | kg | 1.221 | 4, 1, 3, 1, 1 |
| From Glasgow to Methil - manufacturer's data | 0.18 | kg | 1.094 | 1, 1, 3, 1, 1 |
| From Stonehaven to Methil - manufacturer's data | 69.62 | t | 1.094 | 1, 1, 3, 1, 1 |
| From Nottingham to Methil - manufacturer's data | 17.40 | t | 1.094 | 1, 1, 3, 1, 1 |
| From UK to Methil - estimated | 7.86 | kg | 1.094 | 1, 1, 3, 1, 1 |
| From Wales to Methil - manufacturer's data | 9.00 | kg | 1.221 | 4, 1, 3, 1, 1 |
| From Methil to Stornoway | 106.55 | t | 8 |
| **Sea freight**         |          |      |     |                        |                           |
| From China to Methil - estimated | 0.30 | kg | 1.221 | 4, 1, 3, 1, 1 |
| From Holland to Methil - estimated | 0.30 | kg | 1.221 | 4, 1, 3, 1, 1 |

7 Assuming EURO3 standard, as this has the highest emissions and is therefore the most conservative
8 Sum of all component estimates
| Data from Manufacturer | Quantity | Unit | SD² | Uncertainty | Selected Inventory Process |
|------------------------|----------|------|-----|-------------|----------------------------|
| Assembly processes     |          |      |     |             |                            |
| 60T crane              | 120      | hrs  | 1.107 | 2, 1, 3, 1, 1 | Derived from published information. Detailed in Table S1.9. |
| Fork-lift truck        | 14.1     | hrs  | 1.107 | 2, 1, 3, 1, 1 | Derived from published information. Detailed in Table S1.9. |
| Installation processes |          |      |     |             |                            |
| Barge                  | 11.84    | days | 1.094 | 3, 1, 1, 1, 1 | Derived from data from Pelamis Wave Power. Detailed in Table S1.9. |
| Multicat               | 24       | days | 1.094 | 3, 1, 1, 1, 1 | Derived from data from Pelamis Wave Power. Detailed in Table S1.9. |
| Tug                    | 11.83    | days | 1.094 | 3, 1, 1, 1, 1 | Derived from data from Pelamis Wave Power. Detailed in Table S1.9. |
| Maintenance processes  | Per year |      |     |             |                            |
| Tug                    | 4.00     | days | 1.094 | 3, 1, 1, 1, 1 | Derived from data from Pelamis Wave Power. Detailed in Table S1.9. |
| Inspection vessel      | 1.33     | days | 1.094 | 3, 1, 1, 1, 1 | Derived from data from Pelamis Wave Power. Detailed in Table S1.9. |
| Decommissioning processes |        |      |     |             |                            |
| Barge                  | 2.50     | days | 1.094 | 3, 1, 1, 1, 1 | Derived from data from Pelamis Wave Power. Detailed in Table S1.9. |
| Multicat               | 8.50     | days | 1.094 | 3, 1, 1, 1, 1 | Derived from data from Pelamis Wave Power. Detailed in Table S1.9. |
| Tug                    | 2.50     | days | 1.094 | 3, 1, 1, 1, 1 | Derived from data from Pelamis Wave Power. Detailed in Table S1.9. |

Table S1.4 - Input data for assembly and specialist sea vessel processes provided by PWP, with corresponding uncertainty indicator scores.
S1.3 Process approximations
The ecoinvent database does not contain detailed inventory information for some specialist materials, manufacturing processes and sea vessel operations. In order to assess the resource use and pollutant emissions associated with these, data on material quantities and fuel consumption were sourced elsewhere, and new processes were built using inventory data from ecoinvent. The selected materials, quantities and associated uncertainty are given in Table S1.5, Table S1.6, Table S1.7, Table S1.8 and Table S1.9.

S1.4 Waste disposal processes
Table S1.10 details the waste disposal processes selected from the ecoinvent dataset for each of the principal materials within the analysis.

