

Life cycle assessment of electricity generation from an array of subsea tidal kite prototypes

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Supplementary Information

This document contains the detailed lifecycle inventory data used in the LCA for the base case scenario. The document also includes the datasets used to model different materials/processes. The last section contains the life cycle inventory results for both resources and emissions, per kWh generated.

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1 Life cycle inventory data

1.1 kite and umbilical system.

Table S1 LCI of the kite and umbilical system

Material	per 1 kite and umbilical (kg)
Steel, unalloyed	590
Steel, chromium	3020
Steel, low-alloyed	8500
Copper	3470
Aluminium	150
Carbon fibre	790
Glass fibre	2100
Polystyrene	1520
Resin	708
Polyethylene	8330
Polyurethane	3900
Polyethylene	80

1.2 Gravity base foundation

Table S2 LCI of the gravity base foundation

Material	Gravity Base Foundation (tonne)		
	Concrete foundation (Base case)	Steel foundation	Hybrid foundation
Steel, low-alloyed	5.7	84	64
Steel, unalloyed	-	100	-
Concrete	1100	-	290
Reinforcing steel	120	-	30

1.3 Tidal Marine Substation

Table S3 LCI of the tidal marine substation

Material	per 1 TMS (kg)
Steel, low alloyed	107,000
Steel, unalloyed	72,000
Steel, recycled	430,000
Concrete	17,000
Copper	3500
Polyester	6700
Polyethylene	340
Hydraulic oil	6800

1.4 Cables

Table S4 LCI of the cables

Material	per 1 cable (kg)		
	TMS-TMS cable 1000 m (x3)	Export cable 8000 m (x1)	Onshore cable 4500 m (x1)
Copper	5400	32,000	18,000
Steel	1100	35,000	20,000
Polyethylene	16,000	110,000	59,000
Polyester	160	-	-
Polypropylene	-	6200	3500

1.5 Onshore substation

Table S5 LCI of the onshore substation

Material	Unit	Quantity
Multi-storey building	m ³	1000
Road	m*yr	2600
Aluminium	kg	16
Steel, low-alloyed	kg	4000
Copper	kg	880
Polyethylene	kg	84
Hydraulic oil	kg	1700

Table S6 shows the transportation of the components to the construction site, while table S7 shows the transportation in the water for the construction. Note that the figures in table S7 are similar to those used in the decommissioning process.

Table S6 Overview of the transportation of the components to the construction site

Part	Source	Distance (km)	Mode of Transportation
Wing	United Kingdom	480	trailer
Nacelle	Sweden	1200	lorry
Top Joint	United Kingdom	500	lorry
Struts	United Kingdom	530	trailer
Umbilical	Norway	2000	lorry
Tether	United Kingdom	300	lorry
Bottom Joint	United Kingdom	160	vessel
Offshore Foundation (Concrete)	United Kingdom	160	tugboat
Offshore Foundation (Steel)	Netherlands	1800	vessel
Offshore Foundation (Hybrid)	Netherlands	1800	vessel
TMS	United Kingdom	500	lorry

Table S7 Overview of the water transportation during construction

Process	Duration (hrs)	Vessel standby time	Vessel type
Tow kite foundation	24	0%	2.3 MW tugboat
Install kite foundation	24	50%	2.3 MW tugboat
Deploy tether with bottom joint and umbilical	36	20%	3 MW multicat
Deploy one kite	12	90%	3 MW multicat
Deploy one TMS	24	10%	3 MW tugboat
Deploy one export cable	144	67%	10 MW ship

1.6 Maintenance processes

Table S8 Overview of the maintenance operations.

Process	Duration (hrs)	Vessel standby time	Vessel type
Routine inspection and Maintenance (kite)	6.75	70%	3 MW multicat
Non-routine inspection and Maintenance (kite)	6.75	70%	3 MW multicat
Routine inspection (buoys)	12	50%	0.8 MW multicat
Long-term maintenance (buoys)	12	50%	3 MW multicat
Routine inspection (cables)	12	50%	0.8 MW multicat
Routine inspection and maintenance (TMS)	48	50%	0.8 MW multicat
Non-routine maintenance (cables)	96	50%	0.8 MW multicat
Major repair (cables)	96	25%	3 MW multicat
Replacement of tether	24	90%	3 MW multicat

1.7 Recycling ratios

Table S9 Recycling ratios

Material	Recycling ratio
Iron (including steel)	95%
Copper	90%

2 Linked background processes

This appendix lists the background processes directly linked via intermediate flows to foreground model. Most of the processes are taken from the ecoinvent database v3.3 (Ecoinvent, 2016), but others are modelled according to EPDs, reports, and other LCA studies. These in turn are linked to ecoinvent data. The level of detail of materials is higher here than that in the inventory level (for example, more steel types are shown here).

2.1 Core material production

Table S10 Processes used for the background data of the core materials in ecoinvent.