S1.5 Alternative electricity generation
In order to compare the environmental impacts of the Pelamis with those from other types of power generation, selected average electricity generation data from a number of key energy sources was analysed with the ReCiPe Midpoint Hierarchist and Cumulative Energy Demand impact assessment methods. The processes selected from the ecoinvent database (v3.3) are detailed in Table S1.11.
| Process or material | Quantity | Unit | SD²  | Uncertainty       | Selected Inventory Process/ emission                        |
|---------------------|----------|------|------|-------------------|-------------------------------------------------------------|
| Flame cutting       |          |      |      |                   |                                                             |
| Gas welding         | 50       | m    | 1.288| 4, 1, 1, 1, 3     | Welding, gas, steel (RER) | processing                                                |
| Sand blasting       |          |      |      |                   |                                                             |
| Abrasive for jet blasting⁹ | 10   | kg   | 1.237| 2, 4, 1, 3, 3     | Silica sand (GLO) | market for                                               |
| Compressed air supply for jet blasting¹⁰ | 5.8 | m³  | 1.258| 2, 4, 1, 5, 3     | Compressed air, 800 kPa gauge (RER) | <30kW, average generation                                 |
| Particulate emissions¹¹ | 1.35E-05 | kg  | 2.050| 1, 3, 2, 3, 3     | Particulates, > 2.5 μm, and < 10 μm                         |
| Painting, glass flake paint¹² |          |      |      |                   |                                                             |
| Epoxy paint primer/topcoat¹³ | 0.808 | kg  | 1.196| 4, 1, 1, 1, 1     | Detailed below.                                             |
| Glass flake paint 35851¹³ | 1.23 | kg  | 1.196| 4, 1, 1, 1, 1     | Detailed below.                                             |
| Compressed air supply for painting¹⁴ | 12.8 | m³  | 1.131| 2, 4, 1, 1, 2     | Compressed air, 700 kPa gauge (RER) | >30kW, average generation                                 |
| Glass flake paint 35851¹⁵ |          |      |      |                   |                                                             |
| Curing Agent 97652   | 0.034    | kg  | 1.107| 1, 4, 1, 1, 1     | Detailed in Table S1.6.                                     |
| Base 35858           | 0.183    | kg  | 1.107| 1, 4, 1, 1, 1     | Detailed in Table S1.6.                                     |
| Glass flakes         | 0.781    | kg  | 1.107| 1, 4, 1, 1, 1     | Flat glass, uncoated (GLO) | market for                                               |
| Epoxy paint primer/topcoat¹⁶ |          |      |      |                   |                                                             |
| Curing Agent 97652   | 0.156    | kg  | 1.107| 1, 4, 1, 1, 1     | Detailed in Table S1.6.                                     |
| Base 35858           | 0.842    | kg  | 1.107| 1, 4, 1, 1, 1     | Detailed in Table S1.6.                                     |

Table S1.5 - Details of new processes created from data within ecoinvent for manufacturing processes and glass-flake paint, with corresponding uncertainty indicators

⁹ From Jiven et al. (2004 #119).
¹⁰ Quantity derived from Axxiom (2008 #283). Pressure from Kalpakjian et al. (2008 #282). Compressed air sourced locally, so European average data selected.
¹¹ From data for abrasive blasting of aluminium in Classen et al. (2009 #259).
¹² The paint is applied with an airless spray at 250 bar, providing a coverage of 3.9 m²/l with a thickness of 200 μm (Hempel, 2007 #284).
¹³ Parker et al. (2007 #6) estimated an overall 1mm paint thickness requiring a base coat of primer, three layers of paint and a topcoat.
¹⁴ The paint application process was approximated from manufacturer's data for an airless spray pump (Graco, 2010 #285), powered by 200 m³/min of compressed air to provide paint coverage of 12 l/min.
¹⁵ From Hempel (2007 #284)
¹⁶ Assumed to be the same as the glass flake paint, without the glass flakes.
| Process or material                        | Quantity | Unit  | Uncertainty | Selected Inventory Process                                                                 |
|------------------------------------------|----------|-------|-------------|-------------------------------------------------------------------------------------------|
| **Curing Agent 97652**                   |          |       |             | **per kg**                                                                                |
| Xylene                                   | 0.1625   | kg    | 0.125 - 0.2 | Xylene [GLO] | market for                                                                               |
| n-butanol                                | 0.085    | kg    | 0.07 - 0.1  | 1-butanol [GLO] | market for                                                                               |
| p-tert-butylphenol                       | 0.075    | kg    | 0.05 - 0.1  | Phenol [GLO] | market for                                                                               |
| m-xylylene-diamine                       | 0.04     | kg    | 0.03 - 0.05 | Meta-phenylene diamine [GLO] | market for                                                                               |
| Ethanol                                  | 0.03     | kg    | 0.01 - 0.05 | Ethanol, without water, in 99.7% solution state, from ethylene [GLO] | market for                                                                               |
| Ethylbenzene                             | 0.05     | kg    | 0.03 - 0.07 | Ethyl benzene [GLO] | market for                                                                               |
| 2,2,4- and 2,4,4-trimethylhexamethylene diamine | 0.0175   | kg    | 0.01 - 0.025 | Ethylenediamine [GLO] | market for                                                                               |
| 2,4,6-tris(dimethylaminomethyl)phenol     | 0.02     | kg    | 0.01 - 0.03 | O-aminophenol [GLO] | market for                                                                               |
| 3-(aminoethylamino)(propyltrimethoxysilane | 0.00625  | kg    | 0.0025 - 0.01 | Ethylenediamine [GLO] | market for                                                                               |
| Remainder                                | 0.51375  | kg    | 0.365 - 0.6625 | Epoxy resin, liquid [GLO] | market for                                                                               |
| **Base 35858**                           |          |       |             | **per kg**                                                                                |
| bisphenol A-(epichlorhydrin) epoxy resin MW <= 700 | 0.15     | kg    | 0.05 - 0.25 | Epoxy resin, liquid [GLO] | market for                                                                               |
| middle molecular epoxy resin MW 700-1200 | 0.075    | kg    | 0.05 - 0.1  | Epoxy resin, liquid [GLO] | market for                                                                               |
| Xylene                                   | 0.075    | kg    | 0.05 - 0.1  | Xylene [GLO] | market for                                                                               |
| n-butanol                                | 0.04     | kg    | 0.03 - 0.05 | 1-butanol [GLO] | market for                                                                               |
| Ethylbenzene                             | 0.02     | kg    | 0.01 - 0.03 | Ethyl benzene [GLO] | market for                                                                               |
| solvent naphtha (petroleum), light arom. | 0.0175   | kg    | 0.01 - 0.025 | Naphtha (RER) | market for                                                                               |
| alpha’-(1,3-xylenediy)bis(12-hydroxyoctadecanamide) | 0.02     | kg    | 0.01 - 0.03 | Dimethenamide [GLO] | market for                                                                               |
| Remainder                                | 0.6025   | kg    | 0.415 - 0.79 | Epoxy resin, liquid [GLO] | market for                                                                               |

Table S1.6 - Details of materials within glass-flake paint, selected ecoinvent data and corresponding uncertainty indicators

17 Uncertainty ranges taken from material data sheets
18 [Hempel, 2010 #640]
19 [Hempel, 2010 #641]
| Process or material | Quantity | Unit | SD² | Uncertainty Indicators | Selected Inventory Process |
|---------------------|----------|------|-----|------------------------|---------------------------|
| **MV Switchgear and TSG Control Panel** per unit | | | | | |
| MV switch-disconnector cubicle | 2 | | | | Detailed below |
| SF6 MV circuit breaker | 1 | | | | Detailed in Table S1.8. |
| **MV switch-disconnector cubicle** | per unit | | | | |
| Steel | 89.7 kg | 1.231 | 1, 4, 2, 2, 3 | Steel, low-alloyed, hot rolled (GLO) | market for |
| Stainless steel | 6 kg | 1.231 | 1, 4, 2, 2, 3 | Steel, chromium steel 18/8, hot rolled (GLO) | market for |
| Copper | 7.6 kg | 1.231 | 1, 4, 2, 2, 3 | Copper (GLO) | market for |
| Brass | 0.4 kg | 1.231 | 1, 4, 2, 2, 3 | Brass (RoW) | market for brass |
| Polycarbonate | 0.9 kg | 1.231 | 1, 4, 2, 2, 3 | Polycarbonate (GLO) | market for |
| EPDM | 0.7 kg | 1.231 | 1, 4, 2, 2, 3 | Synthetic rubber (GLO) | market for |
| Polypropylene | 0.1 kg | 1.231 | 1, 4, 2, 2, 3 | Polypropylene, granulate (GLO) | market for |
| Polyester | 0.1 kg | 1.231 | 1, 4, 2, 2, 3 | Polyester resin, unsaturated (GLO) | market for |
| Glass | 0.1 kg | 1.231 | 1, 4, 2, 2, 3 | Flat glass, uncoated (GLO) | market for |
| Epoxy | 22.6 kg | 1.231 | 1, 4, 2, 2, 3 | Epoxy resin, liquid (GLO) | market for |
| Sulphur hexafluoride | 0.2 kg | 1.231 | 1, 4, 2, 2, 3 | Sulfur hexafluoride, liquid (GLO) | market for |
| Zinc | 0.5 kg | 1.231 | 1, 4, 2, 2, 3 | Zinc (GLO) | market for |
| Aluminium | 1.1 kg | 1.231 | 1, 4, 2, 2, 3 | Aluminium, wrought alloy (GLO) | market for |
| Paint | 0.8 kg | 1.231 | 1, 4, 2, 2, 3 | Alkyd paint, white, without water, in 60% solution state (GLO) | market for |

Table S1.7 - Details of materials in MV switch-disconnector cubicle, selected ecoinvent data and corresponding uncertainty indicators