Material	Process name	Source
Aluminium 6082	aluminium alloy production, AlMg3 aluminium alloy, AlMg3 APOS, U - RER	ecoinvent 3.3
Carbon Fiber	Carbon Fiber production	Romaniw (2013)
Cast Copper	copper production, solvent-extraction electro-winning copper, from solvent-extraction electro-winning APOS, U - GLO	ecoinvent 3.3
Concrete	concrete block production concrete block APOS, S - DE	ecoinvent 3.3
Copper	copper production, primary copper APOS, S – RER	ecoinvent 3.3
Epoxy	epoxy resin production, liquid epoxy resin, liquid APOS, S – RER	ecoinvent 3.3
Foam	polystyrene foam slab production polystyrene foam slab APOS, S - RER	ecoinvent 3.3
Glass Fiber	glass fibre production glass fibre APOS, S – RER	ecoinvent 3.3
Polyethylene, high density	polyethylene production, high density, granulate polyethylene, high density, granulate APOS, U - RER	ecoinvent 3.3
Polyethylene, low density	polyethylene production, low density, granulate polyethylene, low density, granulate APOS, S - RER	ecoinvent 3.3
Polyurethane	polyurethane production, flexible foam polyurethane, flexible foam APOS, S - RER	ecoinvent 3.3
Polyurethane, in tether	polyurethane production, rigid foam polyurethane, rigid foam APOS, U – RER	ecoinvent 3.3
PVC	Polyvinylchloride resin (E-PVC), production mix, at plant, emulsion polymerisation – RER	ecoinvent 3.3
Reinforcing steel	reinforcing steel production reinforcing steel APOS, S - RER	ecoinvent 3.3

Stainless steel 1.4404	steel production, chromium steel 18/8, hot rolled steel, chromium steel 18/8, hot rolled APOS, S – RER	ecoinvent 3.3
Steel 355	steel production, low-alloyed, hot rolled steel, low-alloyed, hot rolled APOS, S - RER	ecoinvent 3.3
Steel, ballast	steel production, electric, low-alloyed steel, low-alloyed APOS, U - RER	ecoinvent 3.3
Steel, waste	steel production, electric, low-alloyed steel, low-alloyed APOS, U - RER	ecoinvent 3.3
Steel grade R4	steel production, electric, low-alloyed steel, low-alloyed APOS, S - RER	ecoinvent 3.3
Superduplex steel 1.4410	steel production, chromium steel 18/8, hot rolled steel, chromium steel 18/8, hot rolled APOS, S – RER	ecoinvent 3.3
Thermoplastic polyester	polyester resin production, unsaturated polyester resin, unsaturated APOS, S – RER	ecoinvent 3.3
Polyester fibre	Polyester fibre production	Roos, Sandin, Zamani, and Peters (2015)

2.2 Consumable materials (fuels and chemicals) production and infrastructure

Table S11 Processes used for the background data of the consumable materials in ecoinvent.

Material	Process name	Source
Coolant	chemical production, inorganic chemical, inorganic APOS, U - GLO	ecoinvent 3.3
Hydraulic oil	rape oil mill operation rape oil, crude APOS, U - Europe without Switzerland	ecoinvent 3.3
Diesel	diesel production, low-sulfur diesel, low-sulfur APOS, S - Europe without Switzerland	ecoinvent 3.3
Lubricating oil	lubricating oil production lubricating oil APOS, S - RER	ecoinvent 3.3
Paint	Minesto paint production and application	Jotun (2017)

2.3 Sub-components

Table S12 Processes used for the background data of the sub-components in ecoinvent

Sub-component	Process name	Source
Anodes	anode production, for metal electrolysis anode, for metal electrolysis APOS, U – RER	ecoinvent 3.3
Unspecified electrical components in nacelle	capacitor production, electrolyte type, > 2cm height capacitor, electrolyte type, > 2cm height APOS, U - GLO	ecoinvent 3.3
Generator, 500kW Onshore substation and maintenance building	ABB Generator production, 180-471 kW building construction, multi-storey building, multi-storey APOS, S - RER	ABB (2010) ecoinvent 3.3

HV transformer, 12MW	ABB Transformer production, 10MVA	ABB (2003)
MV transformer, 3MW	ABB Transformer production, 10MVA	ABB (2003)
Power converter, 250kW	ABB Converter production, 250kW	ABB (2011)
Reactor Road	ABB Transformer production, 10MVA road construction road APOS, S - CH	ABB (2003) ecoinvent 3.3

2.4 Transport modes

Table S13 Processes used for the background data of the transport modes in ecoinvent

Mode	Process name	Source
Ship	Diesel combustion, medium speed diesel engine	Jivén et al. (2004)
Lorry	transport, freight, lorry 16-32 metric ton, EURO6 transport, freight, lorry 16-32 metric ton, EURO6 APOS, S – RER	ecoinvent 3.3

2.5 Auxiliary electricity production

Table S14 Processes used for the background data of the auxiliary electricity production in ecoinvent