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20 Second cubicle representing TSG control panel  
21 (ABB, 2010 #263)
| Process or material | Quantity | Unit | SD² | Uncertainty Indicators | Selected Inventory Process |
|---------------------|----------|------|-----|------------------------|---------------------------|
| **SF6 MV circuit breaker**<sup>22</sup> per unit | | | | | |
| Steel               | 55.043 g | g    | 1.231 | 1, 4, 2, 2, 3 | Steel, low-alloyed (GLO) | market for |
| Stainless steel     | 1.332 g  | g    | 1.231 | 1, 4, 2, 2, 3 | Steel, chromium steel 18/8, hot rolled (GLO) | market for |
| Aluminium           | 899 g    | g    | 1.231 | 1, 4, 2, 2, 3 | Aluminium, wrought alloy (GLO) | market for |
| Alumina             | 378 g    | g    | 1.231 | 1, 4, 2, 2, 3 | Aluminium oxide (GLO) | market for |
| Copper              | 16.736 g | g    | 1.231 | 1, 4, 2, 2, 3 | Copper (GLO) | market for |
| Copper tungsten 20  | 315 g    | g    | 1.231 | 1, 4, 2, 2, 3 | Copper (GLO) | market for |
| Polyamide 11        | 15 g     | g    | 1.231 | 1, 4, 2, 2, 3 | Nylon 6 (GLO) | market for |
| Polyamide 66        | 183 g    | g    | 1.231 | 1, 4, 2, 2, 3 | Nylon 6-6 (GLO) | market for |
| Polycarbonate       | 140 g    | g    | 1.231 | 1, 4, 2, 2, 3 | Polycarbonate (GLO) | market for |
| Polycarbonate+FB30  | 61 g     | g    | 1.231 | 1, 4, 2, 2, 3 | Polycarbonate (GLO) | market for |
| PVC                 | 8 g      | g    | 1.231 | 1, 4, 2, 2, 3 | Polyvinylchloride, suspension polymerised (GLO) | market for |
| Bronze              | 9 g      | g    | 1.231 | 1, 4, 2, 2, 3 | Bronze (GLO) | market for |
| PTFE                | 227 g    | g    | 1.231 | 1, 4, 2, 2, 3 | Tetrafluoroethylene (GLO) | market for |
| Epoxy Resin         | 23.751 g | g    | 1.231 | 1, 4, 2, 2, 3 | Epoxy resin, liquid (GLO) | market for |
| Epoxy Resin Fe10    | 844 g    | g    | 1.231 | 1, 4, 2, 2, 3 | Epoxy resin, liquid (GLO) | market for |
| SF6                 | 282 g    | g    | 1.231 | 1, 4, 2, 2, 3 | Sulfur hexafluoride, liquid (GLO) | market for |
| Brass               | 198 g    | g    | 1.231 | 1, 4, 2, 2, 3 | Brass (RoW) | market for brass |
| **Transformer, 315kVA, 11kV**<sup>23</sup> per unit | | | | | |
| Core Steel          | 533 kg   | kg   | 1.231 | 1, 4, 2, 2, 3 | Steel, low-alloyed (GLO) | market for |
| Transformer oil     | 340 kg   | kg   | 1.231 | 1, 4, 2, 2, 3 | Vegetable oil methyl ester (GLO) | market for |
| Steel tank          | 324 kg   | kg   | 1.231 | 1, 4, 2, 2, 3 | Steel, low-alloyed, hot rolled (GLO) | market for |
| Aluminium wire      | 113.51 kg| kg   | 1.231 | 1, 4, 2, 2, 3 | Aluminium, primary, cast alloy slab (GLO) | market for |
| Aluminium sheet     | 86.3 kg  | kg   | 1.231 | 1, 4, 2, 2, 3 | Aluminium, wrought alloy (GLO) | market for |
| Transformer insulation material | 59.9 kg | kg | 1.231 | 1, 4, 2, 2, 3 | Kraft paper, unbleached (GLO) | market for |
| Porcelain           | 11 kg    | kg   | 1.231 | 1, 4, 2, 2, 3 | Sanitary ceramics (GLO) | market for |

Table S1.8 - Details of materials in SF6 breaker and transformer, selected ecoinvent data and corresponding uncertainty indicators

<sup>22</sup> (ABB, 2001 #636)
<sup>23</sup> (ABB, 2007 #264)
| Process or material          | Quantity | Unit | SD² | Uncertainty | Selected Inventory Process                                                                 |
|-----------------------------|----------|------|-----|-------------|---------------------------------------------------------------------------------------------|
| **60T Crane**               |          |      |     |             |                                                                                              |
| Electricity                 | 18       | kWh  | 1.568| 4, 4, 1, 2, 4| Electricity, low voltage (GB)| market for                                                                                         |
| **Fork lift truck**         |          |      |     |             |                                                                                              |
| Diesel                      | 2.55     | kg   | 1.511| 1, 4, 1, 2, 4| Diesel, burned in building machine (GLO)| processing                                                                                         |
| **Sea vessels**             |          |      |     |             |                                                                                              |
| Barge                       | 113000   | tkm  | 2.057| 1, 1, 3, 1, 3| Transport, freight, sea, transoceanic ship (GLO)| market for                                                                                         |
| Multicat                    | 5780000  | tkm  | 2.057| 1, 1, 3, 1, 3| Transport, freight, sea, transoceanic ship (GLO)| market for                                                                                         |
| Tug                         | 663000   | tkm  | 2.057| 1, 1, 3, 1, 3| Transport, freight, sea, transoceanic ship (GLO)| market for                                                                                         |
| Inspection vessel           | 194000   | tkm  | 2.057| 1, 1, 3, 1, 3| Transport, freight, sea, transoceanic ship (GLO)| market for                                                                                         |

Table S1.9 - Details of new processes created from data within ecoinvent for manufacturing processes and sea vessel operations, with corresponding uncertainty indicators

24 (SWF, 2011 #287)
25 (Caterpillar, 2011 #290)
26 Scaled to match fuel consumption provided by PWP
| Waste Material       | Selected Inventory Process                                                                 |
|----------------------|---------------------------------------------------------------------------------------------|
| Steel                | Scrap steel {Europe without Switzerland} | treatment of scrap steel, inert material landfill                                      |
| Aluminium            | Waste aluminium {RoW} | treatment of, sanitary landfill                                                          |
| Other metals         | Scrap steel {Europe without Switzerland} | treatment of scrap steel, inert material landfill                                      |
| PVC                  | Waste polyvinylchloride {Europe without Switzerland} | treatment of waste polyvinylchloride, sanitary landfill                               |
| Other plastics       | Waste plastic, mixture {Europe without Switzerland} | treatment of waste plastic, mixture, sanitary landfill                                 |
| Other materials      | Inert waste, for final disposal {RoW} | treatment of inert waste, inert material landfill                                      |

Table S1.10 - Waste processing datasets selected from ecoinvent.

| Type of generation     | Process Name                                                                                      |
|------------------------|-------------------------------------------------------------------------------------------------|
| Coal                   | Electricity, high voltage {GB} | electricity production, hard coal                                                            |
| Gas (CCGT)             | Electricity, high voltage {GB} | electricity production, natural gas, combined cycle power plant                              |
| Nuclear                | Electricity, high voltage {GB} | electricity production, nuclear, pressure water reactor27                                     |
| Hydro                  | Electricity, high voltage {RoW} | electricity production, hydro, reservoir, non-alpine region                                   |
| Onshore Wind           | Electricity, high voltage {GB} | electricity production, wind, 1-3MW turbine, onshore                                           |
| Offshore Wind          | Electricity, high voltage {GB} | electricity production, wind, 1-3MW turbine, offshore                                          |

Table S1.11 - Source data for comparison with other types of generation

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27 Only one nuclear power station in the UK is a pressurised water reactor. The remainder are advanced gas-cooled reactors, but as this is an old technology that is rarely used elsewhere, data for it is not included in ecoinvent v3.3.
S2 Additional Numerical Results

This section contains additional results not presented in the main article. Table S2.1 gives the breakdown of cumulative energy demand results for each primary energy carrier.

| Category                          | Value (kJ/kWh) |
|-----------------------------------|----------------|
| Non-renewable, fossil             | 445            |
| Non-renewable, nuclear            | 23             |
| Non-renewable, biomass            | 0.062          |
| Renewable, biomass                | 6.4            |
| Renewable, wind, solar, geothermal| 1.7            |
| Renewable, water                  | 17             |
| **TOTAL**                         | **493**        |

Table S2.1 - Breakdown of cumulative energy demand

The results of the uncertainty analysis are shown graphically in the paper, but for completeness, the numerical results are given in Table S2.2. Similarly, complete results of the sensitivity analysis are summarised in Table S2.3.
| Impact Category                      | Mean | SD  | Median | 2.5%  | 97.5% | Unit                  |
|-------------------------------------|------|-----|--------|-------|-------|-----------------------|
| Climate change                      | 35   | 7   | 35     | 25    | 51    | g CO₂ eq/kWh          |
| Ozone depletion                     | 3.7  | 1.8 | 3.3    | 1.5   | 8.5   | μg CFC-11 eq/kWh      |
| Photochemical oxidant formation     | 331  | 95  | 315    | 190   | 553   | mg PM10 eq/kWh        |
| Terrestrial acidification           | 410  | 113 | 395    | 244   | 670   | mg NMVOC/kWh          |
| Freshwater eutrophication           | 21   | 11  | 19     | 10    | 46    | mg SO₂ eq/kWh         |
| Marine eutrophication               | 14   | 4   | 13     | 9     | 22    | mg P eq/kWh           |
| Particulate matter formation        | 187  | 41  | 183    | 121   | 279   | g 1,4-DB eq/kWh       |
| Human toxicity                      | 33   | 22  | 28     | 14    | 79    | mg N eq/kWh           |
| Terrestrial ecotoxicity             | 4.3  | 1.0 | 4.1    | 2.9   | 6.8   | mg 1,4-DB eq/kWh      |
| Freshwater ecotoxicity              | 930  | 483 | 814    | 429   | 2191  | mg 1,4-DB eq/kWh      |
| Marine ecotoxicity                  | 948  | 455 | 840    | 471   | 2036  | mg 1,4-DB eq/kWh      |
| Ionising radiation                  | 2.4  | 1.7 | 2.0    | 0.8   | 6.4   | Bq ²³⁵U eq/kWh         |
| Agricultural land occupation        | 920  | 286 | 865    | 538   | 1598  | mm²/a/kWh             |
| Urban land occupation               | 399  | 94  | 385    | 261   | 608   | mm²/a/kWh             |
| Natural land transformation         | 8.5  | 5.5 | 7.6    | 0.2   | 21.1  | mm²/kWh               |
| Water depletion                     | -250 | 37208 | 4387 | -86649 | 60055 | cm³/kWh               |
| Metal depletion                     | 26   | 6   | 26     | 17    | 40    | g Fe eq/kWh           |
| Fossil depletion                    | 10   | 3   | 10     | 6     | 16    | g oil eq/kWh          |
| Energy                              | 494  | 121 | 474    | 317   | 793   | kJ/kWh                |