Location	Process name	Source
British Electricity mix	market for electricity, low voltage electricity, low voltage APOS, S - GB	ecoinvent 3.3
Swedish Electricity mix	market for electricity, low voltage electricity, low voltage APOS, S - SE	ecoinvent 3.3

2.6 Downstream grid distribution and infrastructure

Table 15 Processes used for the background data of the grid distribution and infrastructure in ecoinvent

Type	Process name	Source
High voltage transmission	electricity transmission, high voltage electricity transmission, high voltage APOS, U - GB	ecoinvent 3.3
Voltage transformation, high to medium	electricity voltage transformation from high to medium voltage electricity, medium voltage APOS, U - GB	ecoinvent 3.3
Voltage transformation, medium to low	electricity voltage transformation from medium to low voltage electricity, low voltage APOS, U – GB	ecoinvent 3.3

2.7 End of life

Since the cut-off method was used for the end-of-life, the recycling of the metals at the final use is not modelled. Non-metal parts (textile, fiberglass, and wood) is sent into incineration with energy recovery. The burden of incineration was modelled, without giving credit to the energy recovery. All the EOL transports are assumed to be carried by a lorry (“transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry 3.5-7.5 metric ton, EURO6 | APOS, S – RER” was used from ecoinvent) for a distance of 100 km.

3 Life Cycle Inventory Results

This section presents selected inventory data for both resources and emissions, per kWhe generated for the Base case scenario.

3.1 Use of resources

3.1.1 Non-renewable material resources²

Table S16 LCI results of the non-renewable material resources

Resource	Weight (g/kWhe)
Gravel	28.1
Calcite (calcium carbonate)	3.35
Clay	1.16
Sodium chloride	0.61
Iron	0.97
Aluminium	0.0559
Copper	0.0409
Chromium	0.012
Nickel	0.0088
Manganese	0.00464
Zinc	0.00331
Fluorspar	0.00102
Titanium dioxide	0.000527
Fluorine	0.000108

3.1.2 Renewable material resources

Table S17 LCI results of the renewable material resources

Resource	Volume (m ³ /kWhe)
Wood	0.000000872

3.1.3 Water use

Table S18 LCI results of the water use

Resource	Volume (m ³ /kWhe)
Water, unspecified	0.0559
Freshwater	0.0000126
Saltwater	0.00000508

² Accounts for recycling of steel 90% and copper 95%. No other material recycling has been considered.

3.1.4 Non-renewable energy resources³

Table S19 LCI results of the non-renewable energy resources

Resource	Energy (MJ/kWhe)
Crude oil	0.202
Natural gas	0.0822
Hard coal	0.068
Nuclear	0.0233
Lignite	0.00594

3.1.5 Renewable energy resources

Table S20 LCI results of the renewable energy resources

Resource	Energy (MJ/kWhe)
Biomass	0.0123
Hydropower	0.00762
Wind power	0.00248
Solar power	0.000167

3.2 Pollutant emissions

3.2.1 Potential environmental impacts

Table S21 Overview of the potential environmental impacts

Category	Impact	Unit
Acidifying gases	0.2	g SO ₂ -eq/kWhe
Eutrophying substances	0.00717	g P-eq/kWhe
Global Warming potential	26.7	g CO ₂ -eq/kWhe
Formation of ground level ozone	0.2	g C ₂ H ₄ -eq/kWhe

3.2.2 Emissions to air contributing most to environmental impact categories

Table S22 Emissions to air

Emission	Mass (g/kWhe)
Carbon dioxide, fossil	23.2
Methane, fossil	0.0644
Nitrogen oxides	0.159
Sulfur oxides	0.0428
Sulfur dioxide	0.0622
Carbon monoxide, fossil	0.0685
NM VOC	0.013

³ Includes chemically bound energy in materials, mainly plastics.

Table S23 Emissions to water

Emission	Mass (g/kWhe)
Phosphate	0.0214
COD	0.0591
Nitrate	0.0374
Copper, ion	0.00199
Nickel, ion	0.000688
Manganese	0.00767
Cobalt	0.000237

3.2.3 Emissions of radioactive isotopes

Table S24 Emissions of radioactive isotopes

Emission	Radioactivity (kBq/kWhe)
C-14	0.000201
Rn-222	1.41
Kr-85	0.027
Noble gases, radioactive	0.25941
H-3, tritium	0.0196
Xe-133	0.00106

3.2.4 Emissions of biogenic carbon dioxide

Table S25 Emissions of biogenic carbon dioxide

Emission	Weight (g/kWhe)
Carbon dioxide, biogenic	0.964

3.2.5 Emissions of toxic substances to air

Table S26 Emissions of toxic substances to air

Emission	Weight (g/kWhe)
Particulates, <2.5 μm	0.00949
Particulates, >10 μm	0.0152
Particulates, >2.5 μm and <10 μm	0.0073

3.2.6 Emissions of oil to water and ground

Table S27 Emissions of oil to water and ground

Emission	Weight (g/kWhe)
Oils, unspecified to water	0.0218
Oils, unspecified to soil	0.011

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