Table S2.2 - Complete results of uncertainty analysis
| Impact Category                          | Unit                        | 25% | 55% | 20  | 320 | 213 | 633 | 10  | 30  |
|----------------------------------------|-----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Climate change                         | g CO₂ eq/kWh                | 63  | 29  | 24  | 35  | 35  | 35  | 60  | 27  |
| Ozone depletion                        | μg CFC-11 eq/kWh            | 6.8 | 3.1 | 2.0 | 3.7 | 3.7 | 3.7 | 5.89| 3.02|
| Photochemical oxidant formation        | mg PM10 eq/kWh              | 588 | 267 | 163 | 325 | 325 | 326 | 505 | 265 |
| Terrestrial acidification              | mg NMVOC/kWh                | 730 | 332 | 190 | 404 | 403 | 404 | 616 | 333 |
| Freshwater eutrophication              | mg SO₂ eq/kWh               | 38  | 17  | 20  | 21  | 21  | 21  | 41  | 14  |
| Marine eutrophication                  | mg P eq/kWh                 | 25  | 11  | 8   | 14  | 14  | 14  | 22  | 11  |
| Particulate matter formation           | g 1,4-DB eq/kWh             | 333 | 151 | 114 | 184 | 184 | 148 | 306 | 144 |
| Human toxicity                         | mg N eq/kWh                 | 60  | 27  | 32  | 33  | 33  | 33  | 65  | 22  |
| Terrestrial ecotoxicity                | mg 1,4-DB eq/kWh            | 7.7 | 3.5 | 3.8 | 4.2 | 4.2 | 4.3 | 8.1 | 3.0 |
| Freshwater ecotoxicity                 | mg 1,4-DB eq/kWh            | 1638 | 745 | 867 | 906 | 906 | 906 | 1777| 615 |
| Marine ecotoxicity                     | mg 1,4-DB eq/kWh            | 1671 | 760 | 862 | 924 | 924 | 925 | 1793| 635 |
| Ionising radiation                     | Bq ²³⁵U eq/kWh               | 4.4 | 2.0 | 1.4 | 2.4 | 2.4 | 2.4 | 4.0 | 1.9 |
| Agricultural land occupation          | mm²/a/kWh                   | 1654 | 752 | 770 | 915 | 914 | 916 | 1700| 653 |
| Urban land occupation                  | mm²/a/kWh                   | 712  | 323 | 334 | 393 | 390 | 397 | 734 | 280 |
| Natural land transformation            | mm²/kWh                     | 15.3 | 7.0 | 4.5 | 8.5 | 8.4 | 8.5 | 13.4| 6.8 |
| Water depletion                        | cm³/kWh                     | 436  | 198 | 208 | 241 | 241 | 242 | 453 | 171 |
| Metal depletion                        | g Fe eq/kWh                 | 47   | 21  | 26  | 26  | 26  | 26  | 52  | 17  |
| Fossil depletion                       | g oil eq/kWh                | 18.1 | 8.2 | 6.4 | 10.0| 10.0| 10.0| 16.8| 7.8 |
| Energy                                 | kl/kWh                      | 892  | 405 | 323 | 493 | 492 | 494 | 833 | 380 |

Table S2.3 - Sensitivity analysis results. Highest values for each impact category are highlighted in orange, and lowest values in green.
| Impact Category                     | Probability (%) that impacts of Pelamis are less than: |
|------------------------------------|--------------------------------------------------------|
|                                    | Coal | CCGT | Nuclear | Hydro | Offshore wind | Offshore wind |
| Climate change                     | 100  | 100  | 0.0     | 86.6  | 1.3          | 0.0           |
| Ozone depletion                    | 50.9 | 99.8 | 100     | 0.0   | 0.1          | 0.0           |
| Photochemical oxidant formation    | 100  | 23.3 | 0.1     | 0.0   | 0.0          | 0.0           |
| Terrestrial acidification          | 100  | 1.8  | 0.0     | 0.0   | 0.0          | 0.0           |
| Freshwater eutrophication          | 99.9 | 0.0  | 1.7     | 0.0   | 3.3          | 0.8           |
| Marine eutrophication              | 100  | 17.6 | 98.5    | 0.0   | 0.8          | 0.1           |
| Particulate matter formation       | 100  | 1.2  | 0.8     | 0.0   | 0.1          | 0.0           |
| Human toxicity                     | 98.5 | 0.0  | 32.6    | 0.0   | 4.9          | 2.7           |
| Terrestrial ecotoxicity            | 99.8 | 0.0  | 19.2    | 0.0   | 1.6          | 0.3           |
| Freshwater ecotoxicity             | 99.6 | 0.1  | 8.0     | 0.0   | 29.0         | 98.3          |
| Marine ecotoxicity                 | 99.6 | 11.6 | 9.4     | 0.0   | 20.4         | 98.0          |
| Ionising radiation                 | 81.1 | 100  | 100     | 0.0   | 1.3          | 0.0           |
| Agricultural land occupation       | 100  | 0.0  | 6.1     | 0.0   | 5.9          | 1.1           |
| Urban land occupation              | 100  | 0.0  | 1.8     | 0.0   | 98.5         | 0.0           |
| Natural land transformation        | 76.4 | 99.9 | 0.7     | 99.9  | 2.0          | 0.9           |
| Water depletion                    | 50.8 | 41.6 | 50.9    | 56.5  | 45.1         | 44.4          |
| Metal depletion                    | 0.0  | 0.0  | 0.0     | 0.0   | 1.4          | 0.0           |
| Fossil depletion                   | 100  | 100  | 0.0     | 0.0   | 1.6          | 0.0           |
| Energy                             | 100  | 100  | 100     | 100   | 100          | 100           |

Table S2.4 - Results of comparative uncertainty analysis of Pelamis with other types of generation. Values between 30 and 70% are highlighted, as these show a significant probability that the impacts of the Pelamis relative to the given type of generation may be reversed.
S3 Locational Adjustment Factors

The normalised impact potentials can be estimated for any given installation location, using the following equation:

\[
E = \frac{(a + b \cdot l_{\text{steel}} + c \cdot l_{\text{offshore}})}{20W}
\]

where:

- \( E \) = Embodied impacts per kWh
- \( l_{\text{steel}} \) = Distance from Pelamis plant to steel fabrication yard (km)
- \( l_{\text{offshore}} \) = Distance from dockyard to installation site (km)
- \( W \) = Annual energy output (kWh)
- \( a, b \) and \( c \) = Constants for each impact category (given in Table S3.1)

Note that this formula is a simplification of the results of this analysis, and cannot be used to determine the effect of a change in other factors. Furthermore, this model has been developed for an installation scenario in the UK, and therefore installation in other countries may not have the same impacts.

| Impact Potential               | \( a \)     | \( b \)     | \( c \)     | Unit                       |
|--------------------------------|-------------|-------------|-------------|---------------------------|
| Climate change                 | 1.37x10^9   | 1.73x10^4  | 2.18x10^6  | g CO₂ eq                 |
| Ozone depletion                | 1.09x10^8   | 3.29x10^3  | 3.49x10^5  | μg CFC-11 eq             |
| Terrestrial acidification      | 1.04x10^10  | 9.15x10^4  | 4.23x10^7  | mg SO₂ eq                |
| Freshwater eutrophication      | 1.16x10^9   | 1.26x10^3  | 2.88x10^5  | mg P eq                  |
| Marine eutrophication          | 4.30x10^8   | 5.07x10^3  | 1.17x10^6  | mg N eq                  |
| Human toxicity                 | 1.89x10^9   | 5.14x10^3  | 2.44x10^5  | g 1,4-DB eq              |
| Photochemical oxidant formation| 8.97x10^9   | 1.40x10^5  | 3.22x10^7  | mg NMVOC                 |
| Particulate matter formation   | 6.48x10^9   | 4.62x10^4  | 1.39x10^7  | mg PM10 eq               |
| Terrestrial ecotoxicity        | 2.21x10^8   | 7.86x10^3  | 8.77x10^4  | mg 1,4-DB eq             |
| Freshwater ecotoxicity         | 5.13x10^10  | 7.62x10^4  | 7.66x10^5  | mg 1,4-DB eq             |
| Marine ecotoxicity             | 5.09x10^10  | 1.19x10^5  | 1.23x10^7  | mg 1,4-DB eq             |
| Ionising radiation             | 8.14x10^7   | 1.51x10^3  | 1.92x10^5  | Bq ²³⁵U eq               |
| Agricultural land occupation   | 4.51x10^10  | 2.10x10^5  | 2.86x10^7  | mm²/a                    |
| Urban land occupation          | 1.92x10^10  | 9.50x10^5  | 1.17x10^7  | mm²/a                    |
| Natural land transformation    | 2.49x10^8   | 6.99x10^3  | 7.82x10^5  | mm²                      |
| Water depletion                | 1.22x10^10  | 5.04x10^4  | 6.65x10^6  | cm³                      |
| Metal depletion                | 1.53x10^9   | 6.04x10^2  | 5.12x10^4  | g Fe eq                  |
| Fossil depletion               | 3.64x10^8   | 6.35x10^3  | 7.17x10^5  | g oil eq                 |
| Energy                         | 1.84x10^10  | 2.91x10^5  | 3.38x10^7  | kJ                       |

Table S3.1 - Constants for estimating the environmental impacts at alternative locations
S4 Recycling allocation

S4.1 Comparing recycled content with APOS
Ecoinvent v3.3 includes data for two different allocation methods for attributional LCA: the recycled content method and the “allocation at the point of substitution” (APOS) method. In this study the former was chosen in order to enable consistency in application for foreground recycling processes. The latter is, however, considered by some to be the better approach for more consistent allocation {Schrijvers, 2016}. It is also the only available method in earlier versions of the ecoinvent dataset (v3 and v3.01) so will have been applied in other studies that also employ the recycled content method for the foreground data. The analysis was, therefore, re-run with the APOS approach applied to background processes, and results are given in Table S4.1.

S4.2 Approximating the end-of-life recycling method
Section 5.2 of the main article describes how the analysis was re-run using an approximation of the end-of-life method for allocating recycling credit within the foreground data, in order to replicate the method applied by Parker et al. {, 2007 #6}. Although this method is no longer considered appropriate for use in an attributional LCA, it was tested here to explain the discrepancy in results between the two studies.

The end-of-life recycling method (also known as the avoided burdens or closed-loop approximation method) is a method of allocating credit for the avoided production of primary material in the future by producing recyclable material {Schrijvers, 2016 #1502}. Recycled material consumed in the product life cycle, therefore, does not give an environmental credit so has the same burdens has primary material. The underlying mathematical expression for this method from Schrijvers et al. can be rearranged to form Equation 1, assuming that the impacts of the substituted primary material will be the same as the impacts of the consumed primary material and the quality correction factor is one (as for closed-loop recycling of a material such as steel):

\[
E_{tot} = E_v + r(E_{RC} + E_{RRE} - E_v) + (1 - r)E_d
\]

where \(E_{tot}\) is embodied impacts per unit of material, \(E_v\) is embodied impact of primary material, \(E_{RC}\) is embodied impact of the recycling process, \(E_{RRE}\) is embodied impact of recovery and transport of the recyclable material, \(E_d\) is embodied impact of waste disposal and \(r\) is recycling rate at end-of-life. It can be seen that the first term \(E_v\) is the embodied impacts of all input material, which is considered to have the impacts of primary material. End-of-life impacts include the credit for recycling, described by \(r(E_{RC} + E_{RRE} - E_v)\), which is a function of the difference between embodied impacts of the production of primary and recycled material. Disposal of non-recycled material is represented by \((1 - r)E_d\).

In order to simulate the method applied by Parker et al., the above method was applied only to the foreground data for steel. All background data was still sourced from ecoinvent v3.3, using the recycled content allocation method, as with the main analysis. Modifications were made as follows:

- A new input steel dataset was created by copying the ecoinvent v3.3 data for the global steel market, but replacing all flows of recycled steel with data for primary steel for the same region.
• Recycling credit was estimated by creating a waste flow with a global recycled steel market as input (as above, but with all primary steel replaced with recycled steel), and a global virgin steel market as avoided product.

| Impact Category                  | Recycled Content | APOS | Difference | Unit         |
|----------------------------------|------------------|------|------------|--------------|
| Climate change                   | 35               | 35   | 0.9%       | g CO₂ eq/kWh |
| Ozone depletion                  | 3.7              | 3.9  | -5.6%      | μg CFC-11 eq/kWh |
| Photochemical oxidant formation  | 325              | 318  | 2.2%       | mg PM10 eq/kWh |
| Terrestrial acidification        | 404              | 402  | 0.5%       | mg NMVOC/kWh |
| Freshwater eutrophication        | 21               | 20   | 2.4%       | mg SO₂ eq/kWh |
| Marine eutrophication            | 14               | 14   | 0.0%       | mg P eq/kWh |
| Particulate matter formation     | 184              | 181  | 1.9%       | g 1,4-DB eq/kWh |
| Human toxicity                   | 33               | 33   | 0.2%       | mg N eq/kWh |
| Terrestrial ecotoxicity          | 4.2              | 4.7  | -9.6%      | mg 1,4-DB eq/kWh |
| Freshwater ecotoxicity           | 906              | 947  | -4.5%      | mg 1,4-DB eq/kWh |
| Marine ecotoxicity               | 924              | 959  | -3.7%      | mg 1,4-DB eq/kWh |
| Ionising radiation               | 2.4              | 2.5  | -4.8%      | Bq ²³⁵U eq/kWh |
| Agricultural land occupation     | 915              | 965  | -5.5%      | mm²/a/kWh |
| Urban land occupation            | 393              | 392  | 0.3%       | mm²/a/kWh |
| Natural land transformation      | 8.5              | 8.1  | 4.2%       | mm²/kWh |
| Water depletion                  | 241              | 248  | -2.7%      | cm³/kWh |
| Metal depletion                  | 26               | 26   | 1.9%       | g Fe eq/kWh |
| Fossil depletion                 | 10.0             | 9.7  | 3.2%       | g oil eq/kWh |
| Energy                           | 493              | 483  | 2.2%       | kJ/kWh |

Table S4.1 - Comparing results from the APOS and recycled content approaches to allocating for recycling

The result of running the analysis with this modification is a reduction in all impacts. Of the factors relevant for comparison with Parker et al.: climate change was found to be 28 g CO₂eq/kWh, cumulative energy demand 421 kJ eq/kWh and CO₂ emissions 26 g/kWh. This reduction is likely due to
the recycling rate of 90% being much higher than the average recycled content of the global steel mix in the ecoinvent data (43%) [ecoinvent, 2016 #1513]. Errors may have been introduced to this analysis by using a mixture of allocation methods, so use of the method described here is not recommended.

